Manufacturing Innovation

Engineering an Innovation Approach to Industry 4.0

Larsen, Maria Stoettrup Schioenning

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BY
MARIA STØTTRUP SCHIØNNING LARSEN

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

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by

Maria Støttrup Schiønning Larsen

AALBORG UNIVERSITY
DENMARK

Dissertation submitted

Dissertation submitted:	September 20, 2023
PhD supervisor::	Assoc. Prof. Astrid Heidemann Lassen, Aalborg University
Assistant PhD supervisor:	Esben Skov Laursen, University College of Northern Denmark
PhD committee:	Professor Frank Gertsen (chair) Aalborg University, Denmark
	Professor Jessica Denise Bruch Mälerdalen University, Sweden
	Professor Monica Bellgran KTH Royal Institute of Technology, Sweden
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CV

Maria Støttrup Schiønning Larsen was born in Aalborg, Denmark. She studied at Aalborg University, earning her Bachelor of Science in Business Administration in 2015. The subsequent year, she obtained a Bachelor of Science in Global Business Engineering, and in 2018, she completed her Master of Science in Operations and Supply Chain Management. From 2018 to 2023, she was employed at the Department of Materials and Production at Aalborg University, where she was enrolled as PhD Fellow in 2019 in a collaborative partnership with University College of Northern Denmark. In her research, she combines insights from the disciplines of business and industrial engineering, focusing on the managerial facets of manufacturing innovation. Her research on manufacturing innovation was part of the research program Innovation Factory North targeting manufacturing innovation for Industry 4.0 in small and medium sized Danish manufacturing companies and funded by the European Regional Development Fund.

ENGLISH SUMMARY

It used to be that automation of the manufacturing system was strongly related to repetitive operations in the manufacturing system and, therefore, often associated with mass production, while product variety was managed by using manual processes. However, with the introduction of Industry 4.0, the fourth industrial revolution, automation of manufacturing systems producing a higher product variety is enabled. Automation of more flexible processes in Industry 4.0 is promoted by systemic data exchange and data integration, leading to autonomous decision-making in the manufacturing system. This means that the product design is automatically interpreted and translated to operations by the manufacturing system, thereby producing the product without the need, in theory, for human interference in the process. However, in practice, human is still expected to have an important, yet different, role in the manufacturing system than today. From the perspective of innovation, the operationalization of the vision of Industry 4.0, therefore, requires radical transformations of the manufacturing system, also referred to as manufacturing innovation.

The conceptual and visionary notion of an Industry 4.0 manufacturing system still lacks a translation to operational solutions to visualize the true potential, e.g., presented in examples of best practices. This lack of transparency and the increasing complexity resulting from the systemic and data-driven manufacturing innovations for Industry 4.0 pose new requirements for companies to approach manufacturing innovation. Therefore, this dissertation aims to create a systemic approach to manufacturing innovation for Industry 4.0 extending beyond the technical aspects of these solutions.

The empirical results are derived from case research using data from multiple manufacturing companies' approach to manufacturing innovation for Industry 4.0 inspired by gaps in existing research on the subject and observations from interactions with more than 90 companies. The research uses qualitative research methods to explore and refine the scientific understanding of the approach to manufacturing innovation in the context of Industry 4.0.

The results of this dissertation evolve into three parts that contribute to enhancing the understanding of how to approach manufacturing innovation for Industry 4.0. The first part of the dissertation explores why the adoption of Industry 4.0 is at a standstill despite manufacturing companies showing extensive interest in getting started. The findings reveal an inconsistency between the practical approach in industry and the theory's most effective innovation process. In practice, the companies expect to approach manufacturing innovation for Industry 4.0 using a linear process where the link between problem and solution is easily identifiable. Therefore, the innovation process has high transparency and low risk. However, from a theoretical perspective,

manufacturing innovations for Industry 4.0 encompass a much higher level of complexity, posing more uncertainty and higher risk to the innovation process, thereby requiring a more flexible innovation approach. The second part of the findings explores successful approaches to manufacturing innovation in the context of Industry 4.0, emphasizing the need to use a flexible approach operationalized by, e.g., iterations, learning by doing, and prototyping in the innovation process. Furthermore, a process model for manufacturing innovation in the context of Industry 4.0 is derived, guiding the transformation of an idea to a solution implemented and put into use. The third and last part of the findings delves into the 'sandbox' approach as a tool for manufacturing innovation, presenting characteristics and benefits of using this approach to create manufacturing innovations for Industry 4.0.

The findings in this dissertation contribute to establishing a systemic approach to manufacturing innovation in the context of Industry 4.0 in which both technical and human aspects are considered in the process from start to end. The results contribute with the essential knowledge necessary to advance industry practice to enhance the quality of the approach to manufacturing innovation in manufacturing companies, thereby creating a strategic foundation for manufacturing. From a scientific perspective, the research contributes to establishing manufacturing innovation as a dedicated research area.

DANSK RESUME

Tidligere var automatisering stærkt relateret til gentagne opgaver i produktionssystemet og blev derfor ofte associeret med masseproduktion, mens varians i produktet ofte blev imødekommet med manuelle processer. Men med introduktionen af Industri 4.0, den fjerde industrielle revolution, muliggøres automatisering af produktionssystemer, der producerer produkter med langt højere varians. Automatisering af mere fleksible processer i Industri 4.0 er fremmet af systemisk dataudveksling og -integration, som giver mulighed for autonom beslutningstagning i produktionssystemet. Det betyder, at produktdesignet automatisk fortolkes og omsættes til operationer i produktionssystemet, hvorved produktet, i teorien, produceres uden behov for menneskelig involvering. I praksis forventes mennesket dog fortsat at udgøre en vigtig, men anderledes, rolle i produktionssystemet end i dag. Fra et innovationssynspunkt kræver operationaliseringen af Industri 4.0 visionen derfor nye, radikale, innovative løsninger i produktionssystemet, også kaldet produktionsinnovation.

Der er fortsat et behov for at få omsat den konceptuelle og visionære forestilling af Industri 4.0 produktionssystemet til operationelle løsninger, der synliggør det egentlige potentiale i denne transformation, fx ved best practice. Manglen på gennemsigtighed i kombination med den øgede kompleksitet affødt af systemiske, datadrevne løsninger i produktionsinnovationer til Industri 4.0 medfører nye krav til, hvordan virksomheder skal tilgå opgaven med at innovere deres produktionssystem. Målet med denne ph.d.-afhandling er derfor at bidrage med en helhedsorienteret tilgang til produktionsinnovation i en Industri 4.0 kontekst.

Forskningsresultaterne er udledt på baggrund af caseforskning, som beror på data indsamlet fra adskillige produktionsvirksomheders tilgang til produktionsinnovation i en Industri 4.0 kontekst. Undersøgelserne anvender kvalitative metoder, der er inspireret af gab i den eksisterende litteratur på området samt observationer fra interaktioner med mere end 90 virksomheder.

Resultaterne i denne ph.d.-afhandling udfoldes i tre dele, som tilsammen bidrager til en øget forståelse af, hvordan produktionsinnovation skal tilgås i en Industri 4.0 kontekst. Den første del af afhandlingen undersøger, hvorfor implementering af Industri 4.0 synes at være stillestående trods massiv interesse i produktionsvirksomheder for at komme i gang. På baggrund af resultaterne identificeres en uoverensstemmelse mellem den praktiske tilgang og den, ifølge teorien, mest effektive innovationsproces. I praksis forventer virksomheder, at produktionsinnovation til Industri 4.0 skal skabes via en lineær innovationsproces. En sådan tilgang beror på en tydelig sammenhæng mellem problemet, der skal løses, og den dertilhørende løsning, hvilket betyder, at innovationsprocessen afhænger af gennemsigtighed og lav risiko. Disse forventninger strider dog mod den teoretiske

forståelse af produktionsinnovation til Industri 4.0, der i denne sammenhæng er beskrevet som værende langt mere kompleks, hvilket medfører en større usikkerhed og derved højere risiko i innovationsprocessen. Sådanne krav kalder derfor på en fleksibel frem for en lineær tilgang til produktionsinnovation. Anden del af resultaterne undersøger succesfulde tilgange til produktionsinnovation i en Industri 4.0 kontekst. Disse resultater peger mod brugen af en fleksibel innovationstilgang, operationaliseret vha. fx iterationer, læring gennem handlinger samt udarbejdelse af prototyper. Derudover præsenteres en procesmodel for produktionsinnovation i en Industri 4.0 kontekst, som guider forvandlingen af en idé til en løsning. Den tredje og sidste del af resultaterne udforsker 'sandkasse' tilgangen som et værktøj til produktionsinnovation og præsenterer dens karakteristika og fordele.

Tilsammen bidrager forskningsresultaterne i denne ph.d.-afhandling til at skabe en systemisk tilgang til produktionsinnovation i en Industri 4.0 kontekst, hvor både tekniske og menneskelige aspekter tages i betragtning fra start til slut. Resultaterne bidrager med vigtig og nødvendig viden for at kunne fremme praksis i industrien, således at kvaliteten af virksomhedernes tilgang til produktionsinnovation kan højnes og derved skabe et strategisk vigtigt fundament for virksomhedens produktion. Fra et videnskabeligt perspektiv bidrager resultaterne desuden til at etablere produktionsinnovation som et selvstændigt forskningsområde.

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When I decided to pursue a PhD, I was motivated by wanting to learn how to approach manufacturing innovation, but what I did not know back then was that this would be the center of my research. Even though much of the work related to this PhD dissertation was made by me, I would not have gotten this far without immense support from several people.

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CHAPTER 1. INTRODUCTION

> *"In the past, it was the management who pointed out where we should invest and what we should do. Now, the management no longer has this knowledge and therefore needs to learn how to initiate these new projects"* (Production Manager and participant in Innovation Factory North)

Over the past three centuries, manufacturing systems have undergone remarkable changes, which have enabled new opportunities such as higher productivity, automation, and digital data logging. These radical changes in the manufacturing system through time are moved by industrial revolutions derived from technological advancements, increasing the inherent complexity in the manufacturing system organizing equipment and people (Bellgran and Säfsten, 2010; ElMaraghy et al., 2021; Groover, 2016; Kagermann et al., 2013).

During the period 1760-1830, the first industrial revolution took place, introducing essential innovations to the manufacturing system. The invention of the steam engine, the use of machine tools, and the development of the fabrication system organizing factory workers based on the division of labor principles are some of the most significant contributors to the transformation of the manufacturing system in the first industrial revolution (Bellgran and Säfsten, 2010).

The electrification of the factory is often associated with the second industrial revolution, which took place from the 1870s until the 1980s (Oztemel and Gursev, 2020). During this period, the manufacturing system for mass production was created. One of the major contributors to manufacturing innovation at this time was the introduction of the assembly line and the scientific management movement (Bellgran and Säfsten, 2010; Groover, 2016).

During the third industrial revolution, manual processes were replaced by automated solutions enabled by the introduction of computers, electronics, and IT systems. Technologies which were refined and extended since then and now serve as fundamental technologies to the adoption of Industry 4.0, the fourth industrial revolution (Kagermann et al., 2013). This paradigm shift introduces a vision of seamlessly integrating digital technologies, creating a highly interconnected and intelligent manufacturing system where machines and systems can make autonomous decisions (Kagermann et al., 2013; Monostori et al., 2016). Early visions of Industry 4.0 describe the Industry 4.0 factory as a ‘dark factory’ with no human involvement in operations. However, more recently, such interpretations were disregarded, acknowledging the role of humans in the manufacturing system (ElMaraghy et al., 2021; Oztemel and Gursev, 2020).

The Industry 4.0 manufacturing system is enabled by multiple innovations seeking synergies to the remaining manufacturing system through systemic relations to the technical and human elements (Lassen and Wæhrens, 2021; Marcon et al., 2022). Hence, the Industry 4.0 manufacturing system comprises various interrelated manufacturing innovations combined into one system. Nine pillars of technological advances, illustrated in Figure 1, are denominated as central to manufacturing innovations for Industry 4.0 (Rüßmann et al., 2015):

- Big data and analytics
- Autonomous robots
- Simulation
- Horizontal and vertical system integration
- Industrial internet of things
- Cybersecurity
- The cloud
- Additive manufacturing
- Augmented reality (Rüßmann et al., 2015)

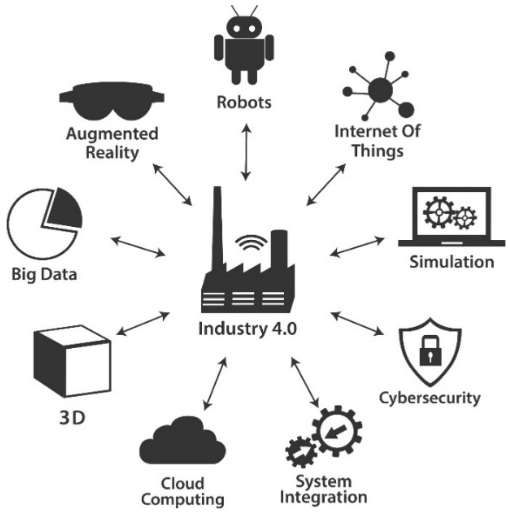

Figure 1: Nine pillars of technological advances for Industry 4.0 (colourbox.dk).

However, despite the availability of these technologies enabling the transformation of the manufacturing system to Industry 4.0, the industry's adoption level is still deficient (Erhvervsministeriet, 2022; IDA, 2020). Denmark, for instance, has one of the most digitally advanced manufacturing industries in Europe, but despite this, the level of digitalization in Danish manufacturing companies is low (Erhvervsministeriet, 2022; IDA, 2020), which emphasizes the lack of progress with the adoption of Industry 4.0 in general. Furthermore, the adoption is distorted by a proportional relationship between company size and the adoption rate of Industry 4.0, which has grown in recent years. This marks an increasing discrepancy between SMEs and large companies that may, over time, result in severe consequences for the competitiveness of SMEs (Erhvervsministeriet, 2021). This is a vital threat to the competitiveness of the Danish manufacturing industry, where 99% of the companies are SMEs (Danmarks Statistik, 2023).

When directing the attention to those companies that are capable of progressing with the adoption of Industry 4.0, these companies tend to focus on low-hanging fruits, e.g., exploiting readily accessible technologies for data collection in the production rather than more advanced technologies such as collaborative robots and machine learning (IDA, 2020; Lassen, 2022). In addition to this, the companies' approaches suffer from sporadic implementations rather than a continuous focus on innovating the manufacturing system (Christensen et al., 2021; Dooley and O'Sullivan, 2000; Frishammar et al., 2013; Hedman et al., 2021) which may be explained by the unclear potential of Industry 4.0 technologies to operations. This means that best practice for Industry 4.0 manufacturing systems is yet to be established (Lassen and Wæhrens, 2021; Napoleone et al., 2020). Exploiting readily accessible technologies in sporadic implementations brings attention to short-term benefits, such as cost reductions and incremental improvements in productivity, instead of more extensive and strategic benefits in the long term (Lassen and Wæhrens, 2021). The consequence is isolated solutions lacking interconnection, otherwise a prerequisite for Industry 4.0. This makes it impossible for these companies to exploit the systemic potential of Industry 4.0 that yields competitive advantages. Hence, even when manufacturing companies adopt Industry 4.0, the solutions implemented are relatively simple compared to the extensive potential of Industry 4.0 (Lassen and Wæhrens, 2021).

This indicates that introducing Industry 4.0 has posed new requirements for approaching manufacturing innovation (Kagermann et al., 2013; Lasi et al., 2014; Møller et al., 2023c). To exploit the synergies in the systemic relations in manufacturing innovations for Industry 4.0 to other parts of the organizational system, for instance, requires adaptations of the manufacturing innovation to fit the complex context of the respective company's manufacturing system (Møller et al., 2023c). This means that the management needs to undertake a more active role, participating, among others, in the idea generation and the technical development of manufacturing innovations for Industry 4.0, accepting a higher level of uncertainty and, thereby, a higher risk in manufacturing innovation than previously (Leonard-Barton, 1992; Li, 2020). However, most manufacturing companies are not used to approaching manufacturing innovation this way. At the same time, research on the approach to manufacturing innovation is scarce (Calabrese et al., 2022), which means that theory cannot guide manufacturing companies in this transition. The research presented in this dissertation addresses this knowledge gap, advancing the theoretical understanding of how to approach manufacturing innovation for Industry 4.0.

CHAPTER 2. STATE-OF-THE-ART

Research related to manufacturing innovation, i.e., the activity of innovating the manufacturing system, remains inadequate, which leaves the gap for further research quite open (Becheikh et al., 2006; Bruch and Bellgran, 2013; Frishammar et al., 2012; Kurkkio et al., 2011; Larsson, 2017; Larsson, 2020; Piening and Salge, 2015). The inadequacy of the research topic is also reflected in the lack of a unified frame of reference for a definition of manufacturing innovation. To align the understanding of what is meant by the term 'manufacturing innovation,' the first part of this chapter aims to define manufacturing innovation as a concept. The second part of the chapter focuses on the approach to manufacturing innovation. As an innovation process is a systematic approach to manage doing an innovation (Papinniemi, 1999), the second part of the chapter presents a review of existing research on the process for manufacturing innovation. The results of this chapter frame the research results of this dissertation.

2.1. MANUFACTURING INNOVATION AS A CONCEPT

Before delving into definitions of manufacturing innovation, the distinction between manufacturing innovation and the two related concepts of process innovation and manufacturing development needs clarification. This dissertation considers manufacturing innovation as a subset of process innovation (Bessant, 1982; Larsson, 2017) as manufacturing innovation refers to innovations of manufacturing-related processes (Braun, 1981), whereas process innovation also considers innovations of other business-related processes beyond the manufacturing system (Davenport, 1993; Papinniemi, 1999). On the other hand, manufacturing innovation is superior to manufacturing development, which refers to the activity of problem-solving (Pisano, 1997) and encompasses both problem-solving for manufacturing improvement efforts, introducing incremental changes to the manufacturing system (Kurkkio et al., 2011; Utterback and Abernathy, 1975), and problem-solving for manufacturing innovation which imply radical changes to the manufacturing system (Davenport, 1993; Kurkkio et al., 2011). This means that manufacturing development as a problem-solving activity in manufacturing innovation is part of the innovation process. The relationship between the three terms, process innovation, manufacturing innovation, and manufacturing development, is illustrated in Figure 2.

Cusumano (1988) defines manufacturing innovation as ”*innovation in production management*” (p. 30), whereas Dooley and O'Sullivan (2000) specify it as ”*innovation within manufacturing systems redesign*” (p. 411), which is, however, very generic and unspecific. Both Yamamoto and Bellgran (2013) and Mamasioulas et al. (2020) use Hammer and Champy's (1993) definition of process innovation as a source of inspiration and thereby consider manufacturing innovation and process innovation as equivalents. Their definition of manufacturing innovation is:

”*an organization-wide effort that involves fundamental rethinking and radical redesign of manufacturing related processes and systems to achieve dramatic improvements in manufacturing performance measures such as cost, quality, service, and speed*” (Yamamoto and Bellgran, 2013, p. 480).

Bessant (1982) disconnects the definition of manufacturing innovation from process innovation, detailing the extent of the change of a manufacturing innovation using the definition: ”*the type of innovation which changes neither the product nor the basic process, but only some elements in the process*” (p. 119). Braun (1981) also defines manufacturing innovation as proportional to the product and the manufacturing processes but adds an organizational perspective to the definition:

”*a new method of producing an essentially established product by an essentially established process. Manufacturing innovation usually involves the installation of novel machinery and/or novel methods of controlling the manufacturing process. Very often the efficient use of the innovation requires a variety of organizational changes, but changes in organization alone do not constitute manufacturing innovation*.” (p. 247).

Larsson (2020) contributes with a contemporary definition relating the value of manufacturing innovation to the interests of stakeholders rather than exclusively internal performance measurements:

”*[Manufacturing] innovation can be described as a process of change, involving development and implementation of new or increased production capability in a [manufacturing] system, manifested as new technology, working methods, processes etc., creating value for stakeholders within or in relation to the [manufacturing] system.*” (p. 35).

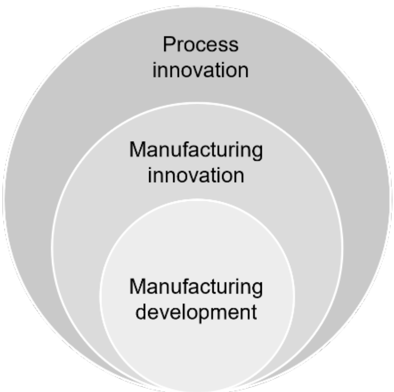

Figure 2: The relationship between process innovation, manufacturing innovation, and manufacturing development.

This definition of manufacturing innovation constitutes a frame of reference for the meaning of manufacturing innovation in this dissertation, as it recognizes the strategic importance of manufacturing and manufacturing innovation for a company. This perspective is consistent with the vision of Industry 4.0 (Møller, 2023c).

2.1.1. CHARACTERISTICS OF MANUFACTURING INNOVATION

Manufacturing innovation enhances the performance of the manufacturing system by, e.g., reducing manufacturing costs or enhancing productivity, flexibility, or product quality (Schroeder et al., 1989). The impact of manufacturing innovation on the company's manufacturing system can be evaluated based on different parameters like the degree of innovation and the area of the manufacturing system being transformed (Chaoji and Martinsuo, 2019; Yamamoto and Bellgran, 2013). The degree of innovation ranges from incremental to radical manufacturing innovations (Boer and Bessant, 2004; Garcia and Calantone, 2002). Incremental manufacturing innovations introduce minor improvements or enhancements to the manufacturing system, often utilizing readily available technologies and methods. By contrast, radical manufacturing innovations impose remarkable changes to the manufacturing system, introducing new technologies and methods (Chaoji and Martinsuo, 2019; Yamamoto and Bellgran, 2013). As incremental innovations rely on readily available technologies and methods, knowledge already exists to support the process of developing and implementing such manufacturing innovations as opposed to radical innovations, where existing knowledge levels are often limited (Bessant et al., 2005). Furthermore, with incremental innovations, only minor changes to the manufacturing system take place, simplifying the process, whereas radical innovations impose more significant changes to the system, making the process more complex (Bessant et al., 2005; Verloop, 2006).

The manufacturing innovation can change either a core manufacturing process, e.g., producing the product in a new way, or an enabling process in the manufacturing system, such as introducing a new planning method or using RFID to track products in the system (Chaoji and Martinsuo, 2019; Yamamoto and Bellgran, 2013). While innovations in core manufacturing processes can have significant impact on a company's competitive advantage in the market, the same accounts for enabling processes (Pisano, 1997). The introduction of the Lean production principles at Toyota exemplifies this. The transformation to Industry 4.0 involves a radical change in both enabling processes and core manufacturing processes. Technologies like the Industrial Internet of Things, horizontal and vertical integration, and big data and analytics are examples of technologies that can be used to change enabling processes in the manufacturing system. Technologies such as collaborative robots and additive manufacturing can enable changes to core manufacturing processes.

In addition to evaluating the internal changes imposed on the manufacturing system by innovation, the innovation can be evaluated externally by its degree of newness.

The theoretical distinction ranges newness of a manufacturing innovation from being new to the company, the industry, and the world (Garcia and Calantone, 2002). The newness transfers from being new to the world to being new to the company as technologies mature and standards emerge, creating a higher level of transparency in applications, expected benefits, and costs (Brown, 1992; Rogers, 2003) and thereby impacts how to approach manufacturing innovation.

2.2. MANUFACTURING THROUGH THE LENSE OF INNOVATION RESEARCH

What is acutely apparent from the literature is that the concept of manufacturing innovation is immature and underdeveloped as a dedicated area of research. One indication of this is found in the fact that manufacturing innovation, here referring to the new solution introduced to the manufacturing system, is often considered a spillover effect of product innovation (Bessant, 1982; Braun, 1981; Davenport, 1993) that facilitates higher productivity and efficiency (e.g., shorter processing time, improved throughput, or cost reductions). Utterback and Abernathy (1975) describe this relationship in three phases: In phase one, a new product is introduced to the market. The best-performing design is still to be determined, so product design is often customized or frequently adapted in this phase. The role of manufacturing is, therefore, to provide a high degree of flexibility to accommodate changes in product design efficiently. At this point, manufacturing innovation is hardly prioritized due to constantly shifting requirements for manufacturing capabilities. In phase two, the product design starts to mature, resulting in fewer requirements for adaptation in the manufacturing system and triggering an intensified price competition. Therefore, the objective of the manufacturing system is specialization and formal operating procedures to enable efficiency and lower costs through radical manufacturing innovations. In phase three, product standardization is reached, and cost reduction is in focus, for which reason manufacturing innovations are incremental innovations aiming to improve productivity and quality. The relationship between product innovation and manufacturing innovation across the three phases is illustrated in Figure 3. Graph A indicates that product innovation starts with a radical innovation establishing the essential product design, which is refined over time, among others, to reduce unit cost. In contrast, graph B indicates that manufacturing innovations are incremental changes that continuously refine the capabilities of the manufacturing system to accommodate new product requirements. Hence, from this perspective, product innovation triggers a need for manufacturing innovation to change the manufacturing system from an uncoordinated process to a systemic process with lower unit cost, resulting in incremental manufacturing innovations. From this perspective, product innovation is regarded the strategic resource creating a competitive advantage in the market, whereas the role of manufacturing innovation is to fulfill the requirements posed by product innovation. This is also reflected in the height and slope of the two graphs, which show that in the beginning, product innovation takes place with a very high rate and very frequently, whereas manufacturing innovation is non-existent. As the product design matures, manufacturing innovation starts to receive attention, however, with a much lower rate and frequency than product innovation, which emphasizes that manufacturing innovation is not regarded a strategic resource. This, however, conflicts with the role of manufacturing from the perspective of Industry 4.0 (Kagermann et al., 2013).

This conceptualization of manufacturing innovation serving as a spillover effect of product innovation may explain why manufacturing innovation is not well-established as a dedicated research area. However, even though manufacturing innovation, in its most widespread understanding, is considered a by-product of product innovation, manufacturing innovation can also act as an enabler of product innovation (Bruch and Bellgran, 2014; Garcia and Calantone, 2002; Kahn, 2018; Pisano, 1997). This relationship is illustrated in Figure 4. With the opportunities related to Industry 4.0 technologies, manufacturing innovation has the potential to enable new product innovation (Kagermann et al., 2013), making manufacturing innovation a more substantial strategic resource with a more long-term view. However, this role of manufacturing innovation for Industry 4.0 still needs to be explored (Napoleone et al., 2020).

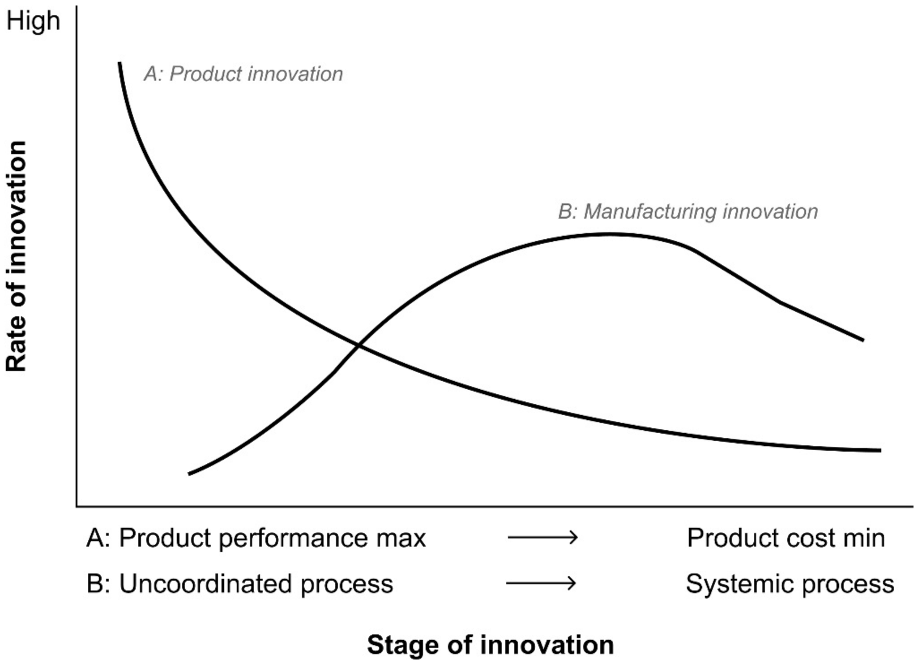

Figure 3: Relation between product innovation and manufacturing innovation. Adapted from Utterback and Abernathy (1975).

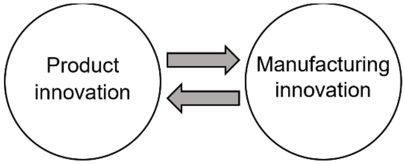

Figure 4: Manufacturing innovation enabling product innovation, and product innovation enabling manufacturing innovation.

Consistent with the traditional realization of product innovation, the realization of manufacturing innovation, in general, covers three phases: 1) Front-end, 2) development, and 3) implementation (Garud et al., 2013; Lassen, 2007; Yamamoto and Bellgran, 2013). Ideas are generated and refined in the front-end phase, and understanding the problem is initiated. The ideas for problem-solving are shaped and transformed into a solution in the development phase, and finally, the solution is implemented in the third and last phase, which covers both technical and human aspects of the implementation (Boer and During, 1987; Garud et al., 2013).

However, the roles of product innovation and manufacturing innovation are different, for which reason the design of the process for manufacturing innovation puts forth other requirements than the process for product innovation (Becheikh et al., 2006; Dooley and O'Sullivan, 2000; Kurkkio et al., 2011). Since manufacturing systems are socio-technical systems, introducing a manufacturing innovation may impact several other aspects of the manufacturing system beyond the changes directly imposed by the innovation (Bellgran and Säfsten, 2010; Larsson, 2017). Consequently, the fit of the innovation for existing operations, impact on production needs (e.g., reliability of the manufacturing system), production costs, product quality, and impact on future product design options are all examples of consequences and decisions that must be considered in the process for manufacturing innovation (Bessant et al., 2005; Frishammar et al., 2013). Furthermore, implementing a manufacturing innovation requires the involvement of the organization to keep motivation high, exploit learning outcomes (Dooley and O'Sullivan, 2000), and creating operating procedures and organizational routines to secure the use of the innovation (Pisano, 1997). These aspects present examples of requirements for the process for manufacturing innovation that differ from those posed on the process for product innovation.

2.2.1. THE PROCESS FOR MANUFACTURING INNOVATION

Despite diverse requirements for the innovation process design, research concentrating on process models for manufacturing innovation is minimal. Existing process models, for instance, address the innovation process focusing on manufacturing innovations using specific technologies (e.g., Boer and During (1987) and Zhang et al. (2021)) or manufacturing innovation within specific industries (e.g., Aliasghar et al. (2019), Frishammar et al. (2013), Wagner (2008)). Even though such research may be a source of inspiration for how to approach manufacturing innovation in the context of Industry 4.0, the results suffer from limited generalizability to contemporary innovation of the manufacturing system.

The process model proposed by Dooley and O'Sullivan (2000) is one of few models that presents a generic process model for manufacturing innovation. The model relies on a funneling approach where first problem identification occurs, followed by a phase of problem-solving, and lastly, implementation. The process proposed by Braun (1981) consists of similar phases. However, these are approached iteratively, shifting between the phases to increase the understanding of the problem and improve solution and implementation. While the process lacks empirical validation, the results inspire to further research as the introduction of digitalization, according to Li (2020), calls for more flexible approaches to innovation, e.g., using iterative process models.

Most of the existing research related to the process for manufacturing innovation focuses on activities related to problem-solving and solution design, also referred to as design engineering (Maier et al., 2022). While these learning outcomes are valuable to the adoption of manufacturing innovation, such focus in research has some limitations. Research related to design engineering supports the development phase, proposing areas of application of technology, expected benefits, tools, and methods for developing a solution (Garud et al., 2013). However, strictly focusing on the development phase disregards relations to the other phases. By neglecting the totality of parts of the process, a risk exists that essential interactions are overlooked, and the innovation is not adapted to its context (Larsson, 2017; Maier et al., 2022). Furthermore, most of the technical aspects of the innovation may be addressed in the development phase. However, the business success of a manufacturing innovation depends on the ability of an organization to adopt and utilize it, activities which are mostly related to the implementation phase (Boer and During, 2001).

While existing research supports understanding how to approach manufacturing innovation in the context of Industry 4.0, the results lack coherence and a systemic perspective on the approach to manufacturing innovation. More research is therefore needed to support the industrial transformation and take advantage of the technological opportunities derived from Industry 4.0 technologies. This dissertation aims to contribute to this knowledge gap.

CHAPTER 3. RESEARCH OBJECTIVE

Despite the importance of manufacturing, the review of existing research concludes that research on how to approach manufacturing innovation is limited and does not support the transformation to Industry 4.0. Therefore, the scientific objective of this dissertation is to contribute to this knowledge gap. The research is framed in the context of Industry 4.0 for two reasons: 1) It is (one of) the most prominent contemporary avenues for manufacturing innovation, and 2) the Industry 4.0 manufacturing system requires much more complex, systemic solutions than prior manufacturing innovations, which increases the requirements for how to approach manufacturing innovation (Møller, 2023c). From an industrial point of view, the research in this dissertation aims to create knowledge that can support the management of manufacturing companies in manufacturing innovation for Industry 4.0.

This dissertation addresses three research questions that contribute to the research area and the understanding of the approach to manufacturing innovation in the context of Industry 4.0. The three research questions are:

1. Why is the adoption of manufacturing innovation for Industry 4.0 at a standstill?
2. How should manufacturing innovation for Industry 4.0 be approached in order to improve the industrial adoption?
3. Which tools can support manufacturing companies' approach to manufacturing innovation in the context of Industry 4.0?

To answer these three questions, the remainder of the dissertation is structured as follows: Chapter 4 presents the research methodology, covering the overall approach to the research in the dissertation. Chapter 5 briefly presents the content of the seven articles appended to this dissertation. The findings are presented more in-depth in Chapters 6-8. Chapter 6 addresses research question 1, Chapter 7 addresses research question 2, and Chapter 8 addresses research question 3. Combined, the three chapters' results constitute the findings of this dissertation. The results are concluded in Chapter 9, and suggestions for future research are presented.

CHAPTER 4. RESEARCH DESIGN

The design of the research that was carried out as part of this dissertation is presented in this chapter. Where the individual articles have separate research methodologies described in the article, this chapter aims to describe the research design from a holistic perspective, focusing on how the research topic was approached in general.

The empirical data available for this research extends far beyond the data used in the individual articles. Although not all the data was used explicitly in data analyses for the articles, the data provided valuable industrial insights into the research topic, contributing to the research and increasing its relevance.

4.1. SOCIO-TECHNICAL SYSTEMS AS FOUNDATIONAL RESEARCH PERSPECTIVE

Transformations of manufacturing systems where the operating model is radically changed impose alterations to the technical and human elements of the manufacturing system. For this reason, such transformation can also be referred to as a transformation of a socio-technical system (Trist and Bamforth, 1951).

Leavitt's (1965) diamond model is one of the most widely applied frameworks representing the effect of socio-technical changes on a system (Sony and Naik, 2020). The framework is illustrated in Figure 5 and depicts the organization as a complex system composed of four interdependent variables: Technology, people, structure, and task. The approach to manufacturing innovation for Industry 4.0 initiates a change to the manufacturing system. The four variables can, therefore, be interpreted in this context, where the 'technology' dimension reflects the manufacturing innovations using Industry 4.0 technologies. The 'people' dimension represents the employees and managers involved in the innovation process and affected by the manufacturing innovation once in operation. The innovation approach and innovation process supporting the making of the manufacturing innovation is reflected in the 'structure' dimension. The 'task' dimension represents the specific actions in the innovation process, such as building a prototype or selecting technology. Changing one dimension will initiate a reaction in the three other dimensions. For instance, implementing a manufacturing innovation using an Industry 4.0 technology, e.g., a collaborative robot, in the manufacturing system (change in technology dimension) can lead to a need for new competences on the shopfloor to operate the robot (change in people dimension). These interrelations between the technical and social elements of manufacturing innovation require continuously balancing the system when trying to change one of its dimensions (Badham et al., 2000; ElMaraghy et al., 2021). Therefore, the effect on all dimensions of the system should be considered in manufacturing innovation.

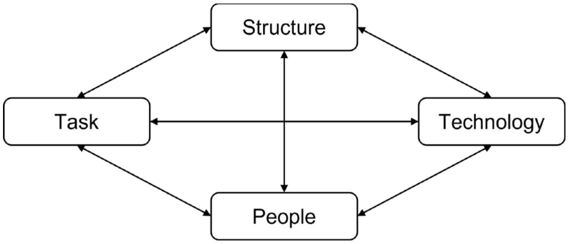

Figure 5: Leavitt's diamond model. Adapted from Leavitt (1965).

The social dimension in the design of socio-technical systems reflects both the users of the system, e.g., operators using the manufacturing innovation, and stakeholders of the system, e.g., production management interested in improving the performance of the manufacturing system (Maier et al., 2022). Both have central roles in the chances of succeeding with manufacturing innovation (Hansen et al., 2021; Lassen and Wæhrens, 2021). Even though the importance of considering the socio-technical system in manufacturing innovation is emphasized in existing research (ElMaraghy et al., 2012), much of the current research streams related to Industry 4.0 focus on the technical aspects of this change (Beier et al., 2020; Davies et al., 2017). However, recently, more research was initiated on the human factors related to the transformation to Industry 4.0 (see, e.g., Lassen et al. (2023) and Hansen et al. (2023)).

From the viewpoint of socio-technical systems, one of the dominant reasons for the failure of manufacturing innovation is the lack of coupling between the change process of the manufacturing innovation and the technical system development process. This is, among others, often manifested in the responsibility being divided between two distinct teams, which mainly coordinate and communicate during the handover of the manufacturing innovation, going from technical development and perhaps implementation to operations (Baxter and Sommerville, 2011). Hence, acknowledging the socio-technical perspective in the design of innovation approaches to manufacturing innovation in the context of Industry 4.0 improves the chances of creating innovations accepted by users and delivering higher value to stakeholders (Baxter and Sommerville, 2011). From this, several characteristics of socio-technical systems are inferred:

- Organizational systems must be considered as consisting of mutually dependent parts and their interrelations: The technical and social parts, which in this research is interpreted as the four dimensions technology, people, structure, and task by Leavitt (1965). In this research, the approach to manufacturing innovation for Industry 4.0 requires a change in the socio-technical system affecting all four dimensions.
- The performance of the system requires a joint optimization of both technical and social parts, which means that the approach to manufacturing innovation

needs to consider not only the technical solution but also, e.g., the effect on employees and how to engage them in the innovation process.

- The solution objective of a socio-technical system can be realized in more than one way. In the innovation process, different alternatives are, for instance, discovered and evaluated, e.g., based on the effect on the other elements of the socio-technical system, like competence requirements and access to technology.
- Change can be initiated in any part of the system. Changing one part of the system will spark a dynamic change where all parts are adjusted to obtain a new system in balance. Implementing a new Industry 4.0 solution to the manufacturing system may change operations and employees' tasks. The innovation process, therefore, needs to consider aspects beyond the technical part of a manufacturing innovation.

The research presented in the current dissertation is conducted based on this fundamental view. For instance, the systemic and dynamic perspectives on manufacturing innovation were essential elements of the research from the start, among others, because the vision of Industry 4.0 is to create a systemic and dynamic manufacturing system. Through the research, more socio-technical elements were discovered and refined, contributing to a more profound understanding of how to approach manufacturing innovation for Industry 4.0.

4.2. RESEARCH APPROACH

At the beginning of this research in 2019, almost no industrial applications of Industry 4.0 existed, and research on the approach to manufacturing innovation for Industry 4.0 had received little attention. Therefore, the research in this dissertation contributes to a nascent research area. Even though the number of cases has increased since 2019, the number of successful cases is still low. Hence, it was irrelevant to use a research approach requiring an extensive number of existing confirmatory cases to be available. Instead, the empirical research needed to take an exploratory approach to solidify existing, fragmented theoretical contributions and build new theory from here. Exploration is done, e.g., by observing and identifying new phenomena and suggesting relations between them (Åhlström, 2016). Qualitative research approaches supporting exploration are, for instance, action research, case research, and longitudinal field studies and are, therefore, helpful to contribute to a nascent research area (Åhlström, 2016).

Case research was used as the basis for researching the topic of this dissertation. Case research is one of the strongest research methods in operations management (Boer et al., 2015) and is an excellent method to study in-depth, emergent practices, such as the adoption of Industry 4.0, and to develop new theory (Flyvbjerg, 2006; Voss et al., 2016; Yin, 2018). Existing research results, including those presented in the seven articles presented in this dissertation, were used to guide the research design, collection of data, and analysis (Yin, 2018).

The total empirical research in this dissertation was based on data and observations from more than 90 companies, of which most were involved in the research program Innovation Factory North. As a researcher, I designed several activities in Innovation Factory North, which the companies engaged in. In 13 of the companies, I used my expertise to facilitate these activities, which may have affected the company's journey. This research may, therefore, be referred to as action research (Coughlan and Coghlan, 2016; Westbrook, 1995). Most facilitation took place in the first year of the research period, after which my role shifted to primarily act as an observer. Hence, while the research in this dissertation was conducted as case research, various research techniques were applied ranging from action research to observational studies.

To guide the research process, I developed a research protocol from the start (Voss et al., 2016; Yin, 2018) focused on the overall research topic, i.e., the innovation approach to manufacturing innovation for Industry 4.0. Interactions with and observations of the companies, initiated discussions and reflections with my supervisors, resulting in continuous incremental changes to the research design. Each month, the direction and scope of the research in this dissertation were reviewed and revised, if necessary, ensuring deliberate and strategic choices for data selection, data collection, data analysis, and research contribution from the beginning of the research process.

4.3. APPLIED RESEARCH METHODS

Seven articles are included in this dissertation, aiming to answer the three research questions presented in Chapter 3. Research question 1 is answered by articles 1 and 2, research question 2 is answered by articles 3-5, and research question 3 is answered by articles 6 and 7. Table 1 presents an overview of the three research questions in this dissertation and the appertaining articles answering each question, including the research question and the applied research method in the respective article.

Table 1: Research questions and applied research methods in articles.

<table>
<tr><td colspan="3">Research question 1: Why is the adoption of manufacturing innovation for Industry 4.0 at a standstill?</td></tr>
<tr><td>Article 1</td><td>Research question: Which barriers hinder Danish small and medium sized manufacturers from adopting Industry 4.0?</td><td>Research method: Multiple case study</td></tr>
<tr><td>Article 2</td><td>Research question: How do different problem characteristics affect the choice of innovation process for manufacturing innovation?</td><td>Research method: Conceptual research</td></tr>
<tr><td colspan="3">Research question 2: How should manufacturing innovation for Industry 4.0 be approached in order to improve the industrial adoption?</td></tr>
<tr><td>Article 3</td><td>Research question: Which parameters in the innovation process design positively affect the innovation outcome in the context of smart manufacturing?</td><td>Research method: Action research, multiple cases</td></tr>
<tr><td>Article 4</td><td>Research question: What characterizes the innovation approach for successful adoption of manufacturing innovations for Industry 4.0?</td><td>Research method: Comparative multiple case study</td></tr>
<tr><td>Article 5</td><td>Research question: How can a process model be designed to support manufacturing innovation in the context of Industry 4.0?</td><td>Research method: Single case study</td></tr>
<tr><td colspan="3">Research question 3: Which tools can support manufacturing companies’ approach to manufacturing innovation in the context of Industry 4.0?</td></tr>
<tr><td>Article 6</td><td>Research objective: Identify characteristics and drivers for using the ‘sandbox approach’ for manufacturing innovation in the context of Industry 4.0.</td><td>Research method: Comparative multiple case study</td></tr>
<tr><td>Article 7</td><td>Research question: How do learning factories support process innovation in Industry 4.0?</td><td>Research method: Literature review, classification, and synthesis</td></tr>
</table>

4.4. DATA SELECTION

The cases in the individual articles, here referred to as the sample of cases, were selected from a pool of case companies, referred to as the population of cases, of which most participated in Innovation Factory North. The population of case companies was chosen based on the following selection criteria:

- The company was a manufacturing company to study the adoption of Industry 4.0 in the manufacturing system.

- The company had initiated a transformation to Industry 4.0 to study the approach to manufacturing innovation in this context.
- The population should represent a mix of multifaceted companies regarding characteristics like prior experience with manufacturing innovation, level of digital maturity, industry, size, level of product customization, and manufacturing innovation budget to increase the generalizability of research results.

All data was collected from research activities at the Department of Materials and Production at Aalborg University. Most of the cases in the sample were companies that participated in Innovation Factory North, an open innovation research program where technology suppliers, manufacturing companies, and researchers from Aalborg University collaborated to introduce new manufacturing innovations for Industry 4.0. These manufacturing innovations should be exploited by technology suppliers to sell and manufacturing companies to exploit in their manufacturing system. The research program paid particular attention to but was not limited to, small and medium sized manufacturing companies as existing frameworks for adopting Industry 4.0 do not match the approach used in these companies (Møller et al., 2023b).

Companies participating in Innovation Factory North entered a process together with typically five or six other manufacturing companies and technology suppliers. The process consisted of three phases resembling a generic innovation process: Awareness, demonstration, and anchoring. The awareness phase, analogous to the front-end of an innovation process, aimed to create awareness about the possibilities created by Industry 4.0. In the demonstration phase, like the development phase of an innovation process, the companies collaborated with researchers and lab engineers at Aalborg University to prototype a manufacturing innovation in the context of Industry 4.0. Most activities in the demonstration phase were concentrated around the learning factory at Aalborg University, where prototypes were built and tested. In some cases, prototypes were built directly in the companies' manufacturing systems instead. Lastly, anchoring, the phase resembling implementation in an innovation process, focused on scaling the prototype and implementing the manufacturing innovation in the company's organization. By participating in all three phases of the process, a manufacturing company underwent an innovation process leading to a manufacturing innovation in the context of Industry 4.0. In Innovation Factory North, the company was assisted in the innovation process by researchers with different areas of expertise (e.g., innovation and change management, automation, and IT), technology experts from the industry, and exchange of experience with other manufacturing companies.

As mentioned, the companies were teamed up with other companies in the phases of Innovation Factory North. In total, 17 courses of an awareness phase, 10 courses of a demonstration phase, and two courses of an anchoring phase were carried out spread out over four years. Each week, interactions with the companies were evaluated, and the learning outcomes were used to improve future interactions, e.g., by offering additional workshops and adding or changing activities (Møller et al., 2023a).

The population of cases consisted of 74 manufacturing companies and additionally 16 technology suppliers which were involved in one or more phases of Innovation Factory North. Even though Innovation Factory North paid particular focus to small and medium sized companies, the composition of the sizes of the companies that participated in the research program was heterogeneous. Furthermore, the manufacturing companies came from diverse industries, different geographical areas, and had different levels of experience with manufacturing innovation.

The interactions with the companies in the population and their reflections on the innovation process contributed to valuable insights forming the research in this dissertation. Based on selection criteria for each of the seven articles in this dissertation, a sample of cases consisting of 31 manufacturing companies and four technology suppliers that participated in Innovation Factory North were, in total, used as cases in articles 1, 3, 4, and 6. The criteria for case selection of each article are described in the respective articles.

In addition, article 5 uses a case from a research activity that my colleagues carried out in an adjacent project. Like Innovation Factory North, this research activity was a collaboration between manufacturing companies, technology suppliers, and researchers from Aalborg University. The research activity aimed to explore a new approach to manufacturing innovation that could be used for more extensive manufacturing innovations, like the adoption of Industry 4.0, and that could accommodate a higher level of exploration in the process. To do so, the research activity staged a transformation of the company's manufacturing system from traditional mass production to one-of-a-kind production enabled by Industry 4.0 technologies. The transformation was conducted using modules from Aalborg University's learning factory and manufacturing equipment from the company's manufacturing system. Hence, even though this case company participated in a different research activity, the company was seeking the same objectives and support in the innovation process as the companies participating in Innovation Factory North, and was therefore included in the sample of cases.

Table 2 presents an overview of the sample of case companies used in the articles, company type, company size, and participation in Innovation Factory North and the three phases. Table 3 presents an overview of which cases in the sample are used as empirical data in which articles.

Table 2: Overview of case companies and their participation in the three phases of Innovation Factory North.

Case	**Type of company**	**Size**	**Innovation Factory North participant**	**Awareness phase**	**Demonstration phase**	**Anchoring phase**
1	Manufacturer	Small	x	x	x	x
2	Manufacturer	Small	x	x	x	
3	Manufacturer	Small	x	x		
4	Manufacturer	Small	x	x		
5	Manufacturer	Small	x	x		
6	Manufacturer	Small	x	x		
7	Manufacturer	Small	x	x		
8	Manufacturer	Small	x	x	x	
9	Manufacturer	Small	x	x		
10	Manufacturer	Small	x	x	x	
11	Manufacturer	Small	x	x		
12	Manufacturer	Small	x	x	x	
13	Manufacturer	Small	x	x		
14	Manufacturer	Small	x	x	x	
15	Manufacturer	Medium	x	x		
16	Manufacturer	Medium	x	x		
17	Manufacturer	Medium	x	x		
18	Manufacturer	Medium	x	x	x	
19	Manufacturer	Medium	x	x	x	
20	Manufacturer	Medium	x	x	x	
21	Manufacturer	Medium	x	x		
22	Manufacturer	Medium	x	x	x	
23	Manufacturer	Medium	x	x	x	x
24	Manufacturer	Medium	x	x	x	
25	Manufacturer	Medium	x	x		
26	Manufacturer	Medium	x	x		
27	Manufacturer	Medium	x	x		
28	Manufacturer	Medium	x	x		
29	Manufacturer	Large				
30	Manufacturer	Large	x	x		
31	Manufacturer	Large	x	x		
32	Manufacturer	Large	x	x		
33	Techn. supplier	Small	x	x		
34	Techn. supplier	Small	x		x	
35	Techn. supplier	Small	x	x		
36	Techn. supplier	Small	x	x	x	

Table 3: Case used in article 1, 3, 4, 5 and 6.

Case	Article 1	Article 3	Article 4	Article 5	Article 6
1	x	x	x		
2	x				
3	x	x			
4	x	x			
5	x	x			
6	x	x			
7	x				
8	x				
9	x	x			
10	x				
11	x				x
12			x		
13	x				
14	x				
15	x				
16	x	x			
17			x		
18	x		x		
19			x		
20	x	x			
21	x				
22	x				
23	x	x	x		x
24	x	x	x		x
25	x				
26		x			
27	x				
28	x				
29				x	
30		x			
31		x			
32		x			
33		x			
34		x			
35		x			
36		x			
Total cases:	24	18	7	1	3

4.5. DATA COLLECTION

As previously described, the empirical data for this research was mainly collected from a population of case companies participating in Innovation Factory North, besides one case that originates from another research activity at Aalborg University.

In this case, the data was collected through interviews and observations of the transformed manufacturing system that was built.

The design of activities and interactions with companies in the awareness phase in Innovation Factory North has undergone minor changes, which in most cases were insignificant to the comparability of the activities and interactions across cases. In general, the awareness phase had two research seminars where a team of companies met at Aalborg University for a whole day each time. The company representatives participated in workshops, listened to lectures on relevant topics such as Industry 4.0 and related technologies, and played an Industry 4.0 awareness game to transform Aalborg University’s learning factory from a manual manufacturing system to an intelligent Industry 4.0 manufacturing system. After each research seminar, one or two researchers visited the company to follow up on the workshops initiated at the seminars. The purposes of the workshops were to 1) make an Industry 4.0 innovation strategy stating where the company wanted to be in the future, 2) make a digital maturity assessment to understand what the current level of digitalization was in the company, and where the company needed to set in, and 3) make a roadmap for how the company would go from the current state identified in the digital maturity assessment to fulfill the Industry 4.0 innovation strategy. The activities in the awareness phase are illustrated in Figure 6. In the awareness phase similar data was collected continuously throughout the 17 courses of an awareness phase. These are:

- Background analysis of the company
- Notes and observations from plenary discussions and reflections at seminars
- Notes and observations from workshops with company representatives
- Formal and informal dialogue and discussions with company representatives
- Company visits with observations of, e.g., manufacturing system
- Industry 4.0 innovation strategy
- Digital maturity assessment
- Industry 4.0 roadmap
- Interviews with company representatives for research presented in articles

The data was documented by my colleagues and I who all actively participated in Innovation Factory North.

The demonstration phase was centered around a technology or an application area, such as paperless production or digital product models, aiming to create a prototype for the company within this area. The companies were grouped into a demonstration phase with other companies with similar interests. Like in the awareness phase, the demonstration phase also consisted of several research seminars where the companies met at Aalborg University to, e.g., participate in relevant lectures related to the topic of the prototype or to see live demonstrations of a prototype showcased in Aalborg University’s learning factory, in another manufacturing company or by a technology supplier. The demonstration phase followed an iterative process using small,

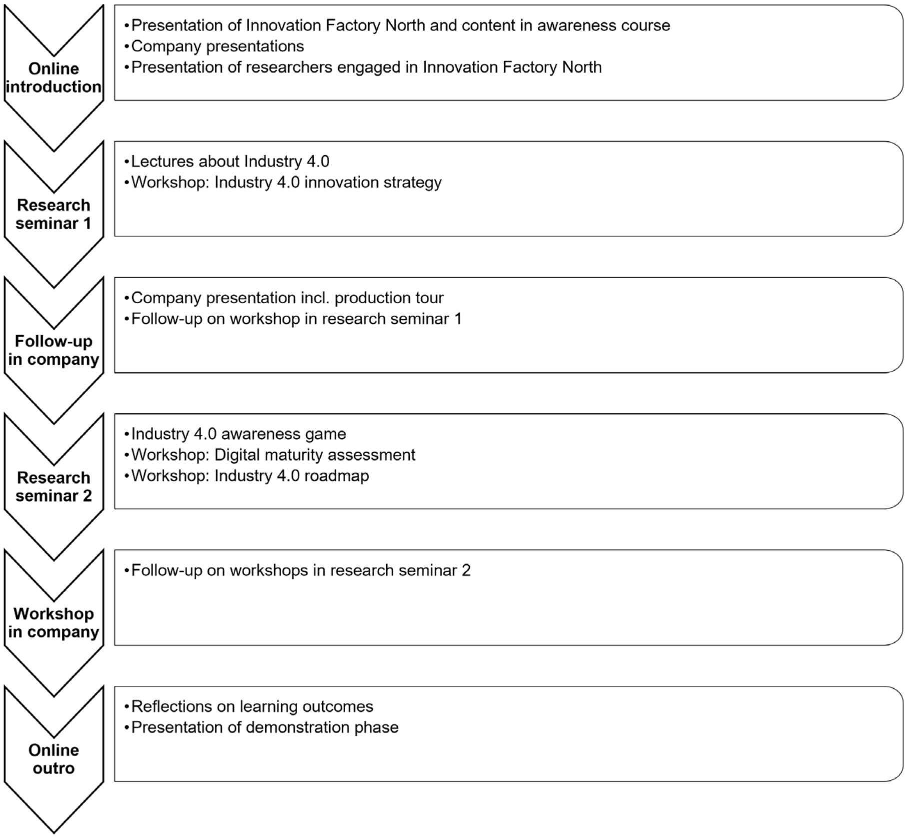

Figure 6: Example of design and activities in awareness phase.

incremental steps to create a prototype using Industry 4.0 technology. To support the companies in the process, researchers, e.g., did workshops on user stories and continuously followed up on the company's progress. Examples of data collection in the demonstration phase are:

- Notes and observations from plenary discussions and reflections at seminars
- Notes and observations from workshops with company representatives
- Formal and informal dialogue and discussions with company representatives
- Company visits with observations of the prototype
- User stories
- Prototypes
- Interviews with company representatives for research presented in articles

The approach applied in the demonstration phase is comparable across demonstration phases. However, some differences exist, which means that the data generated from the demonstration phases are not standardized at the same level as in the awareness phases. An example of the design of a demonstration phase is illustrated in Figure 7.

Figure 7: Example of design and activities in demonstration phase.

Only two anchoring phases were carried out, so the design of this phase did not reach a level of standardization. The phase focused on the implementation and scaling of the prototype and how to support the management with this task from a technical and organizational perspective. Like in the two other phases, the anchoring phase consisted of research seminars, workshops, and follow-ups in the individual companies. This is exemplified in Figure 8. Examples of data collected are:

- Notes and observations from plenary discussions and reflections at seminars
- Notes and observations from workshops with company representatives

- Formal and informal dialogue and discussions with company representatives
- Analysis of the planned anchoring process
- Action plan for anchoring process
- Interviews with company representatives for research presented in articles

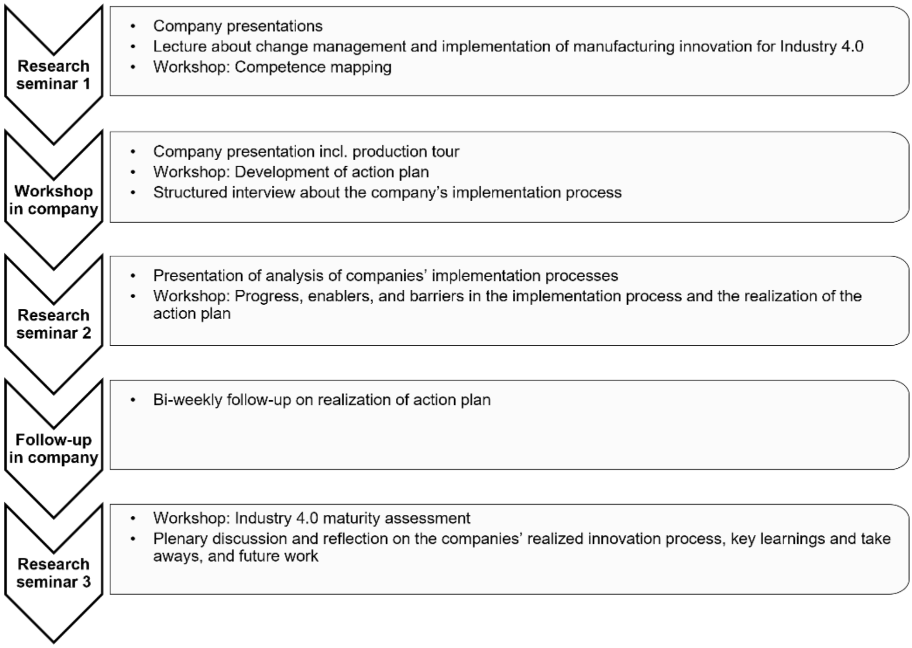

Figure 8: Example of design and activities in anchoring phase.

In addition to the data being generated and collected through activities and interactions in Innovation Factory North, cases were selected for in-depth interviews on topics related to the research in the articles. Table 4 and Table 5 provide an overview of the data available for each case in articles 1, 3, 4, and 6.

The population of companies participating in the three phases of Innovation Factory North made enormous amounts of empirical data available for the research in this dissertation. This, combined with the level of standardization in the process that the companies went through, has enabled cross-case comparisons, which were useful not only for the research presented in the articles but also for enhancing the understanding of the approach to manufacturing innovation for Industry 4.0 in the Danish manufacturing industry. For instance, article 1 was motivated by a mismatch between the many companies showing their interest in adopting Industry 4.0 by participating in the awareness phase of Innovation Factory North compared to the low number of companies that entered a demonstration phase or an anchoring phase where Industry 4.0 plans were to be realized. Another example is article 2, which was motivated by several observations generating a pattern that many companies may approach manufacturing innovation for Industry 4.0 incorrectly.

Table 4: Data collected through Innovation Factory North activities and separate interviews specifically focusing on research in articles.

Case	Background analysis	Notes and observations from discussions and reflections in research seminars	Notes and observations from workshops with case company	Company visit(s) with observations	Interview(s) for articles
1	x	x	x	x	x
2	x		x		x
3	x	x	x	x	x
4	x		x		
5	x		x	x	
6	x			x	x
7	x	x			
8	x	x			
9	x		x		
10	x	x	x		
11	x				x
12	x	x	x	x	x
13	x	x	x		
14	x		x		x
15	x	x	x		x
16	x		x		
17	x	x	x	x	x
18	x	x		x	x
19	x		x	x	x
20	x	x	x	x	
21	x		x		
22	x	x	x		
23	x	x	x	x	x
24	x	x	x	x	x
25	x	x	x	x	
26		x	x		
27	x	x	x	x	
28	x	x	x	x	
29					x
30	x	x	x		
31	x	x	x	x	
32	x	x	x		
33		x			
34					
35		x	x		
36	x	x	x	x	

Table 5: Data collected from workshops with case companies in Innovation Factory North.

Case	Industry 4.0 innovation strategy	Digital maturity assessment	Industry 4.0 roadmap	Industry 4.0 prototype	Analysis of planned anchoring process	Action plan for anchoring process
1	x	x		x	x	x
2		x		x		
3	x	x	x			
4	x	x	x			
5	x					
6	x	x				
7	x	x	x			
8	x	x	x			
9	x					
10	x	x	x	x		
11	x	x	x			
12	x	x	x	x		
13	x					
14	x	x	x			
15	x		x			
16	x		x			
17	x	x	x			
18	x	x	x	x		
19	x	x	x	x		
20				x		
21	x	x				
22	x	x	x			
23		x		x	x	x
24	x	x	x	x		
25	x					
26		x				
27	x	x	x			
28	x	x				
29	n/a	n/a	n/a	n/a	n/a	n/a
30	x	x	x			
31	x					
32	x	x	x			
33						
34				x		
35		x				
36	x	x		x		

In total, more than 1,200 hours of interactions between company participants and researchers from Aalborg University, including me, took place with the sample of case companies. Table 6 shows the distribution of hours of interaction for each case in the sample distributed across the three phases in Innovation Factory North.

Table 6: Hours of interactions with case companies.

Case	Awareness phase	Demonstration phase	Anchoring phase	Total hours pr. company
1	24	16	25	65
2	24	25		49
3	24			24
4	24			24
5	24			24
6	24			24
7	24			24
8	24	30		54
9	24			24
10	24	23		47
11	24			24
12	24	46		70
13	24			24
14	24	23		47
15	24			24
16	24			24
17	24			24
18	24	23		47
19	24	37		61
20	24	35		59
21	24			24
22	24	23		47
23	24	35	25	84
24	24	22		46
25	24			24
26	24			24
27	24			24
28	24			24
29	n/a	n/a	n/a	n/a
30	24			24
31	24			24
32	24			24
33	24			24
34		18		18
35	24			24
36	24	25		49
			Total hours for all companies:	1,247

4.6. DATA ANALYSIS

The analysis approach applied in each article is described and presented in the methodology sections in the respective articles. This section, therefore, presents reflections on how empirical insights from an extensive amount of data generated through Innovation Factory North and spanning beyond the individual subjects being studied in the articles were used to improve the research in this dissertation.

Throughout the research related to this dissertation, analyses, discussions, and reflections of data and observations from activities in Innovation Factory North were used to improve the quality of the research. Several sources have contributed to this. Examples are, for instance, interactions with companies in the population and the preparation of research presented in articles, which have improved the understanding of the research area, leading to additional perspectives in later research. Furthermore, each week, all researchers engaged in Innovation Factory North participated in a weekly meeting, among others, to discuss, interpret, and make sense of our observations from activities in Innovation Factory North. By using this iterative approach to analyze the data continuously, learning outcomes from earlier cases in the population were used to improve the focus of the research and the subsequent data collection for new research, thereby increasing the validity of the research. The learning outcomes were also used to design new interventions with companies, further refining the research. Sometimes, the analyses and reflections shed light on details I had not considered previously, leading to a refinement of the understanding of the research topic and an adaptation of the research protocol (Yin, 2018).

4.7. RESEARCH TRUSTWORTHINESS

The quality of empirical research is generally evaluated by the validity and reliability of the research, manifested in four operational parameters: Construct validity, internal validity, external validity, and reliability (Yin, 2018). Construct validity refers to developing an adequate set of operational measures to avoid subjectivity and bias in the data collection. Internal validity refers to the inference of results and whether inferred conclusions are accurate. External validity evaluates the generalizability of research results, e.g., to other companies, industries, or countries. Lastly, reliability assesses the ability of an independent researcher to replicate the research process and arrive at the same results (Yin, 2018).

Like any research, case research has some limitations, which in this case is, e.g., that most of the empirical data is situationally grounded in the Innovation Factory North context. However, the quality of the research presented in this dissertation also has some significant strengths. One of its main strengths is the amount of data available, shedding light on the research from different sources. To give an example, the data available to study the innovation approach in a company participating in Innovation Factory North was:

- Observations of the company’s progress with manufacturing innovation between seminars in Innovation Factory North reflect the company’s actions.

- Observations at seminars, e.g., which questions the company participants ask, their main concerns, and whether they are actively engaged in the activities or awaiting others' initiatives. Information which can be used to support arguments on how they approach manufacturing innovation.
- Interviews and formal and informal discussions with company representatives about the company's innovation approach provide the key informants' points of view on the company's approach.
- Industry 4.0 innovation strategy and roadmap indicate the company's strategic aim for the adoption of Industry 4.0.

The number of cases with multifaceted characteristics available for this research has strengthened the generalizability of the research results. Even though not all cases of the population were used in the research presented in the articles, most of the cases were observed, and the knowledge obtained from these observations contributed to valuable insights forming the research in the articles.

The engagements with the case companies provided valuable insights in real operational problems, which were used to shape the research. Furthermore, the extensive engagements contributed to develop a holistic understanding of the research topic while recognizing the complexity of the companies' situation (Coughlan and Coghlan, 2016). However, there is always a risk that when a researcher is engaged in activities with case companies, the researcher may affect the case (Coughlan and Coghlan, 2016). In this research, my engagements with several case companies increased this risk. The cases in articles 4 and 6 are a mix of companies with which I was actively engaged or had low or no engagement. The cases indicate similar results irrespective of my level of engagement, which strengthens the reliability of this research.

Table 7 presents an evaluation of the strengths and weaknesses of the quality of the empirical research in this dissertation based on the four parameters: Construct validity, internal validity, external validity, and reliability.

Table 7: Evaluation of research trustworthiness.

Parameters	Strengths	Weaknesses
Construct validity	• Multiple sources of evidence • Key informants have reviewed research results • Central, operational measures were continuously reevaluated and documented in the research protocol independent of research activities related to specific articles	• Case companies are guided by activities in Innovation Factory North which means that the effect of the innovation process may partly be attributed to this guidance.
Internal validity	• Dialogue and discussions with colleagues participating in Innovation Factory North about observations and inferred results • Dialogue and discussion with company representatives participating in Innovation Factory North about inferred results • Pattern matching	• Interaction in research environment increases the risk of inferring biased results
External validity	• Multiple cases • Multifaceted cases, i.e., different sizes, industries, ownership, level of experience with manufacturing innovation etc.	• Situationally grounded research in the Innovation Factory North context • Single case (article 5) is a critical case • Only Danish case companies
Reliability	• Systematic field notes • Formal interview guides • Recordings of interviews • Structured data analysis, e.g., using NVivo software • Research protocol	• Interactions in Innovation Factory North are ‘live’ events which cannot be repeated

CHAPTER 5. RESEARCH SUMMARY

This dissertation is based on a collection of seven articles that together answer the three research questions of this dissertation. Table 8 presents an outline of the findings presented in Chapters 6-8. Article 1 and 2 address research question 1, articles 3-5 address research question 2, and articles 6 and 7 address research question 3.

Table 8: Overview of articles presented in chapters 6-8.

Chapter 6: Standstill in the Adoption of Industry 4.0
Article 1: Industry 4.0 Holds a Great Potential for Manufacturers, So Why Haven't They Started? A Multiple Case Study of Small and Medium Sized Danish Manufacturers. **Published in:** Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021) and the 10th World Mass Customization & Personalization Conference (MCPC2021). **Research method:** Multiple case study. **Summary:** The interest in adopting Industry 4.0 in the manufacturing industry is high, and despite many companies starting the transformation to Industry 4.0, only a few succeed. This article explores barriers to manufacturing innovation for Industry 4.0 in 24 small and medium sized manufacturing companies to understand why this happens. The results indicate that companies face significant barriers related to the initial phases of the innovation process.
Article 2: Managing Manufacturing Innovation: Four Types of Problems and Matching Innovation Processes. **Published in:** Production Processes and Product Evolution in the Age of Disruption. Proceedings of the 9th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2023) and the 11th World Mass Customization & Personalization Conference (MCPC2023). **Research method:** Conceptual research. **Summary:** Manufacturing problems such as high costs, low utilization rates, or lack of qualified labor can be solved by manufacturing innovations. The characteristics of manufacturing problems diverge, and according to Snowden and Boone (2007), four types of problems exist: Simple, complicated, complex, and chaotic problems. This article puts these four types of problems in the context of manufacturing innovation. It relates the four

types of problems to relevant innovation process models from the product innovation research area as a source of inspiration. The result is a conceptual framework matching the characteristics of manufacturing problems and innovation process models. The discussion of the article indicates a conflict between the industrial approach to manufacturing innovation for Industry 4.0 and the most suitable approach from a theoretical point of view.

Chapter 7: Approaches to Manufacturing Innovation

Article 3: Design Parameters for Smart Manufacturing Innovation Processes.

Published in: Procedia CIRP.

Research method: Action research, multiple cases.

Summary: This article explores parameters in the design of the approach to manufacturing innovation for Industry 4.0. Data is retrieved from activities with 14 manufacturing companies and four suppliers of Industry 4.0 technologies and analyzed using the Gioia methodology. The analysis results reveal seven parameters for the design of an approach to manufacturing innovation. The research is the first step to a more systemic understanding of designing approaches and processes for manufacturing innovation in the context of Industry 4.0.

Article 4: Characteristics of (Successful) Manufacturing Innovation for Industry 4.0.

Submitted to: Journal of Manufacturing Technology Management.

Research method: Comparative multiple case study.

Summary: The research in this article studies the approaches to manufacturing innovation being applied in seven manufacturing companies that have successfully introduced Industry 4.0. Multiple characteristics of the companies' approaches to manufacturing innovation for Industry 4.0 are explored and compared across cases. Several prevailing characteristics are derived from this, e.g., a focus on radical manufacturing innovation, management involvement, and a flexible innovation approach. Based on these characteristics, three propositions are inferred, among others suggesting that the innovation approach should be flexible, incorporating elements such as iterations, prototyping, and learning by doing.

Article 5: Manufacturing Innovation: A Heuristic Model of Innovation Processes for Industry 4.0.

Submitted to: Applied System Innovation.

Research method: Single case study.

Summary: This article focuses on the design of the innovation process and presents a case study of a manufacturing innovation project developing an extensive manufacturing innovation for Industry 4.0. The innovation requires converting the manufacturing system from mass production to product customization enabled by Industry 4.0 technologies. Based on observations of the manufacturing innovation and interviews with key informants, the innovation process applied in the case is retrieved, and a heuristic model of a process for manufacturing innovation in the context of Industry 4.0 is derived.

Chapter 8: The 'Sandbox': A Tool for Manufacturing Innovation

Article 6: A Sandbox Approach for Manufacturing Innovation: A Multiple Case Study.

Published in: The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs.

Research method: Comparative multiple case study.

Summary: This article presents a conceptualization of the sandbox approach for manufacturing innovation. The sandbox approach is a tool for manufacturing innovation in the context of Industry 4.0, which can be used in the innovation process. The distinctive feature of the sandbox approach is its experimentation with a solution in a setting resembling the manufacturing system. Based on a multiple case study of three manufacturing companies using the sandbox approach to manufacturing innovation for Industry 4.0, characteristics and advantages of the sandbox approach are inferred. The sandbox approach, among others, leads to an improved understanding of solution requirements and a development in competences.

Article 7: Process Innovation in Learning Factories: Towards a Reference Model.

Published in: Advances in Production Management Systems. Production Management for the Factory of the Future. IFIP WG 5.7 International Conference, APMS 2019.

Research method: Literature review, classification and synthesis.

Summary: The sandbox approach uses experimentation with manufacturing innovation in a setting resembling the manufacturing system. Such a setting could, for instance, be a learning factory. Through a literature review, this article explores existing research on learning factories to understand how learning factories can be used to support manufacturing innovation for Industry 4.0. The results show that although learning factories are used for competence development for Industry 4.0, they are not used as a tool for manufacturing innovation in the industry. The article, therefore, proposes an initial understanding of how learning factories can be used to support the sandbox approach to manufacturing innovation.

The research presented in the seven articles progresses in three parts. In the first part, presented in Chapter 6, the articles explore why manufacturing companies fail with the adoption of Industry 4.0. The articles in the second part, presented in Chapter 7, explore how companies can succeed with manufacturing innovation for Industry 4.0, focusing on the approach and process for manufacturing innovation. In the last part, presented in Chapter 8, the articles delve into a specific tool in the innovation process, the sandbox approach.

CHAPTER 6. STANDSTILL IN THE ADOPTION OF INDUSTRY 4.0

This chapter answers research question 1: *Why is the adoption of manufacturing innovation for Industry 4.0 at a standstill?* The research question is answered by the findings in articles 1 and 2.

The chapter explores the stagnation in the adoption of Industry 4.0 in the industry, focusing on the match between the type of problem being solved by the manufacturing innovation for Industry 4.0 and the appertaining innovation process that fits the requirements for solving such problems. Section 6.1, therefore, presents characteristics of manufacturing innovations for Industry 4.0. Next, barriers that hinder manufacturing companies' adoption of Industry 4.0 are presented in Section 6.2. These results indicate that manufacturing companies approach the adoption of Industry 4.0 incorrectly. For this reason, Section 6.3 explores the fit between the types of manufacturing problems a manufacturing innovation solves and the design of the innovation process. In combination, the results in this chapter lead to an analysis of the industrial expectations of how to approach manufacturing innovation compared to the theoretical expectations. The findings are summarized and discussed in Section 6.4.

6.1. CHARACTERISTICS OF MANUFACTURING INNOVATIONS FOR INDUSTRY 4.0

The vision of Industry 4.0 is to create end-to-end processes with autonomous decision-making and interoperable processes enabled by data collection, data exchange, and data processing (Kagermann et al., 2013; Lasi et al., 2014; Møller et al., 2023c). The introduction of Industry 4.0 is, therefore, expected to radically change how manufacturing systems are operated.

Most manufacturing innovations are systemic by nature, as introducing a change in one part of the system often affects other parts consistent with the socio-technical systems perspective. Manufacturing innovation in the context of Industry 4.0 adds another layer to this, as the interconnection of processes through data exchange introduces more systemic relations to a manufacturing innovation. To make this interconnection where processes can communicate across the manufacturing system through data exchange, the data system needs to formalize and translate product design into processing requirements and operations in the manufacturing system (Lasi et al., 2014; Møller et al., 2023c). The operationalization of the vision of Industry 4.0 therefore requires highly complex manufacturing innovations.

Manufacturing innovations for Industry 4.0 use combinations of technologies not previously used for manufacturing operations (Møller et al., 2023c). A consequence of this is that the operational value of Industry 4.0 technologies still needs to be disclosed (Napoleone et al., 2020). However, the technologies continuously improve and evolve, which means that a steady state does not exist, and therefore, designing standard solutions may not be relevant, all of which impact how to approach manufacturing innovation for Industry 4.0.

6.2. BARRIERS TO THE ADOPTION OF INDUSTRY 4.0

The findings presented in this section are based on the research results presented in article 1, 'Industry 4.0 Holds a Great Potential for Manufacturers, So Why Haven't They Started? A Multiple Case Study of Small and Medium Sized Danish Manufacturers' (Larsen et al., 2021).

From the research activities in Innovation Factory North, it is evident that the interest and willingness to adopt Industry 4.0 in the manufacturing industry is high and that priority is given to the initial steps in the innovation process trying to set the direction for the transformation. However, once these strategic decisions are converted into actions, the progress stops and most companies cannot continue. Several authors have investigated the challenges related to the adoption of Industry 4.0 (e.g., Gebauer et al. (2022), Hoyer et al. (2020), Kumar et al. (2020), Stentoft et al. (2021) and Trolle et al. (2020)). But the pattern emerging from the companies participating in Innovation Factory North indicates that the problem may not be strictly related to challenges prolonging the process. It seems that the adoption of Industry 4.0 is discontinued because companies face barriers obstructing the process. This section, therefore, explores the barriers manufacturing companies face that may hinder the adoption of Industry 4.0.

Based on a case study of 24 companies, ten barriers were identified that may stop companies from adopting Industry 4.0. The barriers are presented in Table 9.

Table 9: Ten barriers to the adoption of Industry 4.0 (Larsen et al., 2021).

Barrier	**Explanation**
Difficult to formulate an Industry 4.0 innovation strategy or have not made one yet	Have a hard time formulating an Industry 4.0 innovation strategy, and those companies that have started the process may be more focused on single projects rather than formulating an overall strategy for Industry 4.0.
Difficult to make a business case that can justify value upfront	Expect to make an economic assessment of the value of the manufacturing innovation upfront but find it challenging to define and quantify the expected costs and benefits of the investment. Furthermore, from an economic point of view, the

	business case may not turn out positive, which, however, is needed to get funding for the project in several companies.
Do not actively work with Industry 4.0	Do not actively work with Industry 4.0 in their organization despite the willingness to proceed. One company, e.g., is not motivated to adopt Industry 4.0. Another company has some level of system integration that could be referred to as Industry 4.0 but have not worked intentionally with an Industry 4.0 agenda.
Lack of understanding of what Industry 4.0 is and its value for the company	Do not understand what the term "Industry 4.0" covers, which makes it difficult for them to relate it to operational value and act on it.
Existing governance structure does not support Industry 4.0 projects	Do not have a governance structure that can support manufacturing innovations for Industry 4.0, e.g., IT is responsible for all IT projects despite the project having a more substantial relation to manufacturing than IT.
Lack of competences	Do not have required competences, may not understand which competences are needed and where to find them. The lack of competences applies to all hierarchical levels of the organization, e.g., top management lacks the competences to initiate and run Industry 4.0 projects, and shopfloor employees lack the competences to operate the solution.
Lack of commitment from management/owners	Lack of commitment from the management/owners in the innovation process, e.g., because of lack of interest in adopting Industry 4.0.
Lack of time or funds to support Industry 4.0 projects	Do not have the time or funds to innovate for Industry 4.0. The funds may be needed e.g., to hire new employees or buy technology. As regards time, operations are often prioritized over innovation.
Getting the organization onboard to ensure support and commitment in the transformation process	Lack of organization support in the process, e.g., caused by an inability to communicate the upcoming changes as the impact of the manufacturing innovation cannot be defined upfront.
The road to fulfilling the Industry 4.0 innovation strategy is uncertain and unclear	Do not know which steps to take and where to start to progress, and ultimately, fulfill their Industry 4.0 innovation strategy.

The barriers appear to be related to different phases of the innovation process, so to understand where the problems are occurring in the innovation process, an overview of each of the barriers' relation to the three generic phases of the innovation process is desirable. Table 10, therefore, categorizes the barriers according to the three generic phases of an innovation process: Front-end, development, and implementation (Garud et al., 2013).

Table 10: Barriers to Industry 4.0 adoption categorized according to the three generic phases of an innovation process. Adapted from Larsen et al. (2021).

Phase of innovation process	**Barriers**
Front-end	• Difficult to formulate an Industry 4.0 innovation strategy or have not made one yet • Difficult to make a business case that can justify value upfront • Do not actively work with Industry 4.0 • Lack of understanding of what Industry 4.0 is and its value for the company
Development	• Existing governance structure does not support Industry 4.0 projects • Lack of competences • Lack of commitment from management/owners • Lack of time or funds to support Industry 4.0 projects
Implementation	• Getting the organization onboard to ensure support and commitment in the transformation process • The road to fulfilling the Industry 4.0 innovation strategy is uncertain and unclear

Table 10 shows that most barriers are related to the front-end and development phases, indicating that companies are hindered in adopting Industry 4.0 early in the process.

Despite the barrier 'the road to fulfilling the Industry 4.0 innovation strategy is uncertain and unclear' being described in isolation, the uncertainty and unknown aspects of the process being emphasized in this barrier appear to be a common denominator for several other barriers. For instance, making a business case requires transparency and certainty about the manufacturing innovation early in the innovation process, which means the main obstacle to the companies' adoption of Industry 4.0 may not be caused by individual barriers. The interdependency between the individual barriers indicates that the companies' approach to manufacturing innovation for Industry 4.0 may be incorrect, assuming the process is less uncertain and more transparent than what may be the case.

6.3. THE PROBLEM/PROCESS MATRIX

This section presents the findings of the conceptual research in article 2, 'Managing Manufacturing Innovation: Four Types of Problems and Matching Innovation Processes' (Larsen et al., 2023c).

The findings in the previous section conclude that manufacturing companies may need to approach manufacturing innovation for Industry 4.0 differently than the companies expect themselves. This article assumes that different manufacturing problems need different innovation processes and, therefore, explores the match between problem and process in the context of manufacturing innovation. From this, a suitable process for manufacturing innovation in the context of Industry 4.0 can be identified.

Manufacturing innovations solve problems in manufacturing, such as bottlenecks, lack of flexibility in operations, high operating costs, low productivity, or labor shortage (Braun, 1981). Some problems are easy to understand, and it is therefore straightforward how to solve them. In contrast, it can be challenging to understand the root causes of other problems, and thereby, more work is needed to create proper solutions to such problems. For example, suppose a company wants to introduce a digital system to control inventory levels. In that case, most activities will focus on searching for available solutions, selecting the best fit for the company, and installing the solution. Solving such a problem place different demands on the innovation process than solving a more complex problem where the solution cannot be retrieved from a supplier's catalog (Bellgran and Säfsten, 2010). This example illustrates how problem characteristics affect the design of the innovation process.

In general, a problem can be solved in two different ways (Buchanan, 1992). One approach is to use a linear process where the problem is first identified and understood followed by the activity of solving the problem as illustrated in Figure 9. The other approach is to continuously iterate between the activities of identifying and understanding the problem, and solving it (Buchanan, 1992) as illustrated in Figure 10.

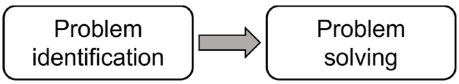

Figure 9: Linear problem solving process.

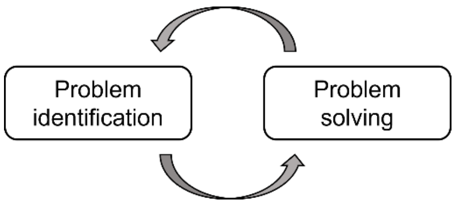

Figure 10: Iterative problem solving process.

Snowden and Boone (2007) present a more nuanced categorization of problems distinguishing between four types: Simple, complicated, complex, and chaotic problems ranging from the most transparent problem with a stable environment to the least transparent problem with a highly dynamic environment, as depicted in Figure 11.

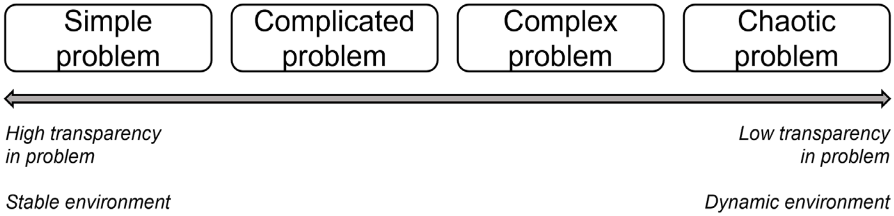

Figure 11: Four types of problems.

Simple problems occur in stable contexts, and therefore, transparent cause-and-effect relationships exist, which means that a common understanding of the problem is present and the best solution to the problem may be obvious (Snowden and Boone, 2007). Complicated problems also have stable cause-and-effect relationships, which, however, are less transparent and may require some analyses to unravel and decide among alternative solutions to find the best fit (Snowden and Boone, 2007). Complex problems are ill-defined and can be challenging to solve due to contradictive requirements, lack of knowledge, and imposed complexity from related problems, which means that characteristics of complex problems change continuously (Rigby et al., 2016; Rittel and Webber, 1973). Consequently, no optimal solution for a complex problem exists as cause-and-effect relationships are dynamic and, therefore, change (Camillus, 2008). Chaotic problems arise under constantly changing circumstances. Thereby, cause-and-effect relationships are continuously changing, meaning no pattern remains stable enough to make a long-term plan. To solve this type of problem, temporary stability is the objective that can be achieved through damage control, thereby attempting to change the chaotic problem into a complex problem that can be managed (Snowden and Boone, 2007).

Different types of manufacturing problems call for different types of innovation processes. The framework presented in Table 11 summarizes the characteristics of process models for each of the four types of problems. The findings suggest that simple problems should be solved using linear process models like the stage-gate process in product innovation, complicated problems should be solved using hybrid process models like an agile-stage-gate process, complex problems should be solved using iterative process models like design thinking, and chaotic problems should be solved using emergent process models like the muddling through process.

Table 11: Overview of four types of problems and matching innovation process characteristics. Adapted from Larsen et al. (2023c).

Characteristic	**Simple problem**	**Complicated problem**	**Complex problem**	**Chaotic problem**
Environment	Static and transparent	Static but complicated	Dynamic and complex	Dynamic
How is the problem defined in the process	Upfront	Explored and studied in process	Problem and solution are continuously studied and understood	The problem is understood incrementally throughout process
Overall process design	Linear and sequential	Linear and sequential with activities within gates managed like agile	Iterative	Emerges one decision at a time
Effective in circumstances characterized by	Predictable and transparent. Cause-and-effect relationships pf the problem are clear immediately	Cause-and-effect relationships of the problem can be identified through analyses	Changing environment with some stability	Chaotic and unpredictable
What drives the process forward	Decision/gate	Decision/gate	Undecided aspects of the problem	Decision or change in circumstances
Degree of predefined process design	High	Medium to high	Low to medium	Low (non-existent)
Example of process model from product innovation	Stage-gate and funnel model	Agile-stage-gate	Design thinking	Muddling through

The fit between the type of problem and process model is illustrated in Figure 12. As described in Section 6.1, manufacturing innovations for Industry 4.0 solve complex problems, indicating that companies should use an iterative innovation process.

	Simple problem	**Complicated problem**	**Complex problem**	**Chaotic problem**
Linear process	Match	*Mismatch*	*Mismatch*	*Mismatch*
Mix of linear and iterative process	*Mismatch*	Match	*Mismatch*	*Mismatch*
Iterative process	*Mismatch*	*Mismatch*	Match	*Mismatch*
Emergent process	*Mismatch*	*Mismatch*	*Mismatch*	Match

Figure 12: Match between type of problem and type of innovation process.

6.4. SYNTHESIS AND DISCUSSION OF RESULTS

The findings presented in this chapter enhance the understanding of why manufacturing companies fail to adopt Industry 4.0. The findings in article 1 suggest that the problem may not be the individual barriers but the companies' approach to Industry 4.0. The companies expect that adopting Industry 4.0 is a transparent process where benefits and costs related to the manufacturing innovation can be evaluated upfront, and the innovation process can be planned from start to finish. Manufacturing innovation for Industry 4.0 is thereby treated as a simple problem. However, the operational values of Industry 4.0 technologies are still to be determined (Napoleone et al., 2020), and at the same time, the technologies continue to be changed and refined. This, combined with the overarching vision of Industry 4.0 to create interconnected processes, makes manufacturing innovations for Industry 4.0 complex. According to the framework presented in article 2, manufacturing innovations for Industry 4.0 require an iterative innovation process consistent with existing research results, which have indicated a need to use more explorative innovation approaches to digitalization and Industry 4.0 (Lasi et al., 2014; Li, 2020; Sjödin et al., 2018). Hence, when combining the findings in this chapter it is suggested that while such approaches may be relevant, the industrial expectations deviate from this, exposing an inconsistency between theory and practice. An explanation for this discrepancy may be found in the lack of competences in the management to approach complex manufacturing innovation in the context of Industry 4.0 and in general, which is also indicated by the barriers identified in article 1. To ensure a sustainable approach to manufacturing innovation in the long term, manufacturing companies need to build competences in creating and implementing more complex manufacturing innovations, e.g., in the context of Industry 4.0 (Lassen and Wæhrens, 2021). Therefore, manufacturing companies need more explicit guidance on the adoption of Industry 4.0 to support the transition to Industry 4.0, e.g., through models of the innovation process and related tools to generate required insights. The remaining research results presented in this dissertation contribute to this agenda.

CHAPTER 7. APPROACHES TO MANUFACTURING INNOVATION

This chapter answers research question 2: *How should manufacturing innovation for Industry 4.0 be approached in order to improve the industrial adoption?* The research question is answered through the findings in articles 3, 4 and 5.

This chapter distinguishes between the innovation approach and the innovation process, where the innovation approach is superior to the innovation process. Besides considering the innovation process, the innovation approach, for instance, also encompasses a company's general way of engaging with manufacturing innovation. In contrast, the innovation process consists of a sequence of actions transforming an idea into an operable solution. Figure 13 illustrates the relation between the two terms.

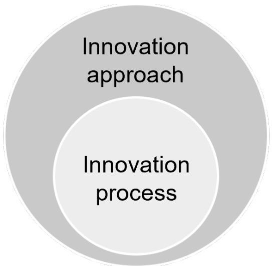

Figure 13: Relation between the definition of an innovation approach and an innovation process.

The findings in the previous demonstrated critical barriers to adopting Industry 4.0. Understanding what hinders the adoption of manufacturing innovation for Industry 4.0 is particularly important in order to understand how to avoid or overcome barriers for companies to succeed with the adoption of Industry 4.0. However, only a few articles present such insights (Larsen and Lassen, 2023) and most research focuses on addressing specific elements of the innovation approach such as how to formulate an Industry 4.0 innovation strategy (Demeter et al., 2021; Dohale et al., 2023), make a technology roadmap (Cotrino et al., 2020; Frank et al., 2019) or a business case (Colli et al., 2022), and defining the competences required to support the process (Hansen et al., 2023; Lassen et al., 2023). Research delving into such themes provides a valuable understanding of an individual parameter concerning the adopt of Industry 4.0. However, to understand how to approach manufacturing innovation, there is a need to understand the approach from a more systemic perspective, considering multiple socio-technical elements simultaneously in the design of the innovation approach.

Addressing this knowledge gap is interesting from a practical and a theoretical perspective. From a practical perspective, these insights inspire and incentivize other manufacturing companies to approach manufacturing innovation for Industry 4.0. From a theoretical perspective, enhancing the understanding of characteristics and parameters of successful cases of Industry 4.0 adoption will provide insights useful for further development of process models for manufacturing innovations (Larsen et al., 2023c; Larsen and Lassen, 2023). Therefore, this chapter starts with a focus on crucial parameters in the design of the approach to manufacturing innovation for Industry 4.0 presented in Section 7.1. These findings are elaborated in Section 7.2, which presents characteristics of successful approaches to manufacturing innovation for Industry 4.0. Based on an improved understanding of the innovation approach, the scope is narrowed down in Section 7.3, strictly focusing on the design of the innovation process, presenting a process model for manufacturing innovation in the context of Industry 4.0. Lastly, the findings are summarized and discussed in Section 7.4.

7.1. DESIGN PARAMETERS FOR THE INNOVATION APPROACH

The findings presented in this section are based on the research presented in article 3, 'Design Parameters for Smart Manufacturing Innovation Processes' (Larsen and Lassen, 2020).

This article explores the innovation approach from a systemic perspective. An explorative data analysis is conducted based on data collected from 14 manufacturing companies' and four technology suppliers' participation in Innovation Factory North. From this analysis, seven design parameters that appear to impact the innovation approach positively have emerged. Table 12 presents these seven parameters explaining the purpose of each parameter to the innovation approach.

Combining the seven design parameters provides an initial understanding of how to approach manufacturing innovation for Industry 4.0 from a systemic point of view. The parameters have inspired the data collection and analysis in article 4, presented next.

Table 12: Seven design parameters for an innovation approach (Larsen and Lassen, 2020).

Design parameter	**Explanation**
Industry 4.0 innovation strategy	The Industry 4.0 innovation strategy defines the strategic direction for a company's manufacturing system utilizing Industry 4.0 technologies. It, therefore, serves as a guiding principle for decision-making. Due to its systemic perspective on the future of the manufacturing system, the

	innovation strategy supports a systemic view of manufacturing innovation. This is needed to exploit the systemic potential of Industry 4.0.
Iterative approach	An iterative approach to manufacturing innovation in the context of Industry 4.0 can support a company's transformation in several ways. As the results in article 2 highlight, a flexible, iterative approach can assist in decomposing the complexity of the problem being solved, thereby enhancing the complexity of the manufacturing innovation. By doing this, knowledge levels continuously increase. This knowledge is exploited in the innovation process serving to improve the final design of the manufacturing innovation.
Short development times	Employees are often involved in multiple projects in the organization concurrently with working on one manufacturing innovation. Therefore, the number of days spent from initiating an innovation project until the innovation is implemented and running in production may be much higher than the number of hours put into the project. The results indicate that a densely packed time horizon with an intense focus on the manufacturing innovation spread across fewer days requires fewer hours to reach a result than using more hours spread across more days.
Building a prototype	Building a prototype assists the company in understanding the needs and requirements of a manufacturing innovation while evaluating what is technologically feasible. It also provides an opportunity for engaging the rest of the organization in the manufacturing innovation, showcasing the idea of the innovation.
Open innovation collaboration	Collaborations with Industry 4.0 technology suppliers, researchers from different fields related to the transformation to Industry 4.0, and other manufacturing companies generate learning and knowledge outcomes that improve the design of the manufacturing innovation.
Employee involvement	Involving employees in the innovation process is necessary to ensure that they will use the manufacturing innovation once it is ready. Sharing the Industry 4.0 innovation strategy with the whole organization and involving them in the prototype are examples of how to involve employees who are not directly involved in the innovation project.
Vertical/ horizontal integration	Vertical and horizontal integration of the manufacturing system is one of the cornerstones of the Industry 4.0 vision. Therefore, how to contribute to an integrated manufacturing system needs to be considered continuously as iterations in the innovation process may change the solution design several times, impacting the systemic relations.

7.2. CHARACTERISTICS OF SUCCESSFUL INNOVATION APPROACHES

This section presents the findings in article 4, 'Characteristics of (Successful) Manufacturing Innovation for Industry 4.0' (Larsen and Lassen, 2023).

A pattern emerges when reflecting on the previous findings compared to the empirical observations made through four years of interactions in innovation activities with manufacturing companies through Innovation Factory North. Especially within small and medium sized manufacturing companies, the interest in adopting Industry 4.0 is strong, but the number of success cases is low. Revisiting all small and medium sized manufacturing companies that participated in Innovation Factory North, seven companies successfully adopted a manufacturing innovation for Industry 4.0. Article 4 explores common characteristics of how these companies approach manufacturing innovation for Industry 4.0, bringing the experiences of the cases into coherent knowledge. Based on these characteristics, a pattern emerges leading to three propositions on how to approach manufacturing innovation for Industry 4.0.

7.2.1. RADICAL INNOVATION OF ENABLING PROCESSES

The results in this article show that manufacturing innovations for Industry 4.0 encompass a high level of complexity imposed by systemic relations both to the existing manufacturing system and to future (yet unknown) manufacturing innovations. Furthermore, manufacturing innovations for Industry 4.0 are characterized by radical innovations of enabling processes that solve complex problems in the manufacturing system. This result is surprising as, historically, industrial revolutions have made radical changes to core manufacturing processes, resulting in remarkable improvements in productivity (Ghobakhloo, 2018), and Industry 4.0 is expected to do the same (Kagermann et al., 2013; Lasi et al., 2014; Lassen and Wæhrens, 2021). The focus on enabling processes may be explained by the companies' access to knowledge partners and low-cost technology (Møller, 2023) or because new possibilities have emerged to change enabling processes with the introduction of Industry 4.0. Another reason for manufacturing companies to focus on enabling processes may be that the strategic consequences of changing enabling processes are less risky than changing a core manufacturing process, which again leads the attention to the companies' uncertainty in approaching manufacturing innovation as a strategic resource (Christensen et al., 2021). However, radical innovations of core manufacturing processes are needed if manufacturing companies want to exploit the strategic advantages of Industry 4.0, changing the manufacturing system to have capabilities acting as an enabler for product innovation. Though, radical transformations of enabling processes may be the focus of initial manufacturing innovations for Industry 4.0. The first proposition is therefore:

Proposition 1: *'The implementation of Industry 4.0 starts with radical innovations of enabling processes encompassing high complexity from the systemic relations within the manufacturing system and to future Industry 4.0 solutions.' (Larsen and Lassen, 2023, p. 13)*

7.2.2. FLEXIBLE INNOVATION APPROACH

Consistent with the findings presented in article 2, the results of this article support the use of a flexible approach to manufacturing innovation for Industry 4.0. The flexibility is used to consistently search for knowledge inputs to improve the design of the manufacturing innovation. Inputs are, for instance, generated from the sporadic involvement of users of the innovation, using a learning by doing approach, or opening the innovation process to receive inputs from other manufacturing companies, technology suppliers, and researchers.

The results furthermore indicate a positive impact from prototyping where the design of the manufacturing innovation evolves through iterations, refining the fit between technology, process structure, and the organization (Davenport, 1993). In addition to this, the prototype assists in creating knowledge on how to scale the solution and improve the companies' understanding of solution requirements, e.g., making it easier to enter into a dialogue with technology suppliers (Larsen et al., 2023b). These characteristics of the innovation approach to manufacturing innovation for Industry 4.0 lead to the second proposition:

Proposition 2: *'Manufacturing innovation for Industry 4.0 requires a flexible approach that can be operationalized through iterations, prototyping, and learning by doing.' (Larsen and Lassen, 2023, p. 14)*

7.2.3. EMERGENT PROCESS TOWARDS INDUSTRY 4.0

The results indicate that after manufacturing companies implement a manufacturing innovation for Industry 4.0, they continue to expand the innovation, increasing its complexity and extent, thereby building on top of the existing solution to create an Industry 4.0 manufacturing system. Such an incremental approach (Li, 2020), also sometimes referred to as an evolutionary process towards Industry 4.0 (Møller et al., 2023c), may have a more substantial effect on the competitive advantage gained from Industry 4.0 than approaching the transformation as a revolution (Ahlskog et al., 2017; Garud and Karnøe, 2003; Møller et al., 2023c).

In addition, the results indicate that accumulating knowledge from conducting dedicated projects on the manufacturing system provides a better foundation for manufacturing innovation in the context of Industry 4.0. Consequently, the higher level of automation in a company's existing manufacturing system, the higher the degree of newness of the manufacturing innovation. The results did not indicate a positive relationship between experience from previous manufacturing innovations for Industry 4.0 and the degree of innovation. However, research has indicated that such a relationship may exist (Chiarini et al., 2020). This means that experience with dedicated manufacturing projects resulting in accumulated knowledge appear to have a positive impact on the adoption of Industry 4.0, which supports an evolutionary process where the manufacturing system is built gradually. Using such an approach, each manufacturing innovation becomes an iteration of the Industry 4.0 innovation strategy (Li, 2020). This leads to the third and last proposition:

Proposition 3: *'Accumulated knowledge is the foundation of the strategic approach to Industry 4.0, so the Industry 4.0 manufacturing system arises from an emergent process.' (Larsen and Lassen, 2023, p. 14)*

The combination of the three propositions characterizes successful approaches to manufacturing innovation for Industry 4.0.

7.3. A PROCESS MODEL FOR MANUFACTURING INNOVATION

This section presents the research in article 5, 'Manufacturing Innovation: A Heuristic Model of Innovation Processes for Industry 4.0' (Larsen et al., 2023a).

Several parameters and characteristics of successful innovation approaches to manufacturing innovation for Industry 4.0 are now identified, among others, the value of an iterative process. However, to guide companies in manufacturing innovation for Industry 4.0, these parameters and characteristics of innovation approaches still need to be translated into a process model instructing which actions to take and in which order (Bruch and Bellgran, 2013; Wynn and Clarkson, 2018).

A process model is derived in article 5 based on a case study creating a manufacturing innovation for Industry 4.0. The process model is presented in Figure 14 and consists of six key actions driving the process forward. A generic innovation process consists of three phases: Front-end, development, and implementation, which transform an idea into a manufacturing innovation (Garud et al., 2013; Lassen, 2007; Yamamoto and Bellgran, 2013). In a classic, linear innovation process, the three phases are arranged consecutively, starting with the front-end phase, understanding the initial problem, and creating and refining the idea for problem-solving. The development phase shapes this idea and transforms it into a solution, which is implemented and put into operation in the manufacturing system in the implementation phase (Boer and During, 1987; Garud et al., 2013). The purposes of each of the three phases are reflected in the six actions in Figure 14. However, the actions are continuously revisited throughout the process to adapt the manufacturing innovation to fit its context (Maier et al., 2022). This means that progress in the process may also imply revisiting earlier stages in the innovation process. Iterations are initiated based on new insights and an improved understanding of the innovation, which may require revising earlier decisions. Examples of such insights and learning outcomes can be related to the manufacturing innovation's effect on the manufacturing system, such as the impact on the reliability of the manufacturing system, production costs, product quality, future product design options, and fit to existing operations, or available technology (Bessant et al., 2005; Frishammar et al., 2013).

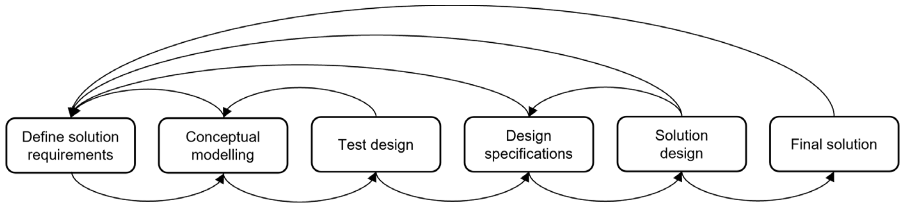

Figure 14: A process model for manufacturing innovation. Adapted from Larsen et al. (2023a)

The first action in the process is to 'define solution requirements,' which focuses on determining requirements of the solution, such as what it is expected to do and who should use it. The requirements are then transferred to a conceptual model of the solution, which may give input for additional requirements. If this is the case, the process returns to the first step, 'define solution requirements'; otherwise, the process continues to the next step, which is to 'test design' of the conceptual model. This action can lead to new insights revisiting the conceptual modeling stage. If this is not the case, the process progresses to determine the 'design specifications' of the solution. The specifications are input to the 'solution design,' which may drive the process back to 'design specifications' or the first step to 'define solution requirements.' The solution design may also be promoted to a 'final solution.' The manufacturing innovation is ready for implementation and commissioning if the final solution is acceptable. Otherwise, it needs to be revised, returning to the first action in the innovation process.

Following this process model, the complex manufacturing problem is decomposed, which brings focus to a defined area of the solution, thereby reducing some of its complexity and creating a foundation for solving the problem efficiently (Rigby et al., 2016). By continuously revisiting the actions in the innovation process, new information is included into the decision-making process as knowledge levels increase, improving the value of the manufacturing innovation to the company (Sjödin et al., 2018). For instance, the initial solution may be straightforward, and through iterations in the innovation process, the level of complexity in the solution is enhanced. Hence, iterations are used to advance the solution at a pace that fits the learning process of the people involved (Von Hippel and Tyre, 1995). As the results in article 4 show, adapting and adding to the manufacturing innovation may not reach saturation before implementation but rather be an ongoing process where the manufacturing innovation is extended as one of the first steps to operationalize an Industry 4.0 innovation strategy.

7.4. SYNTHESIS AND DISCUSSION OF RESULTS

These findings contribute to understanding how to approach manufacturing innovation for Industry 4.0. The first part of this chapter presents parameters and characteristics of the innovation approach to manufacturing innovation for Industry 4.0. These findings provide valuable knowledge about how to organize the process for manufacturing innovation but do not guide a company in the transformation from idea to manufacturing innovation. This is the purpose of an innovation process, so to complete the understanding of how to approach manufacturing innovation, the last part of the chapter presents an iterative process model for manufacturing innovation in the context of Industry 4.0 guiding this transformation.

Manufacturing innovations for Industry 4.0 are systemic by nature, and as the results in article 4 show, manufacturing companies consider the process towards an Industry 4.0 manufacturing system constituting several iterations. In this process, manufacturing innovations (in operation) are continuously extended to create an integrated Industry 4.0 manufacturing system. This means that the manufacturing innovation is not 'finished' after installation and operation but keeps evolving based on the learning outcomes obtained from using the solution. This approach compensates for the lack of transparency in the operational value of Industry 4.0, which is identified from an empirical perspective in article 1 and addressed as a gap in existing research (Napoleone et al., 2020).

Existing research has already addressed the need for more flexible approaches to manufacturing innovation, among others, to keep up with new technology introductions (e.g., Sjödin et al. (2018)). The findings in this dissertation add to this conclusion, validating its relevance in several cases and extending the understanding of why this is needed. The conclusions in article 2 explain that a more flexible approach to manufacturing innovation for Industry 4.0 is needed because the solution has a high level of complexity, among others, because the application of the technologies is immature in a manufacturing system context and the operational value of the technologies are therefore unclear. This relationship is confirmed by the findings in article 4.

CHAPTER 8. THE ‘SANDBOX’: A TOOL FOR MANUFACTURING INNOVATION

This chapter answers research question 3: *Which tools can support manufacturing companies' approach to manufacturing innovation in the context of Industry 4.0?* The research question is answered by the findings in articles 6 and 7.

Chapter 6 explores aspects that challenge the adoption of Industry 4.0 and concludes that companies might approach manufacturing innovation for Industry 4.0 incorrectly. Therefore, Chapter 7 studies how successful companies approach manufacturing innovation for Industry 4.0, providing several characteristics and parameters for how companies should adopt Industry 4.0. More specifically, the last part of the chapter presents a process model for manufacturing innovation in the context of Industry 4.0, guiding the transformation of an idea into a manufacturing innovation. This chapter delves into the innovation process, exploring a specific tool for manufacturing innovation called a sandbox approach. Section 8.1 presents the characteristics and advantages of the sandbox approach, defining its purpose. Section 8.2 explores using learning factories as a learning environment for the sandbox approach in existing research. The findings are summarized and discussed in Section 8.3.

8.1. THE ‘SANDBOX’ INNOVATION TOOL

This section presents the results of a multiple case study described in article 6, ‘A Sandbox Approach for Manufacturing Innovation: A Multiple Case Study’ (Larsen et al., 2023b).

Until now, the findings have already indicated that making a prototype of a manufacturing innovation can be valuable. In product innovation, prototyping is an iterative process in which the design of the product is refined through iterations of customer interactions (Rigby et al., 2016). However, compared to product innovation, the purpose of prototyping in manufacturing innovation is not to validate the design of the solution to users as the user of a manufacturing innovation may be several persons or sometimes even a machine or a process in the manufacturing system. Therefore, the design of a manufacturing innovation needs to be validated differently (Kurkkio et al, 2011).

Observations of the approaches to manufacturing innovation in the companies participating in Innovation Factory North indicate that manufacturing companies have gained significant, yet diverse, outcomes from prototyping a manufacturing innovation. Based on a multiple case study of three manufacturing companies' use of prototyping a manufacturing innovation for Industry 4.0, article 6 derives characteristics and advantages of these companies' approaches. The results show that the outcome of the approach spanned beyond validating the design, i.e., the purpose of prototyping, for which reason the approach was termed the sandbox approach.

The sandbox approach has several characteristics. The approach:

- Explores the potential of new technology, e.g., related to Industry 4.0
- Assists in understanding a complex problem and solving it
- Is associated with low cost and low risk.
- Is an experimental, iterative process where learning outcomes from prior iterations define the subsequent step, improving the design of the solution.
- Experiments in a setting resembling the company's manufacturing system

In one of the case companies being studied, the company used the sandbox approach to explore whether they should replace their metal casting process with a 3D printing process. Before initiating the sandbox approach, the company had no competences in 3D printing. No one, therefore, understood the advantages and limitations of 3D printing metal components and, thereby, which requirements the company would have if buying a 3D metal printer. The company had several challenges and uncertainties:

- Lack of competences for 3D printing
- Unaware of advantages and limitations of 3D printing metal components
- Unaware of requirements for 3D metal printer
- Unclear business case

The company applied the sandbox approach and purchased a 3D printer for plastics, which is cheaper than a 3D printer that prints in metal. The company experimented with the 3D plastic printer to learn about the advantages and limitations of 3D printing and, from this, derived their requirements, which could be used to seek the market for an appropriate 3D metal printer. These insights were used to make a business case to evaluate the economic potential of 3D printing compared to casting metal components. Furthermore, one of the main challenges for the company transferring to 3D printing was the lack of competences. However, by experimenting with 3D printing in the sandbox approach, involved employees started to build the desired competences in 3D printing. This example illustrates several of the advantages of using the sandbox approach as the company:

- Becomes familiar with an Industry 4.0 technology, or Industry 4.0 in general
- Learns and understands solution requirements for a manufacturing innovation for Industry 4.0
- Understands the operational value of the manufacturing innovation, e.g., as input for a business case
- Develops technical competences for Industry 4.0 through hands-on experience

- Clarifies the potential of manufacturing innovation
- Involve other employees in the organization to initiate the adoption of the manufacturing innovation

In the example, 3D printing components did not require validation in the manufacturing system. However, in other cases, validation in the manufacturing system is necessary. For instance, one of the other case companies in the article used the sandbox approach to build and test a sensor solution collecting data from a machine in the manufacturing system. In this case, the company experimented with the solution on another machine with similar capabilities, which was not frequently used. In other cases, companies may use a learning factory as a facility to experiment and test solutions for Industry 4.0. Section 8.2 elaborates on this.

8.2. LEARNING FACTORIES AS A 'SANDBOX' ENVIRONMENT

The results in this section are based on the findings of a literature review on learning factories presented in article 7, 'Process Innovation in Learning Factories: Towards a Reference Model' (Larsen et al., 2019).

Since its installation, the learning factory at Aalborg University is used in multiple collaborations between the university and industry, aiming to create manufacturing innovation for Industry 4.0 in the industry. The setup of the learning factory constantly changes and evolves as several research projects and student projects use the learning factory for different purposes. The case study in article 5 exemplifies how parts of the learning factory are used to create a new Industry 4.0 manufacturing system. In contrast, other parts of the learning factory are being used for other purposes.

Based on these observations, a literature review was initiated focusing on existing usage of learning factories as an exploration environment, e.g., supporting the sandbox approach to manufacturing innovation. However, the results showed that most applications of learning factories related to Industry 4.0 presented in research focus on transferring knowledge from university to industry through predefined learning programs (e.g., Erol et al. (2016), Prinz et al. (2017), Seitz and Nyhuis (2015) and Wagner et al. (2015)). Furthermore, the focus of research is on the implementation and operation of Industry 4.0 technology (e.g., Faller and Feldmüller (2015) Kreimeier et al. (2014), Kreitlein et al. (2015), and Merkel et al. (2017)) rather than as a tool for manufacturing innovation. Examples of learning factories used for innovation purposes in research environments such as university laboratories exist (Abele et al., 2017), and more recently, research has started to study the use of learning factories for innovation purposes (Gärtner and Mark, 2022).

Based on the findings of the literature review, a definition of a learning factory for manufacturing innovation, e.g., as a learning environment for the sandbox approach, is proposed: A learning factory supporting an experimental approach and encouraging creativity compared to the existing use of learning factories in the literature. The learning factory should promote a visionary and long-term perspective on manufacturing innovation for Industry 4.0, supporting its systemic potential.

8.3. SYNTHESIS AND DISCUSSION OF RESULTS

The sandbox approach is a tool to support the process for manufacturing innovation in the context of Industry 4.0 relying on an experimental approach. The sandbox approach makes experiments in a learning environment resembling the manufacturing system to avoid interruptions in operations. Examples of such learning environments are virtual simulations, testing on manufacturing equipment, which is rarely in use, or using a test factory replicating the manufacturing system in operation (Pisano, 1997). However, making a test factory is too expensive for most companies.

A learning factory is a small-scale factory with a manufacturing system producing a product and may, therefore, be a suitable learning environment for the sandbox approach. Furthermore, learning factories are already established as an essential learning environment for competence development for Industry 4.0 (Abele et al., 2019; Sorensen et al., 2023; Wagner et al., 2012). However, learning factories are currently not used as a learning environment for manufacturing innovation in existing research.

Using a learning factory as the learning environment for the sandbox approach has several benefits. For instance, 1) experimenting in a learning factory does not interfere with operations in the company's manufacturing system, which means that experiments can be more extensive without significant consequences, 2) The learning factory reflects an entire manufacturing system, which means that systemic relations from the manufacturing innovation to other parts of the manufacturing system can be evaluated through experiments, and 3) If the company can get access to a learning factory in a university laboratory, no costs are committed in expensive test facilities by the company.

The ten barriers to adopting Industry 4.0 which were presented previously may express that manufacturing companies incorrectly approach manufacturing innovation for Industry 4.0. Furthermore, the findings argue that successful companies use a flexible approach to manufacturing innovation for Industry 4.0, indicating that companies should approach the adoption of Industry 4.0 using an iterative process model. The sandbox approach is a tool used in the iterative innovation process to experiment with the manufacturing innovation before committing to the final design. Concerning the ten barriers, four of these may be overcome with the sandbox approach. The four barriers are:

- Lack of competences
- Lack of understanding of what Industry 4.0 is and its value for the company

- Difficult to make a business case that can justify value upfront
- Getting the organization onboard to ensure support and commitment in the transformation process (Larsen et al., 2021)

The knowledge created through experiments in the sandbox approach, e.g., enhances the competences of the people involved. The approach also clarifies the solution's potential, improving the company’s understanding of Industry 4.0 in general and providing inputs for making a business case. Lastly, the experimental approach has proven to be an excellent opportunity for involving other people in the organization in manufacturing innovation.

CHAPTER 9. CONCLUSION

The research presented in this dissertation aims to explore the approach to manufacturing innovation for Industry 4.0. The results are derived from analyses of extensive qualitative data from multiple manufacturing companies, leading to an advancement in the scientific understanding of manufacturing innovation as a dedicated research area.

The first part of the results addresses the standstill in adopting Industry 4.0 and exposes an inconsistency between expectations in industry and theory. Manufacturing companies approach manufacturing innovation for Industry 4.0 as a simple problem using a linear innovation process anticipating high transparency and low risk. However, manufacturing innovations for Industry 4.0 solve complex problems among others due to the systemic relations imposed by Industry 4.0 and therefore require a more flexible innovation approach, e.g., relying on iterations. In light of this knowledge, the standstill in the adoption of Industry 4.0 may be explained by this mismatch. The results can explain why companies capable of adopting manufacturing innovations for Industry 4.0 tend to focus on incremental, isolated solutions, as they disregard the systemic potential of Industry 4.0, thereby reducing the complexity of the solution.

The second part of the findings confirms the need for more flexible approaches to manufacturing innovation for Industry 4.0, which explores successful approaches to manufacturing innovation in the context of Industry 4.0. The research presents characteristics of successful approaches and a process model guiding the transformation of an idea to a solution in the context of Industry 4.0. The third and last part of the findings presents the sandbox approach as a tool for manufacturing innovation, which both enhances the company's knowledge about the solution and, at the same time, also contributes to advancing requested competences related to the manufacturing innovation. The results suggest that companies that use a flexible approach to manufacturing innovation to exploit the systemic, complex potential of Industry 4.0 and create the Industry 4.0 manufacturing system using an emergent process exploiting accumulated knowledge overcome the standstill facing the majority of manufacturing companies. Characteristics of the innovation approach derived from the research in this dissertation are summarized in Figure 15.

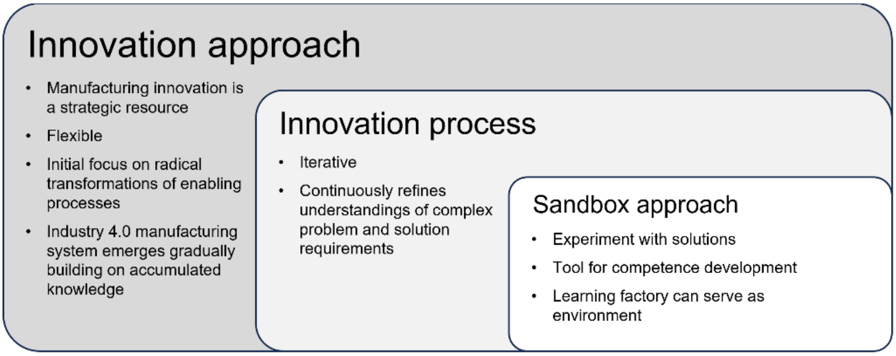

Figure 15: The approach to manufacturing innovation for Industry 4.0.

Previously, manufacturing innovation was treated as solving simple manufacturing problems using a linear innovation process. This was possible, among others, due to the lower level of systemic relations in manufacturing innovation. However, a significant contributor to simplifying the adoption of manufacturing innovation may also be attributed to the vital link to the operational value of the technology used in the manufacturing innovation (Calabrese et a., 2022). For instance, Lean manufacturing presents solutions to reduce waste in the manufacturing system, establishing guidance for solution design and expected outcomes. The consequence of this is that the main task of the management in the innovation process is related to selecting a solution design, deciding on a technology, and implementing the manufacturing system (Larsen et al., 2023c). As the findings in this dissertation show, these tasks are no longer enough to adopt manufacturing innovations in the context of Industry 4.0 as the approach relies on exploration and experimentation to understand the potential of Industry 4.0. This is, among others, a consequence of the missing link between technology and operational value that may not be possible to establish (Li, 2020; Napoleone et al., 2020). The findings suggest that to move the manufacturing industry beyond its current level of standstill and to the adoption of complex manufacturing innovations for Industry 4.0 exploiting the systemic potential, manufacturing companies need to learn how to approach these new types of manufacturing innovations. This dissertation presents how this can be done and thereby presents a solution to the change in approaching manufacturing innovation observed by one of the participants in Innovation Factory North:

> *"In the past, it was the management who pointed out where we should invest and what we should do. Now, the management no longer has this knowledge and therefore needs to learn how to initiate these new projects"* (Production Manager and participant in Innovation Factory North)

9.1. FURTHER RESEARCH

Although the theoretical contributions presented in this dissertation provide a coherent perspective on the approach to manufacturing innovation in the context of Industry 4.0, more research is still needed to strengthen theory on the subject. This section presents directions for further research extending and refining the results of this dissertation:

- More research is still needed to address the innovation process in more detail, e.g., exploring tools and methods to support efficient decision-making and to understand how and when to involve affected employees.
- This research uses a qualitative research approach among others because the number of companies that succeed with manufacturing innovation for Industry 4.0 is still low, which encourages in-depth exploration of cases. However, the number of success cases is increasing, enabling more quantitative research on the topic in the future. Further research may therefore explore the effect of company characteristics to the adoption of Industry 4.0 to understand whether such characteristics affect the outcome of the innovation process. Furthermore, the effect of using an innovation approach that (mis)matches with the theoretical requirements of approaching manufacturing innovation for Industry 4.0 could be examined to understand the effect of a match between type of problem being solved by a manufacturing innovation and type of innovation process.
- In this research, manufacturing innovation for Industry 4.0 is considered a strategic resource in manufacturing companies independent of activities related to product innovation. This positioning breaks with existing interpretations of the role of manufacturing innovation as a spillover effect of product innovation, thereby challenging the role of manufacturing innovation as initially interpreted in innovation research. More research is, therefore, needed to support this line of thinking among others comparing realized potential of Industry 4.0 across cases that consider manufacturing innovation a strategic resource with cases that consider manufacturing innovation as a spillover effect of product innovation.

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APPENDED ARTICLES

Article 1. Industry 4.0 Holds a Great Potential For Manufacturers, So Why Haven't They Started? A Multiple Case Study of Small and Medium Sized Danish Manufacturers.

Article 2. Managing Manufacturing Innovation: Four Types of Problems and Matching Innovation Processes.

Article 3. Design Parameters for Smart Manufacturing Innovation Processes.

Article 4. Characteristics of (Successful) Manufacturing Innovation for Industry 4.0.

Article 5. Manufacturing Innovation: A Heuristic Model of Innovation Processes for Industry 4.0.

Article 6. A Sandbox Approach for Manufacturing Innovation: A Multiple Case Study.

Article 7. Process Innovation in Learning Factories: Towards a Reference Model.

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