Human-Centred Production

The role of competences and learning for industry 4.0

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THE ROLE OF COMPETENCES AND LEARNING
FOR INDUSTRY 4.0

BY
ANDREAS KORNMAALER HANSEN

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AALBORG UNIVERSITY
DENMARK

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THE ROLE OF COMPETENCES AND LEARNING FOR INDUSTRY 4.0

by

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AALBORG UNIVERSITY
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CV

Andreas grew up in Aalborg, Denmark, where he finished both his Bsc. and Msc. at Aalborg University within Engineering Psychology – a discipline that deals with human-centred solutions, ensuring there are user-friendly systems and interactions with technology in the world. Throughout his master's degree, he spent a semester at Auckland University of Technology in New Zealand in 2018, and presented a scientific poster at the IEEE RO-MAN conference in Nanjing, China. He was invited to write his master's thesis at University of Canberra, Australia in 2019 on the topic of human-robot interaction (HRI) and the effect of different settings on the interaction experience. After graduating, his interest in HRI led him into an internship with AAU to become involved in a research project with an interactive drawing robot and a collaboration with Aalborg municipality. Later, Andreas started his PhD in the Materials and Production department at Aalborg University in 2020. Here, his main topic pivoted to the digitalisation of manufacturing companies. However, his interest in human-centred solutions and human-robot interaction persisted as it was evident that these were core challenges in the newfound research field. Through close collaboration with small and medium-sized manufacturing companies within the Innovation Factory North research project, he uncovered human-centred challenges and opportunities for digital transformation. During his PhD, Andreas spent 3,5 months in Reggio Emilia at the University of Modena and Reggio Emilia, where he worked on how to introduce novices to collaborative robots.

ENGLISH SUMMARY

In recent years, the so-called fourth industrial revolution (Industry 4.0) has received much attention as the one to connect manufacturing technologies, integrating machines, supply chains, and data to enable informed decision-making and increased automation. Now, a new paradigm is emerging – the fifth industrial revolution (Industry 5.0). This phase places humans at the centre of production technology, adopting a capability-driven perspective with a profound focus on human centricity, resiliency, and sustainability. While it may be debatable whether Industry 5.0 is a new revolution or a mere reaction to the shortcomings of the highly technology-driven focus of Industry 4.0, Industry 5.0 represents a shift towards a more holistic and integrated approach, signalling a transformative era where the role of humans in manufacturing takes precedence over technology as Industry 4.0 has struggled to become operationalised as visioned. Digitalisation in Denmark has experienced widespread adoption but is now encountering a notable slowdown, particularly evident in small and medium-sized enterprises (SMEs). The digitalisation trajectory in SMEs lags behind that of larger enterprises, which is a critical issue given that SMEs constitute most of the manufacturing sector. Complicating matters is an anticipated shortage of the workforce for current manufacturing operations, a situation expected to intensify in the coming years. The demographic trends in Denmark, marked by an ageing population and population decline, further emphasise the need for increased digitalisation and automation to maintain current living standards sustainably amid a diminishing workforce. Adding to the complexity, manufacturers are grappling with a significant deficiency in the knowledge and competences required for effective digital transformation. As such, there is a pressing need for approaches that guide responsible, sustainable, and human-centred digitalisation.

With these challenges in mind, the objective of this dissertation is to provide actionable insights about the role of competences and learning in advancing digitalisation within manufacturing and production environments. This is presented through five appended research contributions. The empirical results arrive both from desk research and empirical case research from multiple Danish SMEs through the *Innovation Factory North* research program. This program provided a unique insight into 90 manufacturing companies.

The results are centred around three main parts that firstly identify crucial competences needed for digital transformation and tie them to the process of digital transformation. The findings arrive at a novel competence typology in three categories: *management, backend,* and *frontend* and connect them in a necessary feedback loop to support the journey towards digital transformation. Secondly, organisational prerequisites and hindrances for competence development for digital transformation are explored to explain the slow digitalisation observed in SMEs. It is found how specific foundational knowledge areas hinder SMEs in their digitalisation

efforts. Lastly, exemplary case studies illustrate how adopting a human-centred perspective helped mature the SMEs' foundational knowledge and promote learning and understanding of digital transformation. The results also challenged the idea that a digital transformation always needs a long-term strategy to succeed – for SMEs, a more incremental approach seems suitable.

Other researchers may use the results to increase the understanding of the sociotechnical challenges related to digital transformation in SMEs. Practitioners may use the results to focus their operations around the specific highlighted knowledge areas.

DANSK RESUME

I de seneste år har den såkaldte fjerde industrielle revolution (Industry 4.0) modtaget meget opmærksomhed for at være i stand til at sammenkoble produktionsteknologier således, at alt fra maskiner til hele forsyningskæder kan integreres samt øget mulighed for datadrevet beslutningstagen og automation. Nu er et nyt paradigme på vej – den femte industrielle revolution (Industry 5.0). Denne fase placerer mennesket i centrum for produktionsteknologier og advokerer en kapabilitets-drevet perspektiv med særligt fokus på menneske-centrerede, robuste og bæredygtige produktionsmiljøer. Det kan diskuteres hvorvidt Industry 5.0 er en ny revolution eller blot et modsvar på den manglende udbredelse af den i højt grad teknisk fokuserede Industry 4.0. Industry 5.0 repræsenterer dog en mere holistisk og integreret tilgang, hvilket signalerer et skift, hvor mennesket vejer højere end teknologien i takt med at Industry 4.0 har kæmpet med at blive operationaliseret i samme grad, som det var forudsagt. Digitalisering i Danmark er generelt vidt udbredt, men oplever en mærkbar langsommere vækst, især i små og mellemstore virksomheder (SMV'er). Digitaliseringsudviklingen i SMV'er sakker tilmed bagud i forhold til de større virksomheder, hvilket er et kritisk problem taget i betragtning at SMV'er står for størstedelen af produktionsvirksomheder. For at komplicere sagen yderligere forventes den tilgængelige arbejdsstyrke indenfor produktion at mindskes i de kommende år. Problemstillingen indebærer også, at demografien spår en aldrende population samtidigt med, at væsentligt færre børn bliver født, hvilket understreger nødvendigheden af øget digitalisering og automation, hvis vi skal være i stand til bæredygtigt at opretholde den nuværende levestandard med færre tilgængelige arbejdskræfter. Tilføjende til kompleksiteten, så kæmper nuværende produktionsvirksomheder med manglende viden og kompetencer, der er nødvendige for at gennemføre en effektiv digital transformation. Således er der presserende brug for tilgange, der kan guide ansvarlig, bæredygtig og menneskecentreret digitalisering.

Med disse problemstillinger i tankerne, er formålet med denne afhandling at skabe indsigt omkring rollen, som kompetencer og læring spiller for at fremrykke digitalisering indenfor produktionsvirksomheder. Det bliver præsenteret igennem fem forskningsbidrag. De empiriske resultater stammer både fra sekundær vidensindsamling og case-baseret forskning fra flere danske SMV'er igennem forskningsprojektet *Innovation Factory North*. Dette skabte unikke indsigter fra 90 produktionsvirksomheder.

Afhandlingen er centreret omkring tre hovedparter, som først identificerer vigtige kompetencer nødvendige for digital transformation, og binder disse op på processen bag digital transformation. Her præsenteres en ny kompetence-typologi opdelt i tre kategorier: *management, backend*, og *frontend*. Disse forbindes til en nødvendig feedback proces, der bør understøtte rejsen mod digital transformation. Derefter udforskes organisatoriske forudsætninger og forhindringer for kompetenceudvikling

mod digital transformation i SMV'er for at forklare den langsomme digitale udvikling, man observerer i SMV'er. Det fremhæves, hvordan specifikke grundlagsskabende vidensområder forhindrer SMV'er i deres digitaliseringstiltag. Til slut præsenteres case et casestudie med to SMV'er, som har formået at øge deres digitalisering. Resultaterne illustrerer, hvordan et menneske-centreret perspektiv hjælper med at modne SMV'er grundlagsskabende viden og understøtte læring og forståelse for digital transformation. Resultaterne udfordrer også ideen om at digital transformation altid bør tilgås fra et langsynet strategisk perspektiv – for SMV'er virker en mere inkrementel tilgang fordelagtig.

Resultaterne kan anvendes af andre forskere til at øge forståelsen for hvilke sociotekniske udfordringer, der relaterer sig til digital transformation af SMV'er. I praksis kan resultaterne anvendes til at fokusere de operationelle processer omkring de fremhævede vidensområder.

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First and foremost, I would like to thank Aalborg University and University College North, who entrusted me with the task of completing this PhD. Both institutions helped provide a challenging and fruitful research environment where I could learn and expand my skills as a researcher and disseminator of my accumulated knowledge. This journey was eased along by having friendly colleagues who, despite their own professional or personal challenges, were always available for discussions or non-work-related activities.

To Astrid Heidemann Lassen, thank you for your support and constructive discussions throughout the PhD. One of the first things you mentioned to me, when I was feeling overwhelmed with the vast amount of information available and seemingly endless directions to pursue, was that in a PhD, one must be comfortable with shaky ground under one's feet. For a long time, I doubted whether doing a PhD was even for me. I felt uncomfortable telling people that I was doing a PhD as I felt the ground moving beneath my feet and being in unfamiliar territory. It took a while, but thankfully, I now feel like I obtained (and earned) my "PhD sea-legs". Also, when I was torn between the amount of information that I wanted to include in my papers, the word limit, and overall sensemaking, you advised me to write a book later, but now focus on writing a paper. I think this "book" will do for now.

To the people at the ARS Control lab at the University of Modena and Reggio Emilia, thank you for making my stay in Italy scientifically relevant and enjoyable. A special thanks goes to Dr. Valeria Villani and Dr. Andrea Pupa, without whom the stay would not have been the same. Thank you, Valeria, for accepting me as a visiting researcher, challenging my ideas, and taking the time to act as a translator during multiple rounds of Italian bureaucratic steps. Thank you, Andrea, for inviting me into your home and for the extra hours you selflessly spent on my behalf to ensure the research succeeded. However, I still contemplate whether I should forgive you for nearly murdering me with all-you-can-eat pasta.

A thank you also goes to Shaoping Bai, as he allowed me to extend my employment at AAU while assisting him with the Exskallerate project. This allowed me to finish the final appended papers for this thesis. On the topic of papers, a thank you also goes out to the anonymous reviewers who continuously provided constructive (and at times challenging) feedback, without which this work would not have been the same.

Finally, a big thank you to all my friends and family who supported me throughout the PhD. Thank you, Gittemarie, for your loving support and motivational spirit. It made the finalisation of this thesis much more tolerable.

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In-text citation: (Hansen et al., 2023)

B. Hansen, A. K., Christiansen, L., & Lassen, A. H. (2024). Technology isn't enough for Industry 4.0: On SMEs and hindrances to digital transformation. *International Journal of Production Research*, *Accepted/In press*. https://doi.org/10.1080/00207543.2024.2305800
In-text citation: (Hansen et al., 2024)

C. Hansen, A. K., Stoettrup Schioenning Larsen, M., & Lassen, A. H. (2021). *The Role of Absorptive Capacity and Employee Empowerment in Digital Transformation of SMEs* (SSRN Scholarly Paper 3859277). https://doi.org/10.2139/ssrn.3859277
In-text citation: (Hansen et al., 2021)

D. Hansen, A. K., & Lassen, A. H. (n.d.). Enhancing Knowledge Creation in Manufacturing SMEs: A Digital Transformation Imperative. *Journal of Manufacturing Technology Management*, *Unpublished / In process to be submitted*.
In-text citation: (Hansen & Lassen, n.d.)

E. Hansen, A. K., Villani, V., Pupa, A., & Lassen, A. H. (n.d.). *Introducing novice operators to collaborative robots: A hands-on approach for learning and training*. *In review*. https://doi.org/10.36227/techrxiv.22762562.v1
In-text citation: (Hansen et al., n.d.)

LIST OF PAPERS NOT APPENDED TO THE THESIS

The following papers are not appended to the thesis. However, they all contribute to the overall topic and thus the knowledge foundation on which this thesis is built.

1. Møller, C., Hansen, A. K., Palade, D., Sørensen, D. G. H., Hansen, E. B., Uhrenholt, J. N., & Larsen, M. S. S. (2023a). An Action Design Research Approach to Study Digital Transformation in SME. In O. Madsen, U. Berger, C. Møller, A. Heidemann Lassen, B. Vejrum Waehrens, & C. Schou (Eds.), *The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs* (pp. 51–65). Springer International Publishing. https://doi.org/10.1007/978-3-031-15428-7_5
   In-text citation: (Møller, Hansen, et al., 2023a)

2. Møller, C., Hansen, A. K., Palade, D., Sørensen, D. G. H., Hansen, E. B., Uhrenholt, J. N., & Larsen, M. S. S. (2023b). Innovation Factory North: An Approach to Make Small and Medium Sized Manufacturing Companies Smarter. In O. Madsen, U. Berger, C. Møller, A. Heidemann Lassen, B. Vejrum Waehrens, & C. Schou (Eds.), *The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs* (pp. 113–126). Springer International Publishing. https://doi.org/10.1007/978-3-031-15428-7_10
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3. Lassen, A. H., Hansen, A. K., Sørensen, D. G. H., & Larsen, M. S. S. (2023). Labour 4.0: How is the Workforce Prepared for the Future of Manufacturing Industries? In O. Madsen, U. Berger, C. Møller, A. Heidemann Lassen, B. Vejrum Waehrens, & C. Schou (Eds.), *The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs* (pp. 391–403). Springer International Publishing. https://doi.org/10.1007/978-3-031-15428-7_36
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4. Larsen, M. S. S., Lassen, A. H., Sorensen, D. G. H., & Hansen, A. K. (2023). A Sandbox Approach for Manufacturing Innovation: A Multiple Case Study. In O. Madsen, U. Berger, C. Møller, A. Heidemann Lassen, B. Vejrum Waehrens, & C. Schou (Eds.), *The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs* (pp. 421–429). Springer International Publishing. https://doi.org/10.1007/978-3-031-15428-7_38
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5. Sorensen, D. G. H., Lassen, A. H., Larsen, M. S. S., & Hansen, A. K. (2023). Learning Factories for Learning and Experimentation on Industry 4.0 in SMEs. In O. Madsen, U. Berger, C. Møller, A. Heidemann Lassen, B. Vejrum Waehrens, & C. Schou (Eds.), *The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs* (pp. 431–440). Springer International Publishing. https://doi.org/10.1007/978-3-031-15428-7_39
In-text citation: (Sorensen et al., 2023)

6. Larsen, S. K., Colli, M., Hansen, A. K., & Stingl, V. (2023). Prioritizing Technology-Enabled Production Improvements in SMEs: An Interpretive Structural Model. In F. G. Galizia & M. Bortolini (Eds.), *Production Processes and Product Evolution in the Age of Disruption* (pp. 321–329). Springer International Publishing. https://doi.org/10.1007/978-3-031-34821-1_35
In-text citation: (S. K. Larsen et al., 2023)

7. Li, C., Chrysostomou, D., Pinto, D., Hansen, A. K., Bøgh, S., & Madsen, O. (2023). Hey Max, Can You Help Me? An Intuitive Virtual Assistant for Industrial Robots. *Applied Sciences*, *13*(1), Article 1. https://doi.org/10.3390/app13010205
In-text citation: (Li et al., 2023)

8. Li, C., Hansen, A. K., Chrysostomou, D., Bøgh, S., & Madsen, O. (2022). Bringing a Natural Language-enabled Virtual Assistant to Industrial Mobile Robots for Learning, Training and Assistance of Manufacturing Tasks. *2022 IEEE/SICE International Symposium on System Integration (SII)*, 238–243. https://doi.org/10.1109/SII52469.2022.9708757
In-text citation: (Li et al., 2022)

9. Stingl, V., Christiansen, L., Cheng, Y., Hansen, A. K., & Lassen, A. H. (2023). Conceptualising the robotisation of manufacturing work as a soft system: A thematic analysis of the literature. *Journal of Manufacturing Technology Management*, *Accepted for publication*.
In-text citation: (Stingl et al., 2023)

10. Palade, D., Hansen, A. K., & Møller, C. (n.d.). Enterprise integration as a driving factor for digitalization in small and medium sized manufacturing enterprise *(working paper).*
In-text citation: (Palade et al., n.d.)

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”Det har stor betydning for vores virksomheders konkurrenceevne og vores samfunds vækst og velstand, at vi er digitalt foregangsland. Derfor har vi nogle udfordringer, som vi skal tage fat på, hvis vi fortsat skal være i front. Vi skal have flere IT-specialister, vi skal fokusere på digitalisering i de små og mellemstore virksomheder, og vi skal bruge digitalisering til at skubbe på den grønne omstilling. Den digitale udvikling skal balanceres med et fokus på ansvarlighed, hvor vi ikke går på kompromis med vores demokratiske værdier.”

- Marie Bjerre, Digitaliseringsminister og minister for ligestilling, 2023-05-02 (Bang, 2023)

English

“It is of great importance to the competitiveness of our companies and to the growth and prosperity of our society that we are a digitally progressive country. Because of this, we are facing some challenges that we must deal with if we are to continue in front. We need more IT specialists, we must focus on digitalisation in small- and medium-sized enterprises, and we must use digitalisation to pursue the green transformation. The digital development must be balanced with a focus on responsibility, where our democratic values are not compromised."

- Marie Bjerre, Minister for digitalisation and gender equality, 2023-05-02 (Bang, 2023)

CHAPTER 1. INTRODUCTION

December 2023 marks the 120th anniversary of the first motorised flight by the Wright brothers in 1903. Five years later, in 1908, the first Ford Model T rolled off the assembly line. The Model T – now a symbol of a manufacturing paradigm shift – is often highlighted as a turning point within manufacturing both in terms of the division of labour and the use of assembly lines, which paved the way for mass production and affordability to the average consumer.

Spurred on by the pioneering code-breaking efforts at Bletchley Park during World War II, the foundation for the modern computer was laid. Technology transitioned from purely analogue to digital. Decades later, computers became available to consumers and were soon connected via the world wide web – the internet. Today, internet access is virtually omnipresent and easily accessible, e.g., via "smartphones" with significant computing power (more than 100.000 times the computing power onboard the Apollo 11 mission, which led us successfully to the moon and back[1]).

Access to the internet also means access to information and, thereby, knowledge. Gone are the days of reaching for encyclopaedias when in need of information. Discussions can be over quickly – won by a swift search on the internet where information is freely available. This capability, of course, also extends to manufacturing. It is possible to share real-time information between machines, humans, supply chains, and operations in ever-growing quantities with ever-growing computing power available. Following Moore's law about how the number of components within an integrated circuit will double every 18 months (Moore, 1965), technology is evolving at a near-exponential pace while affordability improves. Seeing how a modern smartphone is vastly superior in computing power compared to the computer used in the Apollo 11 mission - surely, then, there is more to technology than raw processing capability when a computing device so primitive by today's standards is capable of such a pivotal achievement in human history. In this case, it was much about how well the Apollo computer operated together with all the other complex systems and processes. Such could also be said about the current manufacturing technology available today. Today, there is a wealth of manufacturing technologies to choose from, capable of complex data flows between systems. Such digital connectivity and its potential to create a manufacturing ecosystem is what laid the foundation behind the thinking under the umbrella term *the Fourth Industrial Revolution* or *Industry 4.0* (Kagermann et al., 2013; Rübmann et al., 2015; L. D. Xu et al., 2018). However, getting there has proven exceedingly challenging, especially

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[1] https://theconversation.com/would-your-mobile-phone-be-powerful-enough-to-get-you-to-the-moon-115933 (accessed 2023-10-11)

for small and medium-sized manufacturing enterprises (M. S. S. Larsen et al., 2022; Lassen & Wæhrens, 2021; Moeuf et al., 2020; Stentoft et al., 2021).

The industrial sector has witnessed three distinct revolutions in the past, with the current era termed Industry 4.0, characterised by seamless technological interactions (Kagermann et al., 2013; Rübmann et al., 2015; L. D. Xu et al., 2018). Recently, discussions about Industry 5.0 have surfaced, despite ongoing efforts to fully implement Industry 4.0. Industry 5.0 focuses on capability-driven goals, emphasising three key areas: human-centric, sustainable, and resilient production (Nahavandi, 2019; X. Xu et al., 2021). See Table 1 for a brief overview of the industrial revolutions.

Term	**Description**
Industry 1.0	Invention of mechanized machines like the spindle for clothes making and the steam engine that revolutionised steel making. This is commonly referred to as *the* industrial revolution.
Industry 2.0	Electrification of manufacturing, leading to mass production using assembly lines.
Industry 3.0	Manufacturing becomes digital. Introduction of computers, industrial robots, and electronic databases. This is also referred to as the information age (L. D. Xu et al., 2018).
Industry 4.0	Manufacturing gains connectivity through the industrial internet of things (IIoT), integrating machines, supply chains, and data for informed decision-making. Nine technological pillars are often referred to as the enabling technology of industry 4.0: Additive manufacturing, simulation, horizontal/vertical integration, industrial internet of things, cyber-security, cloud, advanced robots, augmented reality, big data and analytics (Rübmann et al., 2015).
Industry 5.0	An emerging paradigm placing humans at the centre of production technology, adopting a capability-driven perspective through a focus on human centricity, resiliency, and sustainability (Nahavandi, 2019; X. Xu et al., 2021).

Table 1. A summation of five industrial revolutions. Industry 4.0 is ongoing while Industry 5.0 is emerging.

Succeeding with a digital transformation on par with the vision of Industry 4.0 is challenging on a lot of different levels. Not only is it very hard for manufacturing companies to grasp the Industry 4.0 concepts and strategise towards adopting its enabling technologies (Ghobakhloo et al., 2022), but manufacturing companies worldwide are also grappling with significant challenges in securing an adequate workforce for their current operations (European Commission, 2023; Stevick, 2023). In Denmark, the number of companies who experience a shortage of IT specialists has increased from 34% in 2012 to 62% in 2022 (Digitaliserings- og Ligestillingsministeriet, 2023, p. 23). This shortage in the workforce is likely to persist unless fundamental shifts occur in how manufacturing work and competence development are conducted. Globalisation has historically mitigated some of these issues through offshoring and outsourcing to countries with lower labour costs. However, as these lower labour-cost countries gradually became more industrialised, their economies grew, and slowly, their labour costs increased as well – mitigating the cost advantages seen by Western manufacturers from high labour-cost countries in the first place (Barbieri & Stentoft, 2016). Add to that the recent disruptions in supply chains due to the COVID-19 pandemic, the accident causing the Suez Canal blockage, and geopolitical conflicts – such events have only prompted an even more aggressive strategic shift. Many western manufacturers are now reshoring parts of their production at a faster pace, aiming for shorter supply chains and greater resilience (Harapko, 2023). Consequently, this calls for ways to manufacture goods smarter. Hence, there is a growing interest in automation solutions to boost productivity and maintain competitiveness in the global market by relying on fewer manual labour costs per product produced (Bauer et al., 2023).

While Denmark is commonly well renowned for its high level of digitalisation and has held the first place for the most digitalised country, Finland overtook Denmark in 2022 (measured on the EU Commission's Digital Economy and Society Index (DESI)) (Bang, 2023). This indicates that the advancement of digitalisation in society that we have come to expect of Denmark is slowing down. What is more, it seems that there is a gap in the use of advanced digital technologies between SMEs and large enterprises that appears to be growing (Folketinget, 2021). This means that – not only does a significant digitalisation gap already exist between SMEs and large enterprises – the gap is becoming larger as SMEs fail to advance their digitalisation at the same pace and on the same level as the large enterprises. Digitalisation in Denmark is slowing down and is slowing more in SMEs. As a society, this is not ideal.

Despite advancements in automation, many manufacturing operations still rely on manual labour and craftsmanship due to barriers like financial constraints and the complexity of crafts (Horváth & Szabó, 2019; Müller et al., 2018). Moreover, an ageing global population and declining fertility rates necessitate that the existing workforce remains active for longer to sustain society as we have come to know it. See Figure 1. The manufacturing sector already has a high mean worker age, leading to concerns about the loss of valuable knowledge and experience upon retirement (Calzavara et al., 2020).

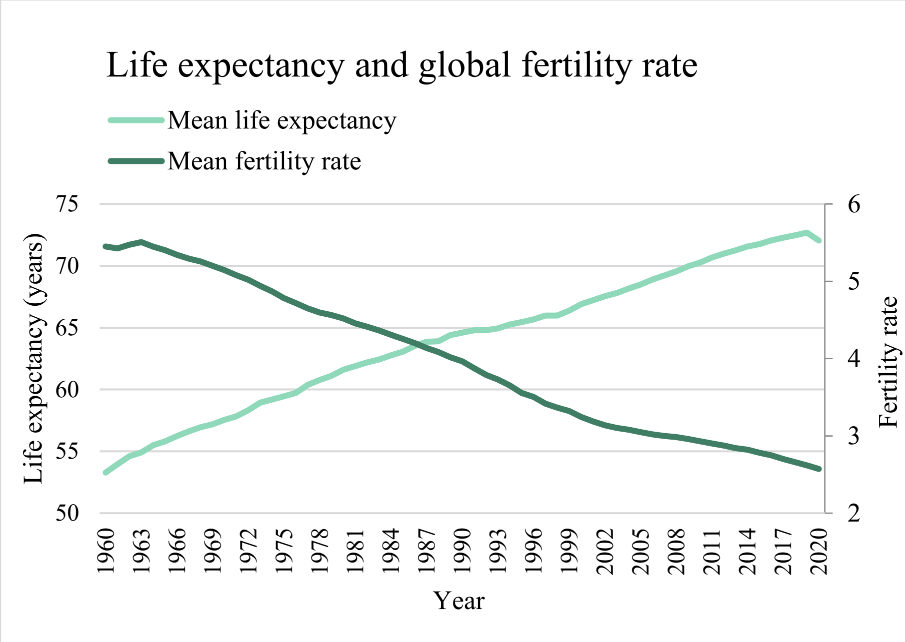

Figure 1. Life expectancy continues to increase while birth fertility declines. Data from (World Bank, 2022a, 2022b).

Such large movements, both within technological advancement and a diminishing workforce, inevitably lead to changing work environments and the way manufacturing enterprises structure their organisations in order to stay competitive (Cimini et al., 2020; Flores et al., 2020).

Addressing these challenges calls for innovative ways to enhance productivity while requiring fewer workers per product, emphasising smarter work organisation enabled by digital and operational technology (Calzavara et al., 2020). In this context, it is vital to continually strive for improvement of working conditions in manufacturing environments, focusing on human factors and engineering (Kadir & Broberg, 2021). This approach can potentially lead to a more effective and sustainable workforce, allowing workers to enjoy fulfilling working lives for extended periods if necessary. Achieving this vision aligns with the Industry 5.0 ideology, emphasising a *human-centric*, *sustainable*, and *resilient* approach to manufacturing. The shift towards more capability-driven values in Industry 5.0 is a response to these challenges, advocating for placing humans at the forefront of technological advancements within manufacturing. However – doing so has proven challenging time after time, and Industry 4.0 is barely present in many SMEs.

Why have we not seen a convincing roll-out of Industry 4.0, despite more than a decade has passed since its introduction? To summarise, there are some significant challenges behind the veil of modern digital manufacturing technologies, which have helped shape this dissertation:

- Digitalisation in Denmark is widespread but is slowing down.
- Digitalisation in SMEs moves slower and is less advanced than in larger enterprises. This is problematised by SMEs, which make up the majority of the manufacturing sector.
- There is an overall lack of workforce for current manufacturing operations, which is expected to grow in the coming years.
- The trend in demographic properties in Denmark (ageing population and population decline) calls for increased digitalisation and automation to maintain current living standards.
- Manufacturers experience a lack of knowledge and competences to enable digital transformation.
- Digitalisation brings changes to the manufacturing work environments. Approaches are needed to guide responsible, sustainable, and human-centred digitalisation in manufacturers to elevate working conditions and to maintain and attract the workforce throughout this process.

These problem areas set the tone for the rest of this thesis.

Digital transformation is a multifaceted challenge hindered by a lack of knowledge, competences, and awareness of available technology, a diminishing active workforce, and organisational structures not set up for the flexibility required by Industry 4.0. More clarification is needed to aid the companies in choosing the right battles at times most opportune for them and their current situation. This thesis exploits a unique opportunity to gain empirical insights from a wealth of small and medium-sized manufacturers within the Danish manufacturing industry through a large research program. This paves the way to uncover both hindrances and driving factors towards digital transformation through a human-centred perspective. Additionally, ways to introduce and learn about manufacturing technology to enable flexible production are explored.

CHAPTER 2. STATE-OF-THE-ART

2.1. DIGITISATION, DIGITALISATION, AND DIGITAL TRANSFORMATION

The terms digitisation, digitalisation and digital transformation appear similar; however, they hold vastly different meanings and should be differentiated (Verhoef et al., 2021). These terms are often mentioned in relation to research on industry 4.0 topics, but the literature is not always transparent about what the term means (Gong & Ribiere, 2021). Therefore, the efforts to create a unified definition are much appreciated (Gong & Ribiere, 2021; Verhoef et al., 2021).

Digitisation simply means a change from an analogue medium to a digital one, e.g., digitising one's notes from a physical notebook into a digital notebook.

While similar sounding, the term *digitalisation* encompasses much more and tends to focus on economic-driven outcomes (efficiency and productivity, process automation, cost reduction) to reinforce an existing value proposition for stakeholders.

Digital transformation refers to a more radical change and redefinition of the value proposition, leading to a more capability-driven outcome (Gong & Ribiere, 2021). Based on Gong & Ribiere and Verhoef et al., digital transformation is defined as:

> A fundamental change process enabled by strategically leveraging digital technologies and resources (human, financial, knowledge) and capabilities (digital capabilities and dynamic capabilities), which aims to improve an organisation (business model innovation, open mindset and innovative culture, agility and flexibility, ecosystem and collaboration) to redefine the value proposition for stakeholders (customers, employees, partners etc.) (Gong & Ribiere, 2021; Verhoef et al., 2021).

Therefore, digital transformation can roughly be organised in three stages (Verhoef et al., 2021), where the outcome of digital transformation leads to better conditions for business model innovation and value proposition for stakeholders through strategically leveraging human and digital resources, see Figure 2. This, in turn, leads to changes in the organisational structure.

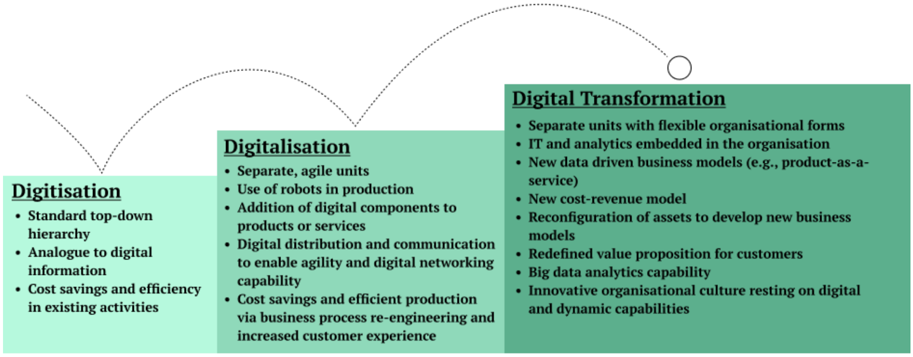

Figure 2. Three phases of digital transformation adapted from (Gong & Ribiere, 2021; Verhoef et al., 2021)

It is important to note that such advances through the phases towards digital transformation, including changes in organisational structure, do not happen organically in a company but require focused strategic effort (Ghobakhloo et al., 2022; Pessot et al., 2020).

2.2. INDUSTRY 4.0 – "THE FOURTH INDUSTRIAL REVOLUTION"

As mentioned in the introduction, a strong emphasis within manufacturing literature in the recent decade has been put on the fourth industrial revolution or Industry 4.0. Industry 4.0 can be viewed as a frame for explaining digital transformation within companies. However, many of the ideas on which Industry 4.0 rests have been around since the 1980s (e.g. Computer Integrated Manufacturing (CIM) (Anjard, 1995)). It seems that the timing of the Industry 4.0 initiative was just right as it landed at a point in time when the world was still recovering from the financial crisis in 2008, while the available sensor and communications technology was mature enough to envision an ambitious, yet realistic, industrial ecosystem enabled by digital technologies. As such, it stands as an overarching vision in which to frame the potentials of connecting digital technologies. It is therefore important to note that the following technologies that are often highlighted in connection with the fourth industrial revolution are not all imperative to be implemented before a digital transformation can happen. However, nine pillars of technology (Figure 3) are typically recognised as the foundation for Industry 4.0 – the enabling technologies:

- **Big data and analytics** refer to vast amounts of structured and unstructured data collected from various sources in manufacturing. Analytics involves analysing this data to derive insights, trends, and patterns, enabling informed decision-making, forecasting and strategic planning (e.g., aided by machine learning).
- **Simulation** involves creating computerised models to imitate the behaviour of real-world systems. It allows for experimentation, testing, and scenario

analysis without the need to manipulate the actual physical components, providing valuable insights and aiding in decision-making. For example, it is possible to simulate a whole re-design of the factory floor to find the optimal solution before significant investments are made.

- **Augmented and virtual reality** to be used for intuitive real-time information. Augmented reality creates information overlays onto real-world environments, whereas virtual reality is a completely virtual environment. For example, it can be used for realistic training purposes in virtual simulated environments while posing little or no risk to the learner.
- **Additive manufacturing** creates products by adding material instead of classic milling techniques, which work by removing material. Additive manufacturing could be 3D printing, which creates opportunities for creating very complex parts or rapid prototyping. It can increase production flexibility by allowing small-batch production when needed (Cohen et al., 2019).
- **Cloud-based services** enable access and utilisation of remote computing resources via the internet. This could be via data storage, additional processing power or software access.
- **Internet of Things** refers to a network of interconnected devices and systems that can communicate and exchange data over the internet. By connecting various manufacturing equipment via the internet, it can create valuable real-time insights and transparency throughout the organisation (Cohen et al., 2019).
- **Cybersecurity** will be crucial as systems become increasingly integrated and digitalised. This opens up weaknesses that can be exploited if the cybersecurity is not up to date. It focuses on protecting computer systems, networks, and data from unauthorised access, breaches, and damage. It involves measures, practices, and technologies to safeguard digital assets and ensure data privacy.
- **Autonomous and collaborative robots** enable automation with little or no human intervention. They use sensors, AI algorithms, and programming to navigate and complete assigned activities, reducing repetitive manual labour and enhancing efficiency. Collaborative robots enable close human-robot collaboration to enable flexible production. Humans and robots will work side-by-side while robots increasingly gain learning capabilities.
- **Horizontal and vertical integration** cover the integration of various digital technologies. Horizontal integration combines IT systems from different manufacturing stages and business planning levels within a company (e.g., inbound and outbound logistics, production processes, marketing, etc.) or between several companies (value networks) (Y. Liao et al., 2017). Vertical integration is the integration of IT systems at different hierarchical levels within a company (e.g., actuator and sensor level, manufacturing and execution level, production planning level, and corporate management level) (Y. Liao et al., 2017).

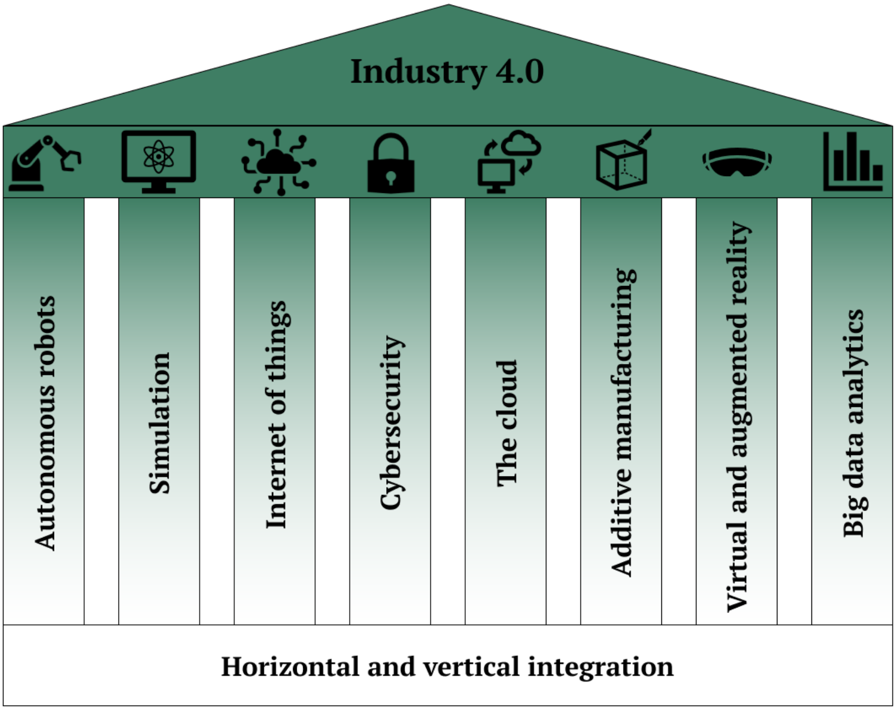

Figure 3. The nine pillars of technology enabling industry 4.0. Adapted from (Rübmann et al., 2015).

In both academia and in consultancy, there has been a tendency to use Industry 4.0 as a brand (Møller, Madsen, et al., 2023, p. 18), which both can be seen as a positive, in the sense that increased attention and funding has been allocated, and a negative, in the sense that the Industry 4.0 vision in itself is not very operational. Therefore, the viewpoint in this dissertation is more towards the *digitisation*, *digitalisation*, and *digital transformation*, and how these different stages are transforming factories and how they are organised.

2.2.1. CHANGING FACTORY STRUCTURES

The integration of these enabling technologies creates a shift from a traditional rigid and hierarchical factory structure towards a more integrated and interconnected one. The organisational structure that emerges is a much flatter structure where the internet and the horizontal and vertical integration enable a much more direct sharing of information (Cagliano et al., 2019; Flores et al., 2020; Pessot et al., 2020). See Figure 4 for an illustration of the shift from such a traditional factory structure to an interconnected one.

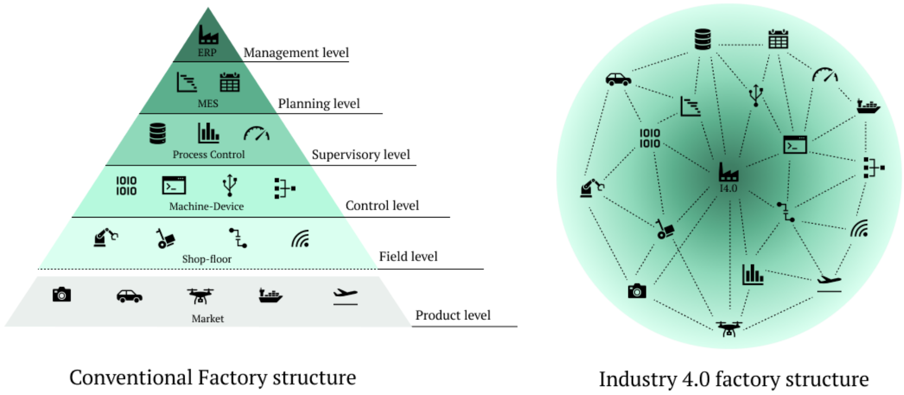

Figure 4. Changing factory structures. Adapted from (Flores et al., 2020).

Such inherent changes in the organisational structure of the factory also create a push for organising work differently to function effectively (Cimini et al., 2020). Traditional work environments change as a consequence which has led to the term *Work 4.0* og *Labour 4.0*.

2.3. CHANGING WORK ENVIRONMENTS: "WORK 4.0"

Work 4.0, *Arbeit 4.0* or *Labour 4.0* are terms encompassing the changing work environment necessary to support Industry 4.0. It covers both human resource management (Liboni et al., 2019), the need for specific digital and problem-solving competences (Hansen et al., 2023; Hecklau et al., 2016), and organisational design to better support meaningful work tasks in an increasingly digitalised work environment (Belinski et al., 2020; Cimini et al., 2020). Focusing on technology alone, and assuming that the right knowledge and competences will follow organically, does not work. There needs to be a parallel focus on both technology and competences to realise the innovative potentials inherent to Industry 4.0 (Hansen et al., 2024; Lassen & Wæhrens, 2021; Rangraz & Pareto, 2021). Lassen and Wæhrens identified three paradigms within digital transformation and Labour 4.0, which seeks to describe the landscape within manufacturing and how Industry 4.0 is approached. The paradigms resemble the steps outlined in Figure 2 when moving from *digitisation* (paradigm 1) to *digitalisation* (paradigm 2) and arriving at *digital transformation* (paradigm 3). See Table 2. It shows how one cannot merely focus on the digital technologies enabling Industry 4.0 but needs to consider both the human workers, organisational strategies and design while weighing the innovative potentials enabled by technology (Hansen et al., 2024; Lassen & Wæhrens, 2021). Currently, however, the vast majority mainly focus on cost reductions rather than extended and innovative potentials (Lassen & Wæhrens, 2021).

	Paradigm 1	*Paradigm 2*	*Paradigm 3*
Strategic driver	***Cost reduction***	***Extended potential***	***Innovation***
# of companies with this focus	Vast majority	Some	Very few
Use of I4.0 technologies	Sporadic application (e.g. single robots) intended to substitute manual processes.	I4.0 technologies are use in connected processes, and interoperability is developed.	I4.0 technologies are use in connected business processes across the value chain.
Competence needs	Primarily oriented towards process understanding & ICT skills	ICT capabilities, system design, cross-functional processes, business development and design.	New capabilities are particularly related to the integration of professional domains.
Competence strategies	- Technology investments - Supplier training - Dependency on external consultants -Staff seek out digital transformation individually - Low absorption of I4.0 competencies, low system awareness	- Part of the discussions regarding technology investments - Life long learning as strategic priority - Internalization of I4.0 competencies, high system awareness.	- Parallel with technology strategy. - Brings new profiles to the production domain (sourcing, OT/IT, design, etc.). - Staff development a strategic priority - Increasing network based I4.0 competences

Table 2. Paradigms within Labour 4.0. Table adapted from (Lassen & Wæhrens, 2021).

How to advance through the different paradigms is still debated in research communities and practice. However, past successful digitalisation implementations were typically achieved through a focused involvement of the organisation (Mütze-

Niewöhner et al., 2022), which may lead to a sense of belonging to the changing work settings (Rangraz & Pareto, 2021). Based on work design principles from the 1980's, Mütze-Niewöhner et al. (2022) outline a few guiding principles to aim for when looking towards work designs that fit with the Industry 4.0 ideology. Workplaces should not only align with technological advancements but also prioritise the wellbeing and motivation of employees. This involves ensuring that individuals work in safe, health-promoting conditions and free from harm or impairments. Work processes and systems should be effective, efficient, and sustainable. Employees must be supported by ergonomically designed technical and digital systems tailored to their tasks. Additionally, work should adhere to ethical, legal, and social standards, covering aspects like content, location, environment, compensation, autonomy, and feedback. Moreover, opportunities for skills development and personal growth through interaction and cooperation with colleagues should be a strategic priority (Kadir & Broberg, 2021; Mütze-Niewöhner et al., 2022). These principles overlap with what Flores et al. call *human capital 4.0*, in which Education and training, competences, wellbeing and innovation are the main components (Flores et al., 2020).

While fear of job losses is still present with the introduction of new digital technologies, results from successful digitalisation implementations in production environments do not reveal a reduction in the number of jobs – in fact, while the number of employees remained the same, it led to an increase in value creation per employee through more efficient processes (Lerch et al., 2017). However, ways through which to combine humans and technology in production environments to elevate both efficiency and worker wellbeing is an ongoing, complicated affair.

2.3.1. OPERATOR 4.0

Thoughts on how the digital technologies inherent to Industry 4.0 are to be used within production environments have led to a typology for an *operator 4.0* (Romero et al., 2016). See Table 3. It consists of eight operator roles, each one with a close connection to the nine pillars of technology for Industry 4.0 (Rübmann et al., 2015, Figure 3). This typology was an important step towards considering the role of the human worker within the industrial revolution, and which roles one could expect to see emerging from Industry 4.0. It inspired multiple human-centred research projects within the ACE Factory cluster (ACE Factory Cluster, 2019), which emphasised the benefits of applying a human-centred approach, e.g., through co-designing workspaces and digital solutions to be implemented in the work environment. AR/VR technologies were demonstrated to be intuitive in both online and offline training and eased on-the-job training, which is beneficial for a continuous learning environment (ACE Factory Cluster, 2019). The research projects also reported increases in both productivity and wellbeing of the workers through their human-centred focus, as long as the workers involved were part of the process and granted that great transparency was shown about how their data was being used (Kaasinen et al., 2020).

Augmented	**Virtual**	**Collaborative**	**Social**
Capable of using AR technologies to combine operator intelligence with error-proofing systems to increase efficiency in manual tasks.	Capable of exploiting virtual factories and interacting with virtual tools for training and development.	Capable of smooth interaction with and programming of cobots.	Skilled in sharing knowledge using ICT to expose tacit knowledge.
Ergonomic*	**Healthy**	**Smarter**	**Analytical**
The use of exoskeletons to increase safety and reduce fatigue. *Originally named "Super strength"	Using wearable devices concerned with well-being.	Capable of using artificial intelligence for operation and planning.	Capable of understanding and using analytic tools.

Table 3. An operator 4.0 typology adapted from (ACE Factory Cluster, 2019; Hansen et al., 2023; Romero et al., 2016). ICT: Information and communication technology

Many technologies mentioned in the operator 4.0 roles are still rather advanced for SMEs and rely on advanced technical knowledge before they are ready to be implemented and utilised by the workers, which is why the results from the ACE Factory cluster are important to better understand the challenges and benefits of applying these technologies. *Collaborative* robots, however, is a technology that is directly affecting the work environment and seem to slowly be making their way into SMEs and with good reason.

2.3.2. COLLABORATIVE ROBOTS AS A TECHNOLOGY EXAMPLE OF CHANGES TO WORK ENVIRONMENTS

The Industry 4.0 technologies mentioned in Figure 3 will change the work environment and the expected worker roles, as highlighted by the Operator 4.0 typology in Table 3. One of the work-changing and most sought-after Industry 4.0 operations technologies in SMEs is the so-called *collaborative robots*, or *cobots* in short. Reasons for their popularity include their inherent safety features, which enable close human-robot interaction outside large security cages, and in some cases, joint collaboration between worker and robot, combining the worker's cognitive abilities with the cobot's endurance and precision – This, in turn, elevates the work tasks to achieve an efficiency not capable with either worker or robot alone (Villani et al., 2018; Weiss et al., 2021). Other explanations for their popularity include the flat learning curve for simple programming tasks as cobots exploit more visual and hands-on programming techniques, allowing complete novices to program a pick-and-place operation in very little time. This allows cobots to be utilised more flexibly throughout the company for smaller batch productions, which suits many SMEs' production well. The cobots oftentimes present a tangible business case for SMEs where they eye ways to reduce costs by reducing the amount of manual labour (Lassen & Wæhrens, 2021). The term *collaborative* robot can be misleading, though, as human-robot collaboration highly depends on how the robot is utilised. Villani et al. summarise three nested levels before a cobot workspace can be considered *collaborative.* See Figure 5.

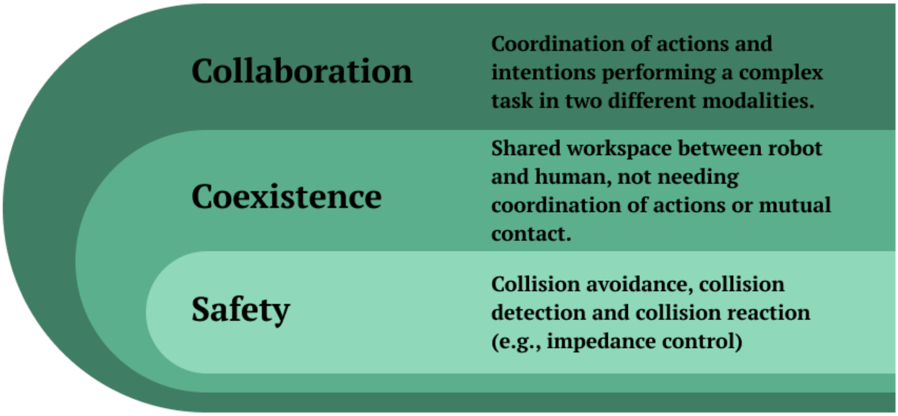

Figure 5. Nested levels of human-robot collaboration. Adapted from (De Luca & Flacco, 2012; Villani et al., 2018).

As pointed out by Weiss et al., there is still a large untapped potential in the use of cobots in industry, where more development needs to happen not only through the inclusion of disciplines within robotics but through a wide array of disciplines from design, psychology, sociology etc. (Weiss et al., 2021). Only very few cases today are actually engaged in human-robot collaboration through joint complex task coordination between the human operator and the cobot (Villani et al., 2018; Weiss et al., 2021). Additionally, it requires training and specialised skills to implement a cobot to be used in meaningful ways in production before it is possible to arrive at a *collaborative operator* or harvest an extended potential from human-robot *coexistence*. Such skills and capabilities to structure meaningful training are mostly absent from manufacturing companies today (Hansen et al., n.d.) – especially within SMEs.

2.4. SMALL AND MEDIUM-SIZED ENTERPRISES AND DIGITAL TRANSFORMATION

Industry 4.0 is more than single, isolated technologies such as cobots. As problematised in the introduction, the digital transformation of SMEs is moving slowly, and it appears that SMEs are increasingly left behind as the advanced digital technology adoption gap between SMEs and large enterprises continues to grow – despite digitalisation developments in both (Folketinget, 2021). SMEs, however, appear stuck at lower levels of digitalisation, and those engaged in digitalisation efforts most often focus merely on cost reductions (Lassen & Wæhrens, 2021). SMEs make up 99.8 % of the manufacturing industry in Europe (European Commission et al., 2022). Therefore, it is a growing issue that the available workforce is decreasing as the SMEs then will not be able to continue their operations if nothing is changed to the way production is currently conducted. Digital transformation of manufacturing companies has been shown to increase the efficiency of operations (Lerch et al., 2017; Veile et al., 2020), which may help solve some of the workforce challenges and lead to product innovation. So why have a lot of SMEs not undergone a digital transformation?

SMEs are often characterised by having short-term strategies that fail to position them well towards digital transformation (Moeuf et al., 2020). Smaller companies typically do not perceive Industry 4.0 as a larger strategic effort and view it more in light of single and isolated technology improvements in their operations (M. S. S. Larsen et al., 2022). A limited understanding of Industry 4.0 and its enabling technologies due to a lack of competences further compounds their ability to create proper business cases (Ibid.). The culture and change management capabilities also affect the governance of digitalisation efforts (Rauch et al., 2019), which amplifies the sense of high uncertainty felt by SMEs when moving towards digitalisation (M. S. S. Larsen et al., 2022).

(Ghobakhloo et al., 2022) highlight the hurdles hindering Industry 4.0 adoption, including investment and cybersecurity risks, together with the inherent complexity and cost of Industry 4.0 technologies. However, perceived benefits, absorptive capacity, digital knowledge, user-friendliness of Industry 4.0 technology, and a competitive environment can facilitate adoption. The organisational culture and structure can both positively and negatively impact the adoption depending on the configuration.

The digital implementation gap between SMEs and large enterprises is accentuated by factors outlined by (Buer et al., 2020; Horváth & Szabó, 2019). Large enterprises exhibit significantly higher digital implementation levels, while SMEs face challenges such as lower organisational IT competences, financial constraints, and external pressures to align with supplier demands. The lack of dedicated financial funds and IT departments in SMEs means that external assistance is very valuable to SMEs (Buer et al., 2020; Ghobakhloo et al., 2022). Within Europe, such external support may come in the form of large European research programmes, e.g., Digital Europe, which has allocated €9.2 billion from 2021-2027 to offer support within cyber-security, supercomputers, artificial intelligence, and elevation of digital skills and ensure widespread use of digital technologies – especially within SMEs. Despite a relatively smaller allocation for advancing digital skills compared to the more technical areas, such programmes are very important assets for SMEs to exploit. Such large programmes provide funding and external support to SMEs and research institutions throughout Europe (European Commission, 2018). These opportunities show themselves in various forms, i.e. Learning Factories (Abele et al., 2019; Sorensen et al., 2023), national research programmes (e.g., in Denmark we have Manufacturing Academy Denmark (MADE, n.d.), Innovation Factory North (IFN) (Møller, Hansen, et al., 2023b)); and international research programmes (e.g., ACE Factory Cluster, 2019, or AddSmart (Erhvervshus Nordjylland, n.d.)). AddSmart is like a hybrid constellation, as it is a Danish national offer for SMEs wanting to advance their digital transformation while being one of Digital Europe's EDIHs (European Digital Innovation Hubs) that are scattered around Europe to enable knowledge creation and knowledge sharing across borders (Erhvervshus Nordjylland, n.d.; European Commission, n.d.).

Estensoro et al. (2022) approach digital transformation similarly to Verhoef et al. (2021). Certain preconditions need to be met before SMEs are able to advance towards digital transformation. However, many of the preconditions mentioned (e.g., skills plan, skills management, strategy and leadership) are frequently found missing in SMEs. This begs the question: How are SMEs supposed to get started with their digital transformation when the preconditions are already out of reach? This could indicate that most models developed for digital transformation start at levels too advanced for

SMEs (Mittal et al., 2018), often using technologies and capabilities more relevant to large enterprises (Rauch et al., 2019), which indicates that different measures are needed before such research can help guide SMEs towards digital transformation.

Knowledge of Industry 4.0 is truly needed before management is able to perceive the benefits of digital transformation and start focused efforts. However, the issue of the slow digital transformation of SMEs is multifaceted. While we here demonstrate that we know the transformation is happening at a slow pace and have identified areas that both hinder and aid the digital transformation, less is known about how to overcome this multifaceted challenge. Many indications point to the fact that the technologies identified to enable digital transformation at large are available today. Thus, we are facing challenges deeper than merely financial hurdles for technology acquisition. Such challenges arise in the competences of the industrial workforce, where the ability to acquire new knowledge and learn about both organisational and technical dimensions becomes of utmost importance.

2.5. SUMMARISING THE GAPS IN THE LITERATURE

Research on Industry 4.0 technologies is already well-explored in literature (Pessot et al., 2020; L. D. Xu et al., 2018). Similarly, different types of competences and operator typologies beneficial to digital transformation have been identified (Hecklau et al., 2016; Romero et al., 2016). The effects on the organisational structures have also been investigated, indicating how changing work environments and flatter hierarchical structures emerge in the wake of digitalisation (Cimini et al., 2020; Flores et al., 2020). However, the connection between the technologies, the human competences, and the organisational aspect remains unclear. How to align these aspects favourably towards digital transformation remains especially underexplored. Drawing an analogy to the term *fog of war* experienced in military conflicts between nations, one could say there appears to exist a *fog of digitalisation,* where each party in the 'conflict' (i.e., Human, Technology, and Organisation) hold important information that is not being shared between one another to create a digital synergy. Thus, it is in the intersection between *humans, organisation*, and *technology*, where the largest gaps still appear – especially when it comes to SMEs that are often characterised by limited resources yet with flat organisational structures and a high level of cooperation shown to benefit the thinking behind Industry 4.0 (Horváth & Szabó, 2019). Figure 6 summarises different facets contributing to digital transformation as seen through a *sociotechnical* lens. Especially the intersections between *human, technology,* and *organisation* are areas where focused effort is still needed in order to better understand the digital transformation of manufacturing companies. The research gaps illuminated through the literature within these intersections lead to the research objectives of this dissertation, explained in the following chapter.

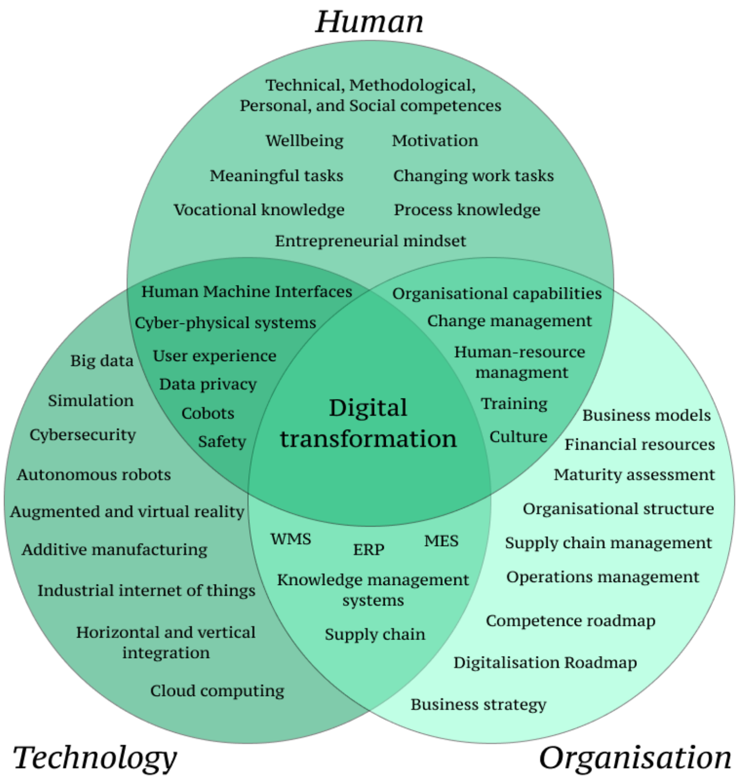

Figure 6. Elements within Industry 4.0 when viewed as a sociotechnical system.

CHAPTER 3. RESEARCH OBJECTIVE

Industry 4.0 has been dominated by a heavy focus on technology. However, we have failed to see a surge in industry 4.0 solutions within manufacturing, especially within SMEs. When viewed from a sociotechnical systems perspective, gaps appear in our knowledge surrounding the digital transformation of SMEs in the intersection between *human, technology,* and *organisation*. The main objective of this dissertation is to generate knowledge that may help explain the patterns of slow digital transformation that we are seeing, which may serve to guide managers in the industry and inspire future research on digital transformation from a human-centred perspective.

The research presented in this dissertation follows three main research questions:

Research Question 1: *What competences are pertinent to Industry 4.0, and how do they interact with the process of digital transformation?*

Research Question 2: *What organisational prerequisites create conducive conditions for competence development towards digital transformation?*

Research Question 3: *How can adopting a human-centred perspective promote learning and understanding of digital transformation?*

Chapter 4 is concerned the overall research context and methodology applied throughout the research project. Chapter 5 tackles RQ1 and presents competences identified for Industry 4.0. Chapter 6 investigates RQ2 and summarises the results from Paper B and Paper C. Chapter 7 dives into RQ3 and presents the results from Paper D and Paper E. Chapter 1 brings the concluding remarks based on the results obtained in this dissertation.

CHAPTER 4. RESEARCH CONTEXT AND METHODOLOGY

The majority of the Danish manufacturing industry consists of small and medium-sized enterprises (SMEs). They are a vital part of our society and affect larger supply chains, whether they produce end-products or act as sub-suppliers. The slow digitalisation of SMEs observed until now can prove unsustainable if nothing is changed. Therefore, it is beneficial to better understand how a digital transformation may be achieved while considering the environment and conditions in which SMEs operate. Such insight and understanding cannot be achieved without close cooperation with representative manufacturing SMEs. The following sections explain the unique research environment that formed the core empirical basis for the dissertation. A research environment that secured access to a representative sample of manufacturing companies from a wide range of industries over the course of three years.

4.1. RESEARCH CONTEXT: INNOVATION FACTORY NORTH

The PhD project has been part of a larger research project funded by the European Regional Development Fund called *Innovation Factory North* (Møller, Hansen, et al., 2023b). The research project deals with digitalisation in small and medium-sized enterprises (SMEs) within manufacturing. It spanned three years, and during that time, 88 companies were engaged in its research activities, bulked in groups between 3-6 companies in each iteration. 11 of these were technology suppliers who either used it as an opportunity to understand their customers better or actively helped facilitate and develop prototypes. It was structured to generate awareness of Industry 4.0 and digitalisation through close collaboration, e.g., workshops and on-site visits. There were three main phases of the research project: *Awareness, Demonstrator,* and *Anchoring.* The companies who agreed to participate in the research project accepted one phase at a time and attended with the agreement that no payment was required. In return, they agreed to spend a specified number of working hours on the project. The following sections will briefly summarise the structure of the research project.

4.1.1. AWARENESS PHASE

The first phase was the *awareness phase*, which served to create a common language and understanding of what "Industry 4.0" means and the potential value creation of digital solutions in the context of each company's operations. This phase is where the majority of the empirical data in this thesis derives from and, therefore, will receive more elaboration compared to the two subsequent phases.

The learning factory activities consisted of two physical workshops at the university and two site visits at the company (see Figure 7). Representatives from 4-6 companies were present in each workshop, where debate was encouraged between companies. The site visits were conducted with two academic sparring partners with each company. Additionally, an online session, both before the first workshop and after the final site visits, was conducted to properly introduce and prepare the companies and to wrap up on overall observations and impressions. Over a period of three years, especially 30 SMEs provided the data used in Paper B, which is appended in this thesis.

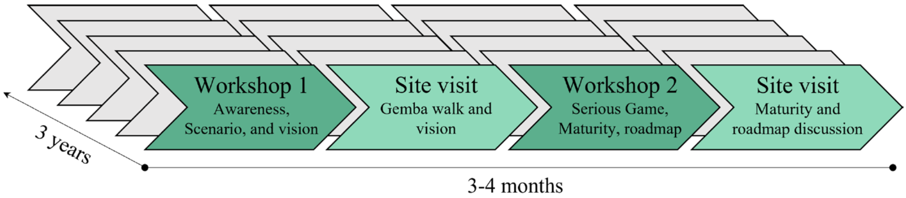

Figure 7. Elements in the awareness phase

Workshop 1 was a physical workshop introducing smart technology (e.g., the nine technological pillars in Figure 3), general industry 4.0 concepts, and their impact on manufacturing industries. All participating SMEs received a compendium of industry 4.0 literature prior to the workshop. The workshop was held in a university smart lab, which contained the majority of the technology listed in Figure 3. The purpose was to initiate relevant discussions with a shared vocabulary and understanding centred around the companies' situation. Academic experts showcased industry 4.0 equipment and facilitated a scenario thinking workshop of possible futures if the companies were to adopt and use smart technology in their business, inspired by (Rowland & Spaniol, 2017). The scenario thinking led to a preliminary definition of scope to prompt the companies to think about their vision for smart technology in their company.

Two academic sparring partners visited the SME and arranged a Gemba-inspired walkthrough of their production facilities. The goal was to encourage the SME to reflect on their digital improvement areas in light of Industry 4.0 and their specific production processes. The information gathered was used to triangulate information from the previous workshop. A semi-structured vision refinement conversation with an assigned note-taker followed the walk.

The second workshop saw the SME representatives participate in a serious game centred around Industry 4.0 and utilising a FESTO cyber-physical didactic system (Festo Corporation, n.d.; Mortensen et al., 2019). The hands-on game prepared the SME representatives for a maturity discussion centred around the 360 Degree Maturity Assessment (360DMA) and its maturity dimensions: *Competences, Governance, Technology, Connectivity*, and *Value Creation* (Colli et al., 2019).

The final site visit served to round off the digital maturity discussion and reflect on potential value creation for the companies moving forward.

4.1.2. DEMONSTRATOR PHASE

The *demonstrator phase* acted as a way for companies to gain easier access to a value-creating technology, which they identified through the more conceptually grounded first awareness phase. The demonstrator phase thus aimed to showcase the technology in a controlled lab environment as prototypes to avoid interfering in their daily operations and later to help the companies demonstrate the technology in their own organisation (Møller, Hansen, et al., 2023b). A learning-by-doing approach was employed in the lab while still maintaining an environment realistic enough to resemble real-world environments, which has been shown to be an important aspect of learning (Collins & Kapur, 2014; Leonard-Barton, 1992).

4.1.3. ANCHORING PHASE

The *anchoring phase* acted as a way for the companies to advance their understanding of their internal processes and the importance of change management initiatives when trying to "anchor" the identified value-creating technology in their organisation. Additionally, a form of competence mapping occurred to ensure that the company had the necessary competences to implement the technology in question. An implementation plan was developed together with the companies with continuous follow-up throughout the phase (Møller, Hansen, et al., 2023b).

4.1.4. OVERVIEW OF COMPANY ENGAGEMENTS IN INNOVATION FACTORY NORTH

The workshops, discussions and company visits conducted in each of the Innovation Factory North phases were all documented in a shared repository by the researchers and student assistants employed in the project. This surmounted to +2800 hours of company engagement across the IFN phases when seen from the individual companies' perspective. Out of these hours, an estimated 602 hours of company engagement have been directly used as the foundation for Paper B, Paper C, and Paper D appended in this thesis, and include physical workshops, interviews, and on-site company visits. The remaining material helped form a general understanding of the challenges that digitalisation presents to small and medium-sized companies – especially when it comes to competence considerations and approaches to relevant knowledge creation. See Table 4 for an overview. In addition, a meeting was held every Friday between 4-6 PhD researchers and 1-4 senior researchers to discuss learnings from the company engagements.

#	Size (S, M, L)	Awareness	Demonstrator	Anchoring	Paper A	Paper B	Paper C	Paper D	Paper E	General	Hours
1	S	X	X	X		X	X				84
2	S							X			12
3	M							X			12
4	L	X								X	12
5	S	X	X			X					54
6	M	X				X					24
7	M	X				X					24
8	M	X				X					24
9	M	X	X			X					47
10	M	X	X			X					61
11	M	X				X					24
12	M	X	X			X					24
13	M	X	X	X		X	X				65
14	M	X				X					24
15	M	X				X					24
16	M	X	X			X					47
17	M	X				X					24
18	S	X	X**			X					24
19	M	X				X					24
20	S	X	X	X		X					72
21	S	X	X			X					47
22	S	X				X					24
23	M	X				X					24
24	M	X				X					24
25	M	X				X					24
26	M	X				X					24
27	S	X				X					24
28	S	X				X					24
29	S	X				X					24
30	M	X				X					24
31	S	X	X			X					47
32	M	X				X					24
33	M	X	X			X					46

34	M	X	X**			X					47
35	S*		X								18
36	M	X								X	24
37	S	X									24
38	S*		X							X	23
39	S	X	X							X	70
40	M	X								X	24
41	S*	X									24
42	S	X								X	24
43	S*	X	X							X	49
44	S	X								X	24
45	M	X								X	24
46	S	X								X	24
47	S	X	X							X	47
48	M	X	X								47
49	S*	X								X	24
50	M	X	X							X	59
51	S	X								X	24
52	M	X	X							X	47
53	S	X		X						X	46
54	M	X								X	24
55	S	X								X	30
56	M	X								X	24
57	S	X								X	24
58	S	X								X	30
59	S*		X**							X	23
60	S	X								X	30
61	S	X								X	24
62	L	X								X	24
63	S	X								X	24
64	M	X	X							X	47
66	M	X	X**							X	47
66	M	X								X	24
67	L	X								X	24
68	M	X								X	24
69	L	X								X	24
70	S	X									24

71	S*	X**	X**							X	65
72	S	X									24
73	S*	X									24
74	M	X								X	24
75	M	X								X	24
76	S	X									24
77	M	X								X	24
78	M	X								X	24
79	S*		X							X	23
80	L	X									24
81	M	X	X**							X	65
82	M	X								X	30
83	M	X								X	24
84	S	X								X	24
85	S*		X								23
86	S	X								X	24
87	S	X								X	24
88	S	X								X	24
89	M	X								X	24
90	S*	X**	X**							X	65
Total		-	-	-	-	-	-	-	-	-	**2857**

*Table 4. Overview of companies and their size, engagement in IFN, contribution to papers and estimated total engagement hours (including workshops, company visits, and interviews). *Technology Provider; **Participation in more than one phase.*

4.2. APPLYING A SOCIOTECHNICAL PERSPECTIVE

> *"Now that the salient environment is becoming that of a turbulent field, a greater emphasis on collaboration is mandatory, and relevant changes need to be fostered in large-scale social systems as well as within organizations. The oncoming information technologies […] give immense scope for solving many current problems – if the right value choices can be made"* – (Trist, 1980, p. 59)

Such wrote Eric Trist in his paper from 1980 in which he presented an overview of *sociotechnical systems* (STS). The importance of his message has certainly not faded as the years have passed, organisations have grown, and digital information technology is now more available and widespread than ever.

Industry 4.0 is not only a matter of digital technologies to be slapped into a production. It is complex and, at times, very abstract and includes a multitude of influencing factors. To gain an overview of the intricacies connected to achieving the vision of Industry 4.0, a *sociotechnical perspective* was adopted to guide the research throughout the thesis. The concept of sociotechnical systems (STS) was first introduced by Trist and Bamforth in 1951 (Trist & Bamforth, 1951) in response to the observations made in coal mines and how the work was organised. Throughout the years, STS has focused on work design, the design of entire organisations, and a broader macrosocial perspective (Trist, 1980). Even in 1980, long before the term “Industry 4.0" was coined, Trist noticed the vast potential for organisational change that the "microprocessor" could bring to how work is organised. This observation has stuck around more than 40 years later, as seen in the works by (Govers & Van Amelsvoort, 2023; Liboni et al., 2019; Oks et al., 2017; Veile et al., 2020). In a recent essay, Van Amelsvoort argues how the core elements of STS are needed to re-arrange organisational designs in line with digital technologies to exploit new ways of working (Govers & Van Amelsvoort, 2023). Such changes in organisational design have oftentimes been highlighted as a necessity for a successful implementation of Industry 4.0 (Cimini et al., 2020). The contemplation around needed changes in organisational designs was also around in the early days of sociotechnical system theory development. Back then, Trist talked about a traditional "old paradigm" and the "new paradigm" (Trist, 1980). These characteristics are summarised Table 5. This thinking has carried on in the way the Industry 4.0 research field views the need for changes in organisational design (Cagliano et al., 2019; Liboni et al., 2019; Pessot et al., 2020).

Old paradigm	**New Paradigm**
The technological imperative	Joint optimisation
Man as an extension of the machine	Man as complementary to the machine
Man as an expendable spare part	Man as a resource to be developed
Maximum task breakdown, simple narrow skills	Optimum task grouping, multiple broad skills
External controls (supervisors, specialist staff, procedures)	Internal controls (self-regulating subsystems)
Tall organisation chart, autocratic style	Flat organisation chart, participative style
Competition, gamesmanship	Collaboration, collegiality
Organisation’s purposes only	Members’ and society’s purposes also
Alienation	Commitment
Low risk-taking	Innovation

Table 5. Organisational paradigms in STS according to (Trist, 1980, p. 42)

Trist specifies three different system levels in which to view sociotechnical systems akin to different units of analysis layers. There is the primary work system, whole organisation systems and macrosocial systems. The macrosocial systems are the farthest-reaching and encompass societal and environmental factors. Whole organisation systems deal with organisations as a whole, e.g. company culture. The primary work systems are focused on specific work tasks and processes (see Figure 8). The research conducted in this PhD was formed from a general understanding of the macrosocial systems through literature but mainly with empirical data collection from both primary work systems and whole organisation systems.

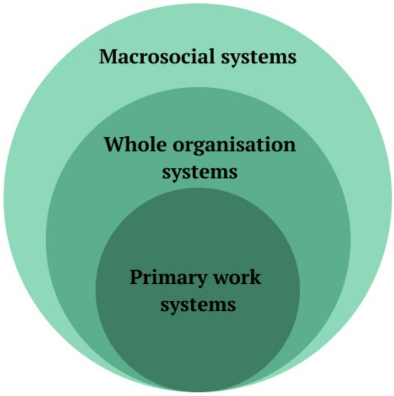

Figure 8. Different system layers within sociotechnical systems theory

4.2.1. MACROSOCIAL SYSTEMS

Macrosocial systems refer to the larger societal and environmental contexts in which organisations operate e.g., governmental policy or programs. These systems encompass the external factors such as economic, political, cultural, and technological influences that impact organisations (Trist, 1980, pp. 50–59). Understanding macrosocial systems helps organisations adapt to changes in the external environment and align their strategies and operations accordingly. A system perspective on the macrosocial level is found in the paper not appended to this dissertation (Stingl et al., 2023) that focuses on the effects that robotisation of production environments has on work. Paper A employ a macrosocial perspective to present which competences are necessary for digital transformation and presents a perspective on the future direction of Industry 4.0 as a whole. One could also argue that research projects such as Innovation Factory North are part of a macrosocial system, as they exist because of the current environment within the EU, which provided the funding to drive such projects.

4.2.2. WHOLE ORGANISATION SYSTEMS

Whole organisation systems encompass the overall structure, culture, strategies, processes, and interactions that define an organisation. This perspective examines the organisation as a complete entity, considering how all parts and subsystems (e.g., departments and teams) interact and influence each other (Trist, 1980, pp. 38–49). Whole organisation systems analysis helps design and manage the organisation to achieve its goals effectively and efficiently. For case study research on digital transformation, a whole organisation systems view is beneficial as it provides important nuances that are critical to the decision-making around digitalisation, which may be missed if one only focuses on individuals and their specific tasks. Paper B, Paper C and Paper D all employ a whole organisation systems view. They also indirectly highlight the challenges that SMEs have in gaining such a holistic view and understanding of their organisation in light of digital transformation.

4.2.3. PRIMARY WORK SYSTEMS

Primary work systems are the fundamental units within an organisation where employees perform their daily tasks and activities. These systems are considered subsystems within whole organisation systems and consist of individuals, their tasks, tools, and the environment in which they work. They may comprise a single line with one worker or entire groups or clusters of groups (Trist, 1980, p. 11). Understanding and optimising primary work systems play an essential role in improving productivity, efficiency, and employee wellbeing within an organisation. Paper E focuses on primary work systems in the sense that it introduces an Industry 4.0 technology (cobots) to individuals. Paper D draws empirically on primary work systems through the observations and interviews conducted therein, while it concludes using a whole organisation systems view.

4.2.4. SOCIOTECHNICAL SYSTEMS AND INDUSTRY 4.0

Originally in Trist and Bamforth's seminal work on sociotechnical systems, STS were all about balancing technology and social relations (Trist & Bamforth, 1951). This balancing was later referred to as a core joint optimisation approach to organisational design (Trist, 1980). Such a constellation was observed to create more efficient organisations, leading to increased Quality of Work Life (QWL) (Fox, 1995; Govers & Van Amelsvoort, 2023; Trist, 1980). The organisation was seen as the output of this joint optimisation focus on sociotechnical factors. Later on, the perspective on STS evolved to include the organisation within the joint optimisation relationship, which exists to create an STS resting on three pillars: *Human, technology* and *organisation.* The organisation itself is needed to interact with the sociotechnical areas and not only emerges from changes to human factors and technological factors. As such, a modern sociotechnical perspective involves a plethora of human factors, organisational factors, and digital technologies (see Figure 6 and Figure 9). This simplified typology and representation of Industry 4.0 have been used in works applying a sociotechnical viewpoint e.g., by Veile et al., Oks et al., Liboni et al. among others (Liboni et al., 2019; Oks et al., 2017; Veile et al., 2020). It provides a fitting stage on which to unpack the concept of industry 4.0 in this thesis – mainly from a primary work and whole organisation systems perspective.

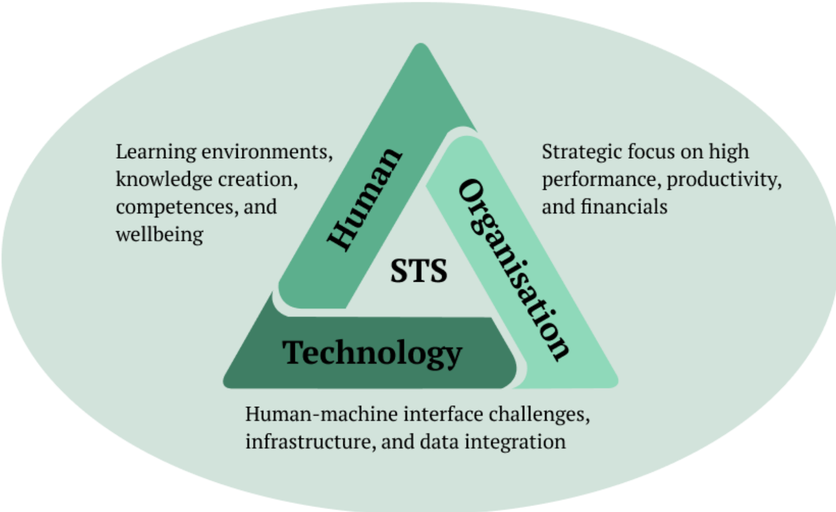

Figure 9. Simplified sociotechnical systems view of industry 4.0. Adapted from (Liboni et al., 2019)

4.3. RESEARCH APPROACH

The ontological and epistemological stance applied in this thesis borrows from both interpretivist and positivist schools of thought – which leads to both a constructivist and pragmatist research paradigm. This is undoubtedly an outcome of the duality in my academic education that mixed classical engineering approaches with interpretive approaches used within psychology and even experimental psychology. A mixed methods approach to the research was then a logical outcome. As such, the research paradigm becomes that of a constructivist and pragmatist in the sense that knowledge needs to be interpreted while choosing the best method or tool to do so. By employing a mixed methods approach, it is possible to highlight the research problems from different angles by using different multimodal levels of enquiry and better deal with the richness and noise of the real world (Mingers & Brocklesby, 1997).

Another important aspect of choosing a fitting research approach is to consider the maturity of the research topic (Karlsson, 2016, pp. 68–75). While Industry 4.0 as a term and vision was introduced as a strategic initiative back in 2011 (Kagermann et al., 2013), the understanding of how to approach such a radical change in the way production companies approach their manufacturing operations was still underdeveloped at the start of the research project in 2020 – especially for SMEs (Matt & Rauch, 2020). Many papers had already been published on the technologies that would help enable the fourth industrial revolution, yet it seemed as though multiple pieces were still missing. It appeared as if the research community did not quite understand the current environment of the manufacturing companies that they tried to steer towards Industry 4.0 and total digital transformation. The research field of Industry 4.0 concerned with sociotechnical factors was nascent. Thus, adhering mainly to an exploratory approach using case study research was deemed fitting. See Figure 10. Add to that, the fortunate position as a researcher of having access to nearly 90 manufacturing SMEs through the Innovation Factory North research project. It provided an opportune moment and environment in which to conduct case study research.

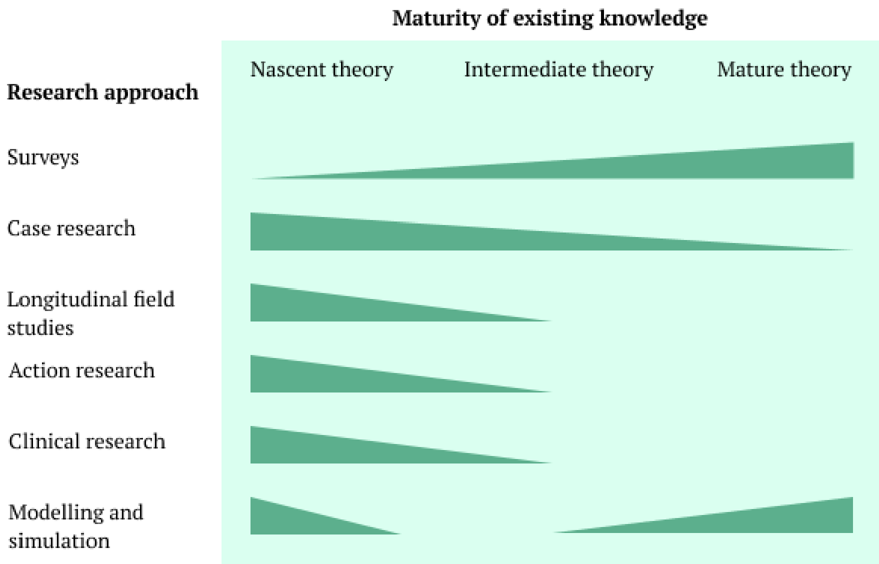

Figure 10. Overview of research approaches in relation to maturity of existing knowledge. Adapted from (Karlsson, 2016, p. 70).

4.3.1. CASE STUDY RESEARCH AND EXPERIMENTAL DESIGN

Matching the research methodology to the research purpose is important in order to achieve reliable and trustworthy results. See Table 6 for rough guidelines for how one may approach research depending on the research purpose. While case studies have proven excellent for conducting explorative, inductive research using a grounded theory approach, case studies may also be used for both deductive research (theory testing) and abductive studies (theory refinement) (Dubois & Gadde, 2002), as outlined in Table 6. Research on Industry 4.0 within operations management has been ongoing since 2011, and scientific journals continue to publish new research on the topic at an increasing rate (Ferrigno et al., 2023). Additionally, operations management research from prior to Industry 4.0 is rich with research focused on similar core issues, namely how to achieve a joint optimisation between humans and technology within manufacturing (e.g., (Appelbaum, 1997; Orlikowski, 1992)). This means that the research field has largely surpassed the need for purely explorative studies, and few seminal theory-building works emerge. As such, the research conducted in this thesis leans more towards theory refinement: Paper E employs an experimental research design and Paper B, Paper C, and Paper D employ a case study methodology.

Research purpose	Focus of the research question	Research structure
Exploration Investigate underexplored areas for further research and theory development.	Is there something interesting enough to justify additional research? What is going on?	*Inductive research* In depth case-studies Longitudinal field study
Theory building Identify or describe key constructs. Identify connections between variables. Identify why these relationships exist.	What are the key constructs? What are the patterns and connections between variables? Why do these relationships exist?	*Inductive research* Few focused case studies In-depth field studies Multiple case studies Exemplary case studies
Theory testing Test existing theories within the research topic. Outcome prediction.	Are existing theories robust against empirical evidence? Was the outcome as expected or were unexpected behaviours observed?	*Deductive research* Controlled experiments Quasi-experiments Multiple case studies Large sample population
Theory refinement Structure better theories	Are observations incongruent with existing theory? How generalisable is the	*Abductive research* Controlled experiments Quasi-experiments

as a consequence of the observed results.	theory? Which contexts does the theory apply? Refinement of constructs, existing structures, and how they are related.	Case studies Large sample population

Table 6. Match between research purpose and methodology. Adapted from (Handfield & Melnyk, 1998; Karlsson, 2016, p. 170)

4.4. TRUSTWORTHINESS AND QUALITY OF RESEARCH DATA

The trustworthiness of research results is inherent to the integrity of scientific research. Researchers should always strive to reduce method- and sampling bias when creating and conducting their research designs. Naturally, bias exists in every decision one makes. However, through scientific rigour in how the research is approached, such biases can be reduced. The choices made by the researcher should be as transparent as possible, which enables (and encourages) reproduction of the results. Within quantitative studies, there are various statistical significance tests and data balancing one can apply to reduce bias and methodically describe what steps have been taken to arrive at the patterns and results presented. Despite often being sold as objective, even such quantitative methods contain biases, e.g., the 0.05 *p*-value threshold (i.e., how often one can expect a result as extreme or more) was once arbitrarily chosen as an instrument to convince readers that what is presented is in fact statistically significant (Dahiru, 2008). The risk here is that one may put an overreliance on the *p*-value to accept a given hypothesis, which may turn out to be misleading or lead to unethical research practices (Head et al., 2015; Karpen, 2017).

In qualitative research, one does not have the luxury of statistical significance tests to determine whether to accept or reject one's hypothesis. However, that certainly does not mean that qualitative research cannot be rigorous. Here, the tests and methods used to reduce bias and increase transparency of the research approach are merely different.

In case research, such "tests" can, for example, be in the four parameters: *construct validity, internal validity, external validity,* and *reliability*.

- **Construct validity:** Refers to the extent to which a measurement or test accurately assesses the theoretical concept or construct that it is intended to measure. In other words, construct validity is about how well a test or measurement tool represents the underlying construct it is designed to capture (Yin, 2018, pp. 42–44).

- **Internal validity:** Refers to the degree to which an experiment or research study accurately determines the cause-and-effect relationship between variables (i.e., how and why *x* led to *y*). In other words, it assesses whether the changes observed in the dependent variable can be explained by the independent variable being studied, and not due to other factors or confounding variables. Hence, it is often not applicable in descriptive or exploratory studies as they often do not seek to investigate cause-and-effect relationships (Yin, 2018, pp. 42–45).
- **External validity:** The extent to which the results of a study can be generalised beyond the specific conditions and participants of the study to a broader population or real-world situations. It assesses whether the findings are applicable to other settings, times, or groups (Yin, 2018, pp. 42–46).
- **Reliability:** Refers to the consistency and stability of a measurement or test. It assesses whether a measurement tool (e.g., the data collection procedures) produces consistent and reproducible results when administered repeatedly under similar conditions (Yin, 2018, pp. 42–46).

Additionally, *triangulation* has been used as a method to increase the trustworthiness of the research by relying on *multiple researchers* throughout IFN with close weekly knowledge-sharing; *multiple data* in the form of literature, observations, transcriptions, and performance metrics; *multiple methods* through (mainly) qualitative and quantitative methods; *multiple theories* through the applied sociotechnical lens. See Figure 11 for a depiction of the triangulation matrix.

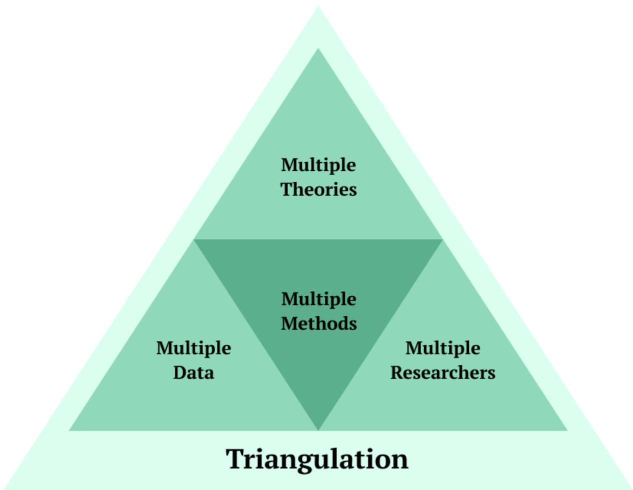

Figure 11. The triangulation matrix adapted from (Hanson-DeFusco, 2023).

The bulk of the empirical data used in this thesis came from the Innovation Factory North research project, which naturally brings some limitations and strengths. See Table 7 for an overview of how the test parameters of *construct validity, internal validity, external validity,* and *reliability* were approached in this dissertation.

Test	Tactic used	Limitations
Construct validity	• Use of multiple sources of evidence • Use of established models and terminology within industry 4.0 to guide the research consistently between cases • Detailed data documentation (“*chain of evidence”)* for every data extracted	• Most data are generated from in-situ, noisy interactions with companies in Innovation Factory North • Some information in the chain of evidence may be lost / obscured due to multiple people registering the data
Internal validity	• Alignment with colleagues participating in Innovation Factory North about observations and results in Friday and standup meetings • Dialogue and discussion with company representatives participating in Innovation Factory North about the results • Pattern matching existing understandings to observed patterns	• Interaction in research environment may increase the risk of inferring biased results
External validity	• Multiple cases were used • Multifaceted cases and respondents, i.e., industries, ownership, level of experience with digital technologies, shop-floor to CEO level	• Innovation Factory North ecosystem may be hard to replicate • Only Danish case companies, which may carry unique cultural and societal components not generalisable
Reliability	• Systematic field notes based on protocols • Formal interview guides • Recordings of interviews and transcriptions (ad verbum data) • Structured data analysis, e.g., using NVivo or Excel software • Following a research protocol	• The engagements with the companies involved a diverse set of representatives and access to a smart lab, which hardly can be replicated 1:1.

Table 7. Construct validity, Internal validity, external validity, and reliability in the context of the conducted research.

4.5. APPLIED RESEARCH METHODS

In the end, five main contributions have been appended to this dissertation. Combined, they help elaborate on the three main research questions presented in Chapter 3. While Paper A mostly deals with RQ1, Paper B and C mostly with RQ2, and Paper D and E mostly with RQ3 – they all tie together the overall topic of human-centred production focusing on learning and competences. They alone would not provide the needed nuance to address such a fairly complex topic that is industry 4.0. While the majority of the methods used rely on qualitative methods, Paper E employed a mixed methods approach and relied on both quantitative and qualitative methods to compare the user performance in two cobot conditions. The following table provides an overview of the five papers, their research question, which methods were applied, and which data sources were relied upon. See Table 8.

The following chapters will present the findings from the appended papers. Each chapter will end with a discussion of the results and how they tie into the main research questions and form a contribution.

Research Question	Research Activity	Research method	Data sources
RQ1: *What competences are pertinent to Industry 4.0, and how do they intersect with the process of digital transformation?*	**Paper A:** Identification of competences in a new typology tied to the digitalisation process	Literature review	Scientific literature databases, academic and grey literature
RQ2: *What organisational prerequisites create conducive conditions for competence development towards digital transformation?*	**Paper B:** Theory elaboration on SMEs approach to digitalisation and propositions as to how their lack of content knowledge and metacognitive knowledge hinders them.	Multiple case study	Interviews, observation, documentation, workshops
	Paper C: Outline of management practices shown to increase absorptive capacity.	Multiple case study, literature review	Observations, semi-structured interviews, scientific literature databases
RQ3: *How can adopting a human-centred perspective promote learning and understanding of digital transformation?*	**Paper D:** Theory development on the effect knowledge and competences have on strategic digitalisation focus.	Multiple case study	Observations, semi-structured interviews
	Paper E: Introducing novice operators to collaborative robot programming. Finding and showcasing a suitable didactic learning approach.	Conventional experimental design	Observations, time on task, cartesian datapoints, semi-structured interviews

Table 8. Research overview and applied methodology

CHAPTER 5. COMPETENCES FOR INDUSTRY 4.0 AND HUMAN FACTORS

The following chapter summarises the results from Paper A ("Competence Considerations for Industry 4.0 and Future Trends", Hansen, Lassen, et al., 2023) and aims to answer RQ1:What competences are pertinent to Industry 4.0, and how do they interact with the process of digital transformation? The chapter is based on a literature review on identified competences for Industry 4.0 and leads to a reflection of how these competences tie into the process of digital transformation.

Given the sociotechnical lens with which the research has been conducted, it is crucial to understand what capabilities and competences have been shown to affect Industry 4.0 in manufacturing firms positively. If one understands these, it will become more manageable to tie both technological and organisational aspects together with human capital so as to not inadvertently counteract progress.

What exactly is understood to be a competence is not firmly agreed upon. As an example, in nursing, the terms competence and competency are differentiated so that competence refers to knowledge of how to handle specific tasks, and competency refers to a demonstration of skills for a specific task (Moghabghab et al., 2018), whereas in many areas those two are used interchangeably (Abele et al., 2019, pp. 27–28). In this work, competences are understood using Merriam-Webster and Rangraz and Pareto's understanding to form the definition:

> *The quality or state of having sufficient knowledge, attitude, skill (or strength) for a particular duty or in a particular respect.* (Merriam-Webster, n.d.; Rangraz & Pareto, 2021).

Taking a step further back, then the capability to obtain such knowledge, skills and attitude, which help create competences can also be described as a *meta-competence* (Le Deist & Winterton, 2005). In the following chapter, identified competences for Industry 4.0 will be presented along with a novel typology for competences and reflections on the role that competences will lead in the near future. This chapter summarises the contribution of Paper A (Hansen et al., 2023).

5.1. COMPETENCES FOR INDUSTRY 4.0

“Competence and skills can be viewed in the same way as methodology and methods: A methodology is an approach often comprised of many different methods to achieve a desired outcome. Similarly, competence is the ability to efficiently solve specific problems by relying on a plethora of knowledge, skills, and attitudes.” (Hansen, Lassen, et al., 2023, p. 381)

Many attempts to create an overview of competences have been made in literature so far. Most rely on literature reviews (Belinski et al., 2020; Hecklau et al., 2016; Jerman et al., 2018; Kipper et al., 2021) or surveys of managers in manufacturing companies (Moldovan, 2019; Motyl et al., 2017). As competences are abstract in nature, it can be difficult to strike a balance between creating an overview of the right set of competences without arriving at a set of broad overarching descriptions, e.g., "programming skills", which could entail a plethora of different programming languages. However, just as there is no one-size-fits-all for Industry 4.0, there is no finite set of competences, which fit every situation. A certain level of abstraction is therefore needed, thus making it rather categorical in nature to describe competences.

Multiple attempts have been made to describe competences in different levels of abstraction. For example, Heyse and Erpenbeck divided competences into four categories: Personal competence, activity & action competence, Social-communicative competence, and technical & methodological competence (Heyse & Erpenbeck, 2009, p. xiii). These main categories were used to create a competence atlas or matrix (see also Abele et al., 2019, p. 29). However, the categories and their content were not created specifically or targeted for Industry 4.0 like more recent work. For example, Erol et al., 2016 investigated competences specifically for Industry 4.0 and divided competences into personal, social, action, and domain-related competencies, whereas Hecklau's categorisation is structured in *Technical*, *methodological, social,* and *personal* competences (Hecklau et al., 2016). This is seemingly the categorisation most used in literature (e.g., used by (Alhloul & Kiss, 2022; Hernandez-de-Menendez et al., 2020; Jerman et al., 2018).

- *Technical competences* cover most of what has been referred to as hard skills or hard workforce (Flores et al., 2020). This means competences for hardware and software such as programming and setting up automation solutions involving physical handling robots, digital software robots (e.g. robot processing automation (RPA)), information and communication technology (ICT), cyber-security, wireless networks and data analytics.
- *Methodological competences* cover how workers approach their everyday work tasks. This includes strong problem-solving capabilities, creativity, and analytical thinking towards an entrepreneurial-like mindset that enables

decision-making. Such a worker profile would also be more inclined to experiment with new ideas in their work environment.

- *Social competences* cover communicative competences such as language proficiency, intercultural understanding and strong social capabilities crucial to effective teamwork and networking with relevant knowledge partners. Knowledge management is increasingly important in line with the growing network of collaborative partners enabled by the connectivity inherent in Industry 4.0 solutions. This means that the ability to transfer knowledge is crucial. This social category's composition also emphasises the relevance of communicative leadership abilities.
- *Personal competences* cover more introspective traits, such as a person's attitude and mindset in a work environment. A flexible and highly dynamic work environment such as Industry 4.0 requires a flexible mindset and a certain openness to new initiatives (e.g., not only related to operations but also sustainability). As new digital technologies are introduced, an inherent motivation to learn is needed along with a certain degree of compliance (e.g., following procedures required by necessary data standards).

5.1.1. COMPETENCES CATEGORISED FOR MANAGEMENT, BACKEND, AND FRONTEND

While multiple existing typologies exist, such typologies still revolve around abstract competence categories removed from operational considerations of how to engage them in operational stages towards digital transformation. Common words and concepts have made their way into our digital interfaces, where their functionality resembles real-world objects to increase user acceptance and understanding of their functionalities (e.g., "library", "folder", "desktop"). Likewise, it may be preferable to borrow already established terminology from software development and connect them to an ideal digitalisation process to increase the understanding of the importance of competences and how they can support digitalisation. As such, competences could be categorised in a *management*, *backend,* and *frontend* typology (see Table 9).

Management	Backend	Frontend
Knowledge acquisition and perceived benefits	ICT infrastructure	Communication skills
Change management	Wireless networks	Motivation to learn
Strategic vision of technology	Coding skills	Creativity
Strategic vision of competences	Cyber security	Adaptability and flexibility
Design thinking	Automation	Interdisciplinarity
Problem-solving	Knowledge management	Ability to transfer knowledge to others
Project leadership	Process understanding	Knowledge of user-friendly interfaces
Disruptive leadership	Machine learning	Understanding of IT security
Lean management	Data analysis	Understanding of data quality
Worker participation		

Table 9. A far from exhaustive list of competences (knowledge, skills and attitudes), which have been identified for industry 4.0 based on (Erol et al., 2016; Hecklau et al., 2016; Jerman, Bach and Bertoncelj, 2018; Abele, Metternich and Tisch, 2019; Liboni et al., 2019; Belinski et al., 2020; Flores, Xu and Lu, 2020; Ghobakhloo, 2020; Kipper et al., 2021; Shet and Pereira, 2021). The table is from (Hansen et al., 2023, p. 382).

Numerous competences and skills outlined in Table 9 have broad relevance across various roles in manufacturing, spanning from managerial positions to shop-floor workers. Consequently, categorising these competencies within rigid boundaries becomes challenging, as they tend to interconnect seamlessly. Take, for instance, the case of cybersecurity, a vital concern across the entire organisation. In this classification, it falls under the backend category due to its demanding technical expertise requirements for proper implementation and subsequent upkeep. However, this classification should not imply that those in management or frontend roles should disregard cybersecurity. In practice, individuals should be capable of fluidly transitioning between competences associated with management, backend, and frontend functions.

- *Management:* We know that the right leadership with a focus on the benefits of digitalisation combined with managing the right human resources is essential for Industry 4.0 from (Ghobakhloo, 2020; Kadir & Broberg, 2021; Liboni et al., 2019). The human capital is the very foundation that enables Industry 4.0 technologies and, in many ways, could be interpreted as the catalyst for industry 4.0. A bottom-up process may start, but if the management is not on board or the right organisational structures are not in place, real change is effectively not going to happen. The formation of these strategic initiatives relies heavily on the managers' awareness of Industry 4.0 and their understanding of the relevant technologies, skills, and competences needed to advance their business through digital technologies (Ghobakhloo, 2020). For instance, factors such as the perceived benefits of digital technologies, the presence of a well-defined strategy with managerial backing, and the acknowledgement and identification of essential competences play pivotal roles in kickstarting these initiatives (Ghobakhloo, 2020).

To ensure continuous learning across the organisation, there must be a determined effort to develop competences and cultivate the right organisational culture for effective communication and collaboration. This demands specific managerial competences (Shet & Pereira, 2021) that enable the acquisition of relevant knowledge, the recognition of its significance, and its integration into actionable business strategies, a concept often referred to as absorptive capacity (Sjödin et al., 2019). Shet and Pereira's identified managerial competences encompass a wide array of skills, including disruptive leadership, a collaborative mindset, proficiency in project leadership, adept problem-solving, and effective decision-making, among others. These competences notably align with findings from other studies seeking to identify the essential skills and competences for Industry 4.0 (Jerman et al., 2018; Kipper et al., 2021). Consequently, distinguishing between competences applicable only to managers and those relevant to other employees can prove to be a complex task. As a manager, one needs to adapt continuously based on feedback from the organisation. This feedback loop may come directly from colleagues or be facilitated by the growing connectivity and increased availability of information. Such a feedback mechanism is valuable for perpetually defining the digital strategy while taking into account the evolving needs, challenges, and considerations of the organisation (Hansen et al., 2023).

- *Backend – Technical backbone:* Competences listed in the backend category are mostly concerned with the digital technologies that enable both horizontal and vertical integration as envisioned by Industry 4.0 (Kagermann et al., 2013; L. D. Xu et al., 2018). These include specialised knowledge and skills within information and communication technologies, automation, wireless communication, cyber-security, machine learning, analytics, and sensor technology for data collection. The high specialisation needed often means that they are hard to develop organically in an organisation and thus highly sought after on the job market. This may present a bottleneck for companies pursuing Industry 4.0 solutions, as the technologies mentioned above provide the backbone of Industry 4.0.
- *Frontend – End-users:* This category holds crucial significance in facilitating the smooth functioning of manufacturing operations. It contains a multitude of soft skills and represents the competences needed from the people engaging directly with digital technologies in dynamic work environments. As such, it represents the majority of the workforce, from management to shop-floor workers. The workers in frontend positions will need broader skillsets such as great communication and teamwork skills, motivation to learn continuously, a flexible attitude and the capability to adapt to changing work environments and production setups. There is a need for user-friendly interfaces and general knowledge of IT and data in order to effectively

engage with digital technologies. Here, knowledge transfer will be an important skill. Given that the frontend category encompasses the largest fraction of personnel engaged in manufacturing processes, it stresses the imperative of incorporating their needs into decision-making processes regarding Industry 4.0 solutions.

5.1.2. OPERATOR 4.0 AND HUMAN FACTORS INITIATIVES

The operator 4.0 roles presented in Section 2.3.1 involves the adaptation of the technologies and workplace to the workers' needs. Such human-centred solutions have been shown to increase not only productivity but also the wellbeing of the workers involved (ACE Factory Cluster, 2019). Isolated, the capabilities in the operator 4.0 roles could all be placed within the *frontend* category mentioned in Section 5.1.1, as there is no consideration about how to manage a transition, which would help build the needed competences or enable the technical backbone for the technology to work. However, none of the case companies in the research projects were able to experiment and demonstrate these results alone. It required close collaboration from external partners, e.g., academic institutions (ACE Factory Cluster, 2019). The importance of collaboration with external knowledge partners has previously been emphasised e.g., see (Ghobakhloo et al., 2022), who advocate how external support is a driving force for SMEs who lack the resources and knowledge to get started; see (Ellström et al., 2020), who argues for the advantages of merging practice with academic institutions to enable co-development of knowledge.

5.2. SYNTHESIS AND DISCUSSION OF THE RESULTS

This chapter served to present which competences are relevant for Industry 4.0 and how they interact with digital transformation (RQ1). The findings from Paper A presented a novel typology for identified competences in Industry 4.0, and tied them together with what is known about the digitalisation process. It went further to highlight the Operator 4.0 typology and how such a human-centred typology helped inspire valuable research on how including people in the digitalisation process helps advance manufacturing companies' digital maturity.

Different competences are needed at different stages of a digitalisation process (Cimini et al., 2020; Liboni et al., 2019). Therefore, it can be beneficial to include this knowledge in the pursuit of digital transformation in a company. Digitalisation will ideally entail a process initiated by and from the management. This requires that they have the right knowledge and skillset to initiate such a process in the first place. Viewing the digitalisation process from the management, backend, and frontend typology means that the point of departure happens based on the management's knowledge and awareness of Industry 4.0. Then, to increase the maturity of digitalisation, it will rely on competences inherent to the backend category, which contains highly specialised technical skillsets. This makes the backend category prone to become a bottleneck in the digitalisation process as such skillsets are currently heavily sought after, and the demand for IT specialists outweighs the supply of available, specialised workers (Digitaliserings- og Ligestillingsministeriet, 2023, p. 23). Suppose the company manages to clear this hurdle, and a technological backbone emerges. In that case, sustained focus on the frontend category will become of utmost importance as the workers within this category impact production efficiency, e.g., if they are unable to interact with the new digital solutions, the investments made will not prove viable due to the untapped productivity potentials. Therefore, a constant feedback loop across the categories is important in order to continuously adapt the organisation's strategies according to the needs, challenges, and considerations of the workers (Hansen et al., 2023) (see Figure 12). This essentially means that the digitalisation process never ends, which also means that the best time to start this iterative process is now. From a macrosocial perspective, this may prove challenging if no profound changes are made both nationally and internationally to elevate conditions for knowledge creation or education within digital transformation.

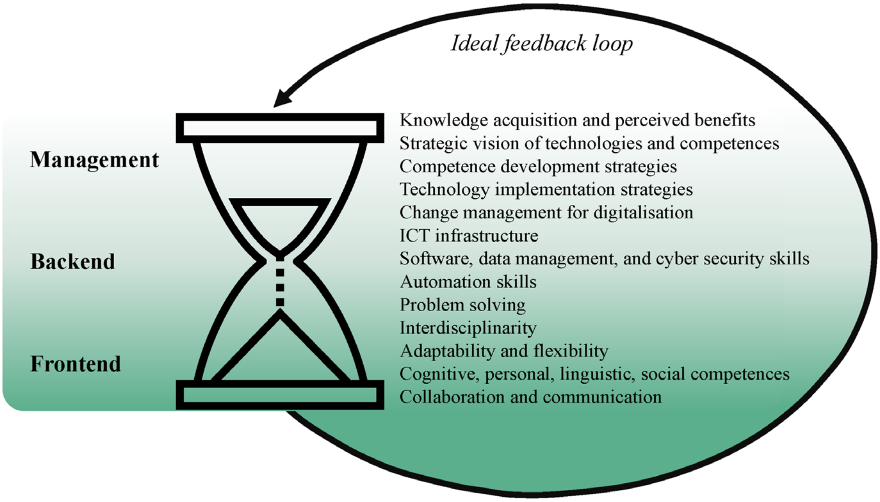

Figure 12. Management, backend, and frontend competences in an ideal feedback loop.

Knowing this interaction between competences and the digitalisation process, it is vital that we understand why manufacturers – and SMEs in general – seemingly face great challenges in engaging with such a feedback loop. The next chapter will present the findings from +30 SMEs who pursue digitalisation yet face challenges.

CHAPTER 6. HINDRANCES TO DIGITALISATION AND LACK OF ORGANISATIONAL CAPABILITIES

The following chapter will present results from Paper B ("Technology isn't enough for Industry 4.0: On SMEs and hindrances to digital transformation", Hansen et al., 2024) and Paper C ("The Role of Absorptive Capacity and Employee Empowerment in Digital Transformation of SMEs", Hansen et al., 2021) . For Paper B, 30 SMEs were analysed from an estimated 600 hours of engagement through physical and virtual workshops, interviews, and on-site visits to companies. Paper C is based on a literature study and interviews from two SMEs. The chapter mainly contributes to RQ2: What organisational prerequisites create conducive conditions for competence development towards digital transformation? It focuses on the challenges of and approaches to digitalisation as experienced by Danish SMEs, and it identifies ideal focus areas and management practices for knowledge absorption in the companies.

The competences mentioned in Chapter 5 are crucial to the success of Industry 4.0. However, the competences do not emerge organically in the organisation. It requires an understanding of the potential value creation that Industry 4.0 may bring (Colli et al., 2019; Ghobakhloo, 2020) and a focused strategic effort from management (Stentoft et al., 2021). When taking a look at the work produced on Industry 4.0, a picture emerges of a heavy technical focus that often disregards the sociotechnical aspects such as human factors (Hansen et al., 2024; Kadir et al., 2019; Neumann et al., 2021). A focus beyond merely technical solutions is necessary before a feedback loop between *management, backend*, and *fronted* can exist.

6.1. MODELS FOR SMART MANUFACTURING

To further complicate things, the technical backbone of Industry 4.0 has yet to be unanimously agreed upon despite multiple attempts to arrive at a unifying reference architecture that guides the technical implementation. A reference architecture for Industry 4.0 aims to materialise the needed vertical integration (internally in the different layers of an organisation) and horizontally (externally, e.g., between customers and across supply chains). They strive to show how technologies may enable such integration and, in some cases, point to specific digital technologies and suggest communication standards between different platforms (Nakagawa et al., 2021). Most of these reference architecture models employ a technical viewpoint and disregard aspects, for example, related to change management, implementation strategies or the competences required to do so. See Table 10. Such reference architectures also seem to favour large multi-national enterprises as opposed to SMEs

– this has also been identified in digital maturity- and readiness assessments. They assume a starting point that is already too advanced for SMEs (Mittal et al., 2018). For SMEs, a model closer to an operational reality upon which they can adhere to and act upon may, therefore, prove more constructive, i.e., focusing more on the process behind digitalisation as opposed to ideal technical reference architectures that most organisations will neither have the capital for, nor the competences to achieve.

Industry 4.0 model	Type	Focus	View on competences	Available Documentation
RAMI4.0	RA	Technical	○	(Hankel & Rexroth, 2015)
IIRA	RA	Technical	◗	70-page document (Lin et al., 2022)
SITAM	RA	Technical	◗	(Kassner et al., 2017)
IVRA Next	RA	Technical	○	36-page document updated at the Hannover fair (IVCI, 2018)
IBM Industry 4.0	RA	Technical	○	Limited information on IBM's website (IBM, 2017)
LASFA	RA	Technical	○	(Resman et al., 2019)
5C	RA	Technical	○	Conference paper (Lee et al., 2015)
Smart manufacturing adoption framework	PM	Socio-technical	●	Journal publication (Mittal et al., 2020)
Determinants of SM adoption	PM	Socio-technical	●	Journal publication (Ghobakhloo, 2020)
Development stages & resources toward I4.0	PM	Socio-technical	●	Journal publication (Estensoro et al., 2022)

Table 10. Various industry 4.0 models and their type, focus, and view on competences.[2] *Table is from (Hansen et al., 2024).*

6.2. DETERMINANTS FOR DIGITAL TECHNOLOGY IMPLEMENTATION

Taking the onset in a process model for digitalisation provided by (Ghobakhloo, 2020) and comparing it to the reality of 30 SMEs from the Innovation Factory North research project, a pattern emerges of an unsustainable and sporadic approach. Ghobakhloo

[2] ○ = Not part of the model and no mention of human-centred aspects such as competences, skills, or training.

◗ = Not part of the model. Brief mention of human-centred aspects.

● = Part of the model. Human-centred aspects are an integrated part of the model.

Abbreviations: Reference architecture (RA), process model (PM), interpretive structural model (ISM), smart manufacturing (SM). The table is from (Hansen et al., 2024).

arrived at six levels of determinants towards implementing smart manufacturing technologies:

Level 1	Perceived Benefits
Level 2	Financial resource availability; management support; and Strategic roadmapping for Digitalisation
Level 3	Employees qualification
Level 4	Digitalisation maturity
Level 5	Openness to change; corporate social responsibility policy; Seamless integration capability
Level 6	Operations technology maturity; Cybersecurity maturity

However, when contrasted with the situation of the SMEs, they experience challenges at every level of the model that indicate a lack of organisational capabilities related to digital transformation. See Figure 13. Especially, many SMEs seem to struggle with knowledge-related themes falling outside the steps provided in the model. The themes fit into existing theory on *prior knowledge* as the hindrances experienced could be categorised as either *content knowledge* or *meta-cognitive* knowledge (Dochy et al., 2002; Hansen et al., 2024). These knowledge-related themes, thus, were described in two main prior knowledge themes (also referred to as aggregated dimensions using Dennis A. Gioia's terminology (Gioia et al., 2013)):

Content knowledge: Relates to Industry 4.0 domain-specific knowledge.

- *Lack of understanding* of Industry 4.0, its technologies and value potential.
- *Data handling:* lack of knowledge related to digital data collection and analysis, leading to an overwhelming number of manual operations.
- *Integration challenges:* Knowledge of the integration between IT systems is low, and current systems are typically outdated, making internal and external information sharing difficult.

Meta-cognitive knowledge: A more reflective knowledge that enables understanding of how to approach learning and strategic processes.

- *Strategic management capabilities* are mainly focused on operation, and digital visions and roadmaps to guide their digitalisation are not present.
- *Upskilling and competence needs:* A general understanding of important competences exists, but knowledge on how best to approach competence development or upskilling is typically missing.

These knowledge themes lead to three propositions as to why they are struggling with digitalisation due to a lack of foundational knowledge.

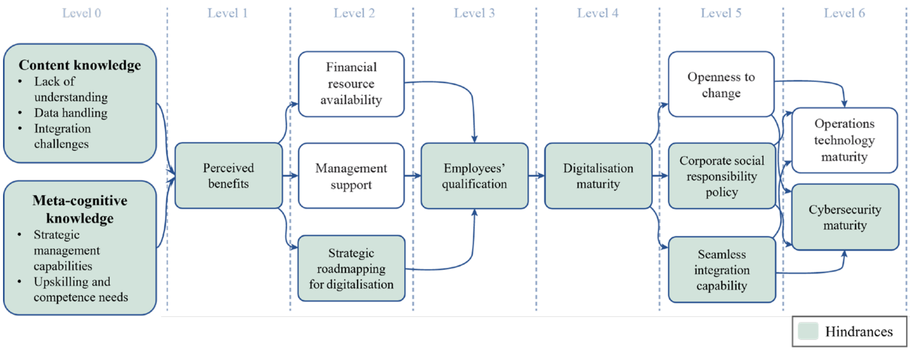

Figure 13. Model of determinants showcasing areas where SMEs express lacks and challenges. Adapted from (Ghobakhloo, 2020) and (Hansen et al., 2024)

6.2.1. FOUNDATIONAL LACK OF KNOWLEDGE RELATED TO INDUSTRY 4.0

The SMEs exhibit a level of understanding that is not fit to advance with important determinants for digitalisation. This manifests as a lack of prior knowledge, which consists of *content knowledge* and *meta-cognitive knowledge*. This leads to the first proposition:

> **Proposition 1:** "*Challenges towards digitalisation experienced by SMEs can be mitigated by an increased focus on both their understanding of* content knowledge *and* meta-cognitive *knowledge related to industry 4.0. Content knowledge relates heavily to the general conceptual understanding of Industry 4.0, and specifically, value creation through data exploitation methods and integration capabilities. Meta-cognitive knowledge encompasses how to work strategically with digital technologies and how to target competence development early to increase digitalisation capability." (Hansen et al., 2024)*

When the prior knowledge is low in the highlighted key areas from Proposition 1, it stagnates progression in the areas otherwise identified as determinants for Industry 4.0 technology implementation (see Figure 13). When no new knowledge is generated, there is nothing to disrupt the current knowledge inertia (S. Liao et al., 2008), i.e., the company continues in the same manner, applying outdated knowledge or approaches to problem-solving solely based on past experience. This leads into the second proposition:

> **Proposition 2:** "*A lack of foundational prior knowledge leads to knowledge inertia, which explains lack of progress regarding digitalisation observed in manufacturing SMEs."(Hansen et al., 2024)*

Lastly, to combat knowledge inertia, Liao et al., 2008 propose proactive encouragement of new ideas and methods, often spurred by government-supported programs like interactive research (Ellström et al., 2020) or engaged scholarship (Van De Ven & Johnson, 2006). Our three-year engagement with SMEs involved multiple representatives, fostering a shared language and strategic vision regarding Industry 4.0 through hands-on experience and digital workshops. Despite this support, SMEs struggled with smart technology adoption, requiring ongoing assistance, as noted by (Ghobakhloo et al., 2022; Saabye et al., 2022), aligning with our revised model of determinants (see Figure 13). These SMEs "have yet to reach the event horizon (i.e., the point of no return), where they leave knowledge inertia behind and become self-sufficient to identify value-adding technology, manage competence development and pursue digital transformation towards Industry 4.0." (Hansen et al., 2024). Another analogy to be used here (or more generally to explain STS and digitalisation): It is like a combustion engine. You may have an intact engine, but it needs fuel, air, compression, and spark – if all are not set up in unison, the engine will never run. This highlights the need for competent management in guiding competence development and digital transformation (Hecklau et al., 2016; Shet & Pereira, 2021). Facilitating this transformation requires managerial proficiency in project leadership, design thinking, collaborative mindset, and data analytics (Shet & Pereira, 2021). Facilitative support and nurturing prior knowledge at *level 0* are vital to guide SMEs toward enhanced digitalisation. This leads to the third proposition:

> **Proposition 3:** "*Technology investment alone is not enough to succeed with digitalisation. A supportive scaffold to help with the facilitation of digitalisation initiatives is needed to escape the knowledge inertia present in SMEs and help guide strategies for competence development in parallel with operational technology development." (Hansen et al., 2024)*

Such a supportive scaffold may be in the form of knowledge consortia to provide thorough technical reference architecture documentation and ensure readily available and current training resources for companies (Nakagawa et al., 2021). For example, (Ellström et al., 2020) present promising results from a consortium model acting as an intermediary knowledge hub, bridging the gap between practitioners and researchers. Likewise, learning factories are an effective way of absorbing new knowledge into companies, often through close collaboration with research institutions (Abele et al., 2019; Møller, Hansen, et al., 2023b, 2023a).

6.3. MANAGEMENT PRACTICES FOR KNOWLEDGE ACQUISITION – THE ABSORPTIVE CAPACITY

Introducing knowledge in companies to increase the understanding of Industry 4.0 and the processes surrounding digitalisation is crucial in order to avoid knowledge inertia and a stagnated digitalisation process. *Absorptive capacity* is seen as a dynamic organisational capability linked to the ability to generate knowledge within an organisation and efficiently utilise its resource base to address organisational change and enhance competitive advantage (Zahra & George, 2002). It is closely tied to both learning capability and problem-solving skills, and its effectiveness hinges on the extent of prior relevant knowledge. Thus, it is important to foster this capability within organisations in pursuit of a digital transformation. Table 11 summarises the findings from Paper C (Hansen et al., 2021). It becomes clear that enhancing one's absorptive capacity relies on changes to how the organisation works, with a large focus on its human capital.

Managerial practices	**Description**
Independent and flexible work structures	Cross training and job rotation among core employees and partners support knowledge transfer, mitigate knowledge held by few, allows augmentation of current knowledge base and helps stimulate networking and transspecialists (T-shaped skills). Self-managed teams with the freedom to continuously solve problems.
Knowledge sharing and network	Establishing archival-based mechanisms to make knowledge accessible (e.g. know-how reports) and to homogenise knowledge in organisation (difficult if very hierarchically structured and easier in smaller companies with one or few locations). Encourage new knowledge via knowledge scanning to create a virtual research organisation drawing on alliances and networks from external partners (e.g. universities, similar companies, suppliers etc.). Communicate clearly the company vision, values and goals through participatory goal setting. Use selected employees to disperse newly learnt skills/knowledge to their colleagues.
Continuous learning and training	Identify key individuals and make sure they possess adequate domain knowledge by offering education programs. Support on-the-job training, continuous learning by doing, and adaptive training to fit competence level. Utilise staff in training new employees (e.g. in combination with job-rotations/cross training), which helps develop common component/architectural knowledge (shared understanding of tasks/organisation). Encourage experimentation and prototyping and allocate means to do so. Create formal grievance procedures for continuous improvement and increased employee impact.
Incentive structures	Support motivation by offering result-based incentives e.g., pay/rewards equivalent to skills, performance appraisal, shared rewards for group efforts, stock ownership. Offer a clear path of advancement in the company.

Table 11. Managerial practices for absorptive capacity. The table is from (Hansen et al., 2021)

6.4. SYNTHESIS AND DISCUSSION OF THE RESULTS

Chapter 5 concluded with the importance of having a well-established feedback loop in the organisation that can utilise *management, backend,* and *frontend* competences and continuously adapt as the competences or technology matures. In this chapter, we dove into the specifics of 30 manufacturing firms to uncover what hindered them in advancing their digital transformation.

Despite the recent focus on the importance of including human-centred considerations when approaching digital transformation, Section 6.1 highlighted the tendency for research on Industry 4.0 to apply a technical angle. Even in research focusing on human technology interfaces like the operator 4.0 typology, there is a tendency to neglect the process of getting there, which involves strategic efforts built on a sufficient knowledge foundation. Section 6.2 highlighted the importance of having the right organisational capabilities before advancing through specific digitalisation determinants. For example, it does not immediately benefit the organisation to purchase operational technology if no real consideration was made as to what value the technology may bring the organisation and how – this includes ensuring that the right skills and knowledge are present, which can enable the technological potential. To get there, the organisational capability should rest on foundational knowledge within both *content knowledge* and *meta-cognitive knowledge* related to digital technologies and knowledge on how to approach learning.

Certain managerial practices have been shown to benefit the *absorptive capacity* of companies, i.e., a dynamic capability to recognise the importance of new knowledge, seek it out and absorb it into the company (Hansen et al., 2021; Zahra & George, 2002). The main managerial focus areas identified in Paper C to support the absorptive capacity (and thus new organisational knowledge) are as follows:

- Independent and flexible work structures
- Knowledge sharing and networking
- Continuous learning and training
- Providing incentive structures

For SMEs pursuing digital transformation, it may be difficult to recognise the benefits and structure such managerial practices themselves. This shows in the themes within the content knowledge surrounding digital technologies and a general understanding of Industry 4.0. Here, SMEs struggle to understand what value Industry 4.0 may bring their business and often struggle to work efficiently with their data collection to create valuable insights for them to use proactively. Similarly, the interconnectivity inherent to Industry 4.0 is mostly absent. Their approach to digitalisation is sporadic and lacks a strategic goal and structure as to how to achieve their digital goal, e.g., through dedicated competence development plans or roadmaps. External support for SMEs to structure their efforts and elevate their prior knowledge could help guide them onto a better path towards digital transformation, e.g., through large funding programmes like the Digital Europe Programme (European Commission, 2018). Through such funding emerge interactive research projects and offers that provide learning *scaffolds* suited for SMEs stuck in lower levels of digital maturity. The pivot in the research community towards *Industry 5.0* and its focus on human-centred, sustainable, and resilient solutions may help increase the understanding and the importance of competence development strategies in parallel with technology adoption strategies.

The next chapter further unfolds examples of how SMEs have overcome barriers related to their foundational knowledge through a sociotechnical perspective and how a scaffolding approach to knowledge creation may help introduce digital technologies to non-specialised workers, considered digital novices.

CHAPTER 7. WORKING WITH DIGITAL TRANSFORMATION IN SMES AND LEARNING ABOUT DIGITAL TECHNOLOGIES

The following chapter summarises the results from Paper D ("Enhancing Knowledge Creation in Manufacturing SMEs: A Digital Transformation Imperative", Hansen & Lassen, n.d.) and Paper E ("Introducing novice operators to collaborative robots: A hands-on approach for learning and training", Hansen et al., n.d.). The chapter mainly contributes to RQ 3: How can adopting a human-centred perspective promote learning and understanding of digital transformation? To answer this, a case study of two SMEs who have managed to effectively advance their digitalisation is presented along with an experimental study that investigates how industry 4.0 technology may be introduced to novices with a focus on their learning. The latter paper uses collaborative robots as an example of technology due to the already established SME interest and relevance for their manufacturing context.

In Chapter 6, we learned that the troubles experienced by SMEs regarding digitalisation may be explained by a few foundational knowledge themes under *content knowledge* and *meta-cognitive* knowledge. It was proposed that if a company manages to increase their prior knowledge within these themes, it could position them better when tackling their digitalisation. However, even within these themes, there are contradicting claims of them acting as either enablers or barriers for digital transformation. Much work has gone into defining barriers and drivers for digital transformation, but when compared to each other, it ultimately reads like important focus areas that can swing both ways, meaning they can act either as a barrier or as an enabler. What determines which way the pendulum swings must, therefore, heavily rely on the overall approach and capability to effectively address these focus areas. See Table 12 for an overview of such perceived differences in the literature.

	Content knowledge			Meta-cognitive knowledge		
Author	Lack of understanding	Data handling	Integration challenges	Strategic management capabilities	Upskilling and competence needs	Terminology used
(Masood & Sonntag, 2020)	X/✓					Financial, awareness and knowledge constraints, implementation time. Training, support, investment, awareness, and knowledge are enablers.
(Müller, 2019)	X	X	X	X	X	Lacking strategy, competencies and know-how, different standards limit availability and use of data, too cost-driven, unclear benefits and don't understand the value of data
(Stentoft et al., 2021)	X	X	X	X/✓	X	Lack of standards, data protection, qualified workforce, knowledge about I4.0, and strategic importance of I4.0. Conscious strategy around I4.0, public advisor system are drivers.
(Estensoro et al., 2022)	X			X/✓	X	Unavailability of financial resources, lack of qualified staff. Integrated I4.0 management strategy, financing resources, collaboration culture (mainly tech centres), external advisors.
(Kamble et al., 2018)	X	X	X		X	Security and privacy issues, high implementation cost, lack of comprehension about IoT benefits, lack of standards and reference architectures, need for enhanced

						skills, seamless integration, and compatibility issues.
(Ghobakhloo, 2020)	✓	✓	✓	✓	✓	Perceived benefits, management support, employees' qualification, strategic roadmapping for digitalisation, openness to change, seamless integration capability, cyber security maturity.
(Ghobakhloo et al., 2022)	✓	X/✓	X	✓	X/✓	Absorptive capacity, digitalisation knowledge accumulation and development, industry 4.0 management competency, perceived strategic benefits of industry 4.0 technologies, financial resource availability, data volume, management and processing constraints.
(Veile et al., 2020)	✓	✓		✓	✓	Development of industry 4.0 specific know-how, proper handling of data interfaces and data security, comprehensive planning processes, cooperation with external partners, and an adaptable organisational structure.

Table 12. Literature on the meta-cognitive and content-knowledge themes. X: Barrier; ✓: Enabler.

Few empirical studies exist to guide the digital development in the right direction for SMEs (Mittal et al., 2018); supposedly because of the complexity of digitalisation efforts towards a digital transformation. For this reason, few SME success cases exist from which we can draw important insights from. The purpose behind Paper D was to elucidate *how* exemplary SMEs have increased their digitalisation maturity by focusing on their activities related to the foundational knowledge themes identified in Chapter 6.

These activities were explained in 12 dimensions connected to the foundational knowledge categories from Figure 13 and Table 12.

7.1. STEERING SMES TOWARDS DIGITAL TRANSFORMATION THROUGH KNOWLEDGE CREATION

The two exemplary cases were Danish manufacturing SMEs working in the metal sector and were chosen based on their digital transformation journey, which differs from the 30 SMEs analysed in Paper B. The data used for the study span observations, semi-structured interviews around the prior knowledge themes from Paper B, and grey literature, e.g., news articles on the companies' digital achievements. In total, 20 hours of observations and 613 minutes of interview data was transcribed based on interviews with staff ranging from CEO to shopfloor workers. The analysis was approached abductively, as previous theories were not ignored as with the case of grounded theory. Rather, the prior knowledge themes from Paper B were used as a *codebook* (Vila-Henninger et al., 2022) or *index codes* (Deterding & Waters, 2021) to perform our initial coding, before axial coding began to elucidate the actionable approaches done by the SMEs to mature the digitalisation determinants from Figure 13. The results showed that efforts to mature the *content knowledge* and *meta-cognitive knowledge* had a profound effect on their digitalisation transformation when viewed through the lens of the digital determinants listed in Section 6.2. This was achieved mainly through the cultivation and addition of new competences and knowledge creation, which was captured in 12 themes. See Table 13.

Approach	Description
Effectual approach	A start-up mentality for internal improvement projects and incremental problem-solving approach with continuous improvement in mind.
Experimental approach	No waiting for the perfect solution but inclined to test out technology or concepts to learn which direction seems most promising. This trait is connected to an entrepreneurial mindset and affected the perceived benefits and understanding of the value potential.
Employee involvement	Agency given to employees to influence decisions affecting them or promote ownership over technology implementation projects.
Team composition	Understanding of personally types and how individuals approach work tasks differently to support a healthy work environment and increase communication.

Vision & Milestones	Guided by overall vision related to production improvements and communication through milestones to serve as a motivational progress markers.
Hands-on experience	Examples of new technologies in a familiar production setting and hands-on demonstration help increase understanding of the potential benefits to the individual and positively affect attitudes.
"One year development, one year operation"	Focus on raising financial resources to be invested into the company. E.g., by switching between an operational year and a development year where employees are upskilled via tertiary education.
Development paths	Focus on developing the competences of workers through diverse and challenging tasks, tertiary education offers, and career opportunities internally.
New hires	New colleagues on-boarded on multiple hierarchical levels to expand the knowledge foundation and introduce new work processes.
External knowledge	Increase the knowledge foundation through external consultants, networking, internships and university collaboration e.g., in the form of internships and student groups.
Process understanding	Increased understanding of internal processes and optimisation of those (typically through *external knowledge* and *new hires*).
Data cleanup	Increased data hygiene and trustworthy master data (typically through *external knowledge* and *new hires*).

Table 13. Approaches beneficial to digital transformation in SMEs. Adapted from Paper D (Hansen & Lassen, n.d.)

The combination of these approaches allowed the case companies to navigate disruptive events we call *lighting strikes*. These cover unexpected, disruptive events which initially seem catastrophic. The organisational capabilities present in a company determine how such an event is acted upon. In our exemplary cases, such events spawned more well-defined processes as they provided time to reflect and optimise on inefficient processes or operations technology. Slowly, the increased knowledge generated from their entrepreneurial and experimental approach and a focus on their employee development led them onto a path that was more strategically driven. The high uncertainty in the early stages of their digitalisation efforts lends itself to *effectuation* processes rather than *causation* processes. These terms are typically used within entrepreneurship (Chandler et al., 2011; Sarasvathy, 2001) but are deemed applicable in this context due to the overlapping qualities between successful entrepreneurship and successful digital transformation: for example, to diminish uncertainty, one must "fail fast" through iterative knowledge creation, i.e. an experimenting approach characterised by high flexibility. Also new venture creation from entrepreneurship resembles digital transformation as new products or business models typically help define a digital transformation (Gong & Ribiere, 2021; Verhoef et al., 2021). Approaches characterised by effectuation are more concerned with flexibility and experimentation, and choices made are based on loss affordability – opportunity is generated through incremental experimentation and an adaptability to change direction with new information, creating an emerging strategy based on available means (Chandler et al., 2011; Sarasvathy, 2001). Causation is characterised by a much more rigid and planned strategic approach towards a specified goal (Ibid.). See Figure 14 for the proposed relationship between competences and digitalisation approach for SMEs who share the characteristics outlined in Table 13.

Such an experimental approach and entrepreneurial mindset to get started on small, incremental digitalisation projects has also been identified as a *sandbox* approach, which benefits the innovation process of manufacturers while reducing the high uncertainty experienced by SMEs when it comes to digitalisation efforts (M. S. S. Larsen et al., 2023). In essence, it is the progression through smaller, incremental steps that defines a viable development path within the means of SMEs.

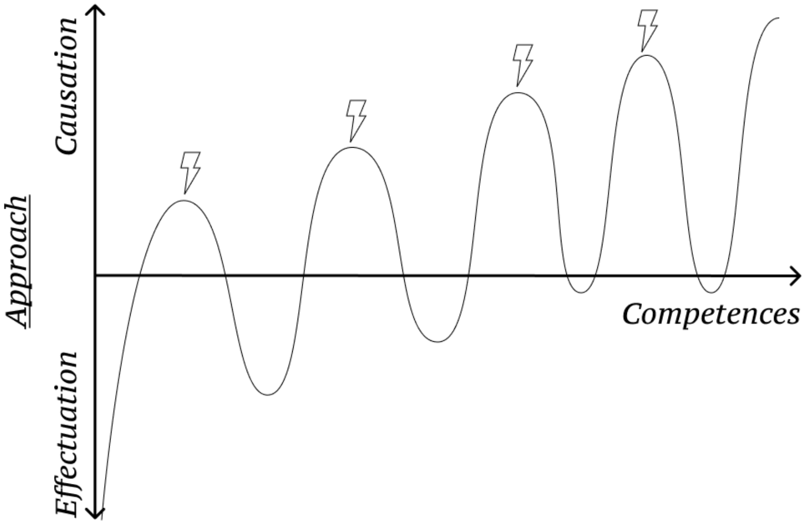

Figure 14. Model to illustrate the approach of effectuation and causation in SMEs when competences increase over time and lightning strikes are overcome. Figure from Paper D (Hansen & Lassen, n.d.)

The analysis of how these dimensions listed in Table 13 were benefitting the SMEs' digital transformation led to two propositions:

> **Proposition 1:** "*Digital transformation in manufacturing SMEs is positively affected by effectuation and persistence"* (Hansen & Lassen, n.d.).
>
> **Proposition 2:** "*Digital transformation in manufacturing SMEs is highly dependent on the involvement employees and external knowledge."* (Hansen & Lassen, n.d.).

In the SMEs, such knowledge came in the form of new hires, external consultants, or internships and collaborations with relevant educational institutions

7.2. ENGINEERING THE LEARNING PROCESS: COGNITIVE APPRENTICESHIP FOR INDUSTRY 4.0 TECHNOLOGIES

The following section presents the results from Paper E ("Introducing novice operators to collaborative robots: a hands-on approach for learning and training" Hansen et al., n.d.), which concerns how to obtain effective learning outcomes when introducing operational technology to novices. For this, collaborative robots were *chosen as an example technology due to the value potential for SMEs and already established interest.*

When it comes to digital transformation, the need for competences is rather unquestionable at this point. However, as digital transformation is regarded as a complex sociotechnical endeavour, such competences cannot be expected to arrive solely from universities or other vocational institutions. There is an inherent need to create supportive learning environments within the manufacturing industries at multiple levels, from the shopfloor all the way to the top management. In this chapter, we focus on collaborative robots (also called *cobots*) as an example of a relevant operational technology within Industry 4.0.

For learning about Industry 4.0 and its enabling technologies, so-called learning factories have been shown to be effective and act as conducive learning environments (Abele et al., 2019; Sorensen et al., 2023). They are typically a collaboration between universities and industry, which targets both shopfloor workers and students at various abstraction levels. However, despite their rising popularity, collaborative robots have been underexplored in these settings when it comes to introducing them to industry workers who have no or very limited experience with robots. Mayrhofer et al. represent one of the few studies within the learning factory literature that address the robot learning process from a human perspective (Mayrhofer et al., 2021), calling it *learning nuggets*. The idea is to start the learning process at the current skill level of the learner and offer learning paths adapted to their progress. However, they do not go into detail about which topics or skills are relevant nor how to approach such a learning process operationally.

Additionally, it is worth noting how a large research stream within industrial human-robot interaction deals with how the *robot* learns, not how *people* learn. This means that industrial human-robot interaction has mostly been investigated from a technical angle and by endowing the robot with extra capabilities or different interfaces. A lot of focus has been put into additional control algorithms that allow the robots to be operated and programmed more intuitively, e.g., speech (Li et al., 2022), gestures (Makrini et al., 2019), or “robot skills” (Schou et al., 2013). The latter refers to a system comprising of simple elementary robot operations called device primitives (e.g., move, open gripper, close gripper, etc.)., which can be chunked together to create a task (e.g., "pick up object", which comprises of at least the three mentioned device primitives). These tasks can then further be chunked to create what is called a robot skill, which is more advanced robot operations (e.g., end-of-line palletising). These tasks and skills can be presented to the user, which allows them to choose from the robot’s skillset to create their needed program (Schou et al., 2013). Such functionality has barely made it out of research labs, yet thousands of collaborative robots are implemented each year (global cobot installations were up by 37% between 2017-2021 (IFR, 2022)). Therefore, it is useful to approach "robot skills" from the human perspective to build up the knowledge and skills needed to program such a collaborative robot and to enable a flexible production capability.

We approached this by first investigating what *knowledge* is important to understand when it comes to collaborative robots and what *skills* are necessary to master. Such knowledge and skills are just like when a person is getting their driver's license; it starts with theory and *knowledge* about how a car functions; meanwhile, *skills* are needed to operate it physically. For our work, a questionnaire was sent out to robot experts from academia and industry, which identified the elemental skills and knowledge areas needed to design a hands-on learning approach for novices. See Table 14.

Knowledge about cobots	Count	Cobot programming skills	Count
Emergency Stop	19	Set waypoints	18
Turn system on/off	17	Activate/deactivate tool (e.g. open/close gripper)	17
Motion types	11	Adjust speed and acceleration	12
Tool Center Point (TCP)	11	Structure a program (e.g. sequence of operations)	12
Degrees of Freedom (DoF)	10	Mount tool	11
Payload and center of gravity	9	Adhere to safety standards	9
Safety standards	9	Configure payload and center of gravity	9
Collision avoidance	8	Use wait commands	9
Jogging the robot	7	Optimize trajectories	2
Speed and acceleration	7		
Kinaesthetic teaching	5		
Interfaces to external equipment, safety precautions	5		

Robot joint	2	

Table 14. Elementary cobot skills and knowledge (N = 19). Table from (Hansen et al., n.d.)

These elementary skills and knowledge were used to design physical hands-on training with a *problem-based* didactical learning framework called *cognitive apprenticeship* (Collins & Kapur, 2014).

In a cognitive apprenticeship learning setting, tasks are deliberately chosen to impart specific knowledge and techniques applicable across diverse real-world contexts (Collins & Kapur, 2014). The progression of tasks follows a deliberate pattern, starting with simpler components and gradually integrating them into more meaningful and complex tasks as the learner advances. This gradual progression supports the evolving learning needs (Collins & Kapur, 2014), often referred to as *scaffolding* – a supportive theoretical structure that is progressively dismantled as the learner gains proficiency. See Figure 15.

According to Collins and Kapur, cognitive apprenticeship is founded on four fundamental principles: content, methods, sequencing, and sociology (Collins & Kapur, 2014). Below, we outline the key elements employed in our work:

*"**Content:** Involves domain knowledge encompassing essential concepts, procedures, and factual subject matter.*

***Methods:** Central to the approach is scaffolding, ensuring structured and supported learning for the learner. As they progress, the level of support is gradually reduced in sync with their learning development.*

***Sequencing:** Tasks are presented in an escalating order of complexity and diversity, aligning with the scaffolding methodology.*

***Sociology:** Emphasizes situated learning, wherein the learner engages with realistic tasks in a contextual setting, such as interacting with an actual collaborative robot instead of a simulated environment."* (Hansen et al., n.d.)

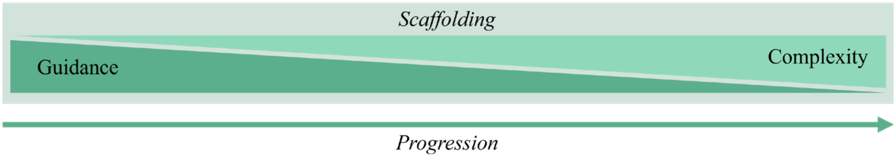

Figure 15. The concept of scaffolding within a cognitive apprenticeship approach. As the learner progresses, the guidance becomes less as the task complexity increases.

The learning approach was pilot-tested on 20 students, who all had no or very limited cobot experience in two different settings and using two different robots. The hands-on approach to learning and training based on the cognitive apprenticeship approach demonstrated that all participants went from having no ability to program a collaborative to learning how to program simple pick-and-place tasks independently. This leads us to infer that learning about new digital technology is effective if the learner is:

- Provided the right *content* and domain knowledge;
- a *scaffolding method* is used to structure and guide the training;
- *Sequencing* is used to increase complexity and diversity of tasks;
- *Sociology* is used to represent real-world environments.

In our study, these points were ensured by first identifying the right content and domain knowledge as advised by field experts. Then a simple interface was created to guide the learner in both practical tasks and theoretical knowledge to assist them in learning the task at hand. Sequencing was ensured in the way the on-screen help diminished along with their progression and the complexity of the tasks increased. Sociology was ensured by having a real robot for them to interact with and try out their presumptions on the right interface in a physical environment resembling a real-world production setup.

Such considerations are important if we ever are to succeed in teaching non-experts digital technologies. A lack of training is a blockade in diffusing new technology in the companies, e.g. robot programming to enable a flexible production environment using cobots, making it possible to move beyond simple start/stop operations as is currently observed in manufacturing environments (Michaelis et al., 2020).

7.3. SYNTHESIS AND DISCUSSION OF THE RESULTS

When viewed from a whole organisation perspective, a commonly noted barrier to digitalisation for SMEs is the lack of a digital strategy in the organisation. However, our findings seem to suggest that this may be a moot point as SMEs who portrayed rather large *effectuation* traits could capitalise on digitalisation through their persistence and flexibility in the face of uncertainty, combined with an experimenting approach that helped develop internal competences and understanding of which solutions could generate value specific to their situation. This points towards how SMEs focusing on their *tactical* approach as opposed to a *strategical* approach, may prove a more effective and realistic way to view digitalisation in SMEs – at least in the early stages of digitalisation. As the SMEs work through these incremental obstacles and gain knowledge and competences through their experimenting and entrepreneurial character, they lean more towards an approach guided by *causation*. They then have the experience to know which digital technologies provide value for them and can begin to capitalise through new product development or customer segments defined by their emerging strategy and increased level of competence.

This implies that companies who get started sooner than later, and who employ an effectuation approach (e.g., innovating through incremental *sandbox* projects (M. S. S. Larsen et al., 2023)), are more robust in the face of barriers or disruptive events (*lightning strikes).*

Investments within the company and a continuous focus on learning and competence development or acquisition were cornerstones in driving digitalisation in the SMEs. Note that their successes relied not only on technical implementations but mostly through increased understanding of digital technologies and more structured processes – which was enabled through external knowledge or new hires and upskilling.

An analogy can be drawn to a push/pull manufacturing systems approach or a make-to-stock vs. make-to-order. In the former make-to-stock analogy, we posit that companies who acquire new digital or operational technologies first and foremost and only then begin training their employees risk struggling to implement them properly in their production. They perhaps even discover it was the wrong technology for their environment and tasks in the first place. This is analogous to a made-to-stock production strategy – we stock up and hope we meet the demand when the surge comes. If the thinking is reversed, and the acquisition of new digital or operational technologies relies on an informed workforce, who has obtained a baseline understanding of which technologies exist to match the current (or future) production processes in the company, then technology acquisition is pulled by a demand from a competent workforce, who has received appropriate training prior to the implementation. This is analogous to a make-to-order production strategy – the technology here is the product, which is acquired based on the demand of customers (i.e., competent production staff). In such a way, competences could be said to build the foundation for value adding technologies.

On a primary system level, the use of cognitive apprenticeship wrapped in a learning scaffold provided an effective and enjoyable way for novices to learn cobot programming. Here *knowledge* is essential (*content knowledge)* and the way it is introduced, and learners supported in the process *(meta-cognitive knowledge).* However, such setups do require a person skilled in the technology to ensure that the correct domain knowledge is taught to the learner, which is difficult for SMEs to do alone. Therefore, it may be advantageous to look towards learning factory setups in collaboration with universities and industry (Sorensen et al., 2023) to fully exploit cognitive apprenticeship in physical hands-on setups.

That being said, the two case companies managed to mature important content knowledge and meta-cognitive knowledge without a learning factory setup. They did so through activities in the 12 areas, which was highlighted in Table 13. The active focus in these areas were found to positively affect digital determinants towards digital transformation.

CHAPTER 8. CONCLUSION

On a macrosocial level, digitalisation in Denmark has generally seen widespread adoption. However, there is a noticeable deceleration in its pace. Particularly, the digitalisation journey within SMEs is slower and less advanced compared to larger enterprises. This issue is compounded by the fact that SMEs constitute the majority of the manufacturing sector. Adding to the challenge is an overarching workforce shortage for current manufacturing operations, a situation anticipated to intensify in the coming years. The shifting demographic landscape in Denmark, marked both by an ageing population and a population decline, underscores the necessity for increased digitalisation and automation to sustain current living standards with fewer available workers. Moreover, manufacturers grapple with a significant deficiency in knowledge and competences required for effective digital transformation. As digitalisation continues to reshape manufacturing work environments, it becomes imperative to look for approaches that guide responsible, sustainable, and human-centred digitalisation to elevate working conditions and simultaneously address the pressing need for skilled workers. The lack of skilled workers, an ageing population and population decline suggest that digital transformation of manufacturers will become harder if no interventions on both national and international scale happens that can either utilise current skilled workers better or create better conditions for knowledge creation locally. The European Union must continue its focus on supporting digital technology implementation in manufacturing but increasingly look towards lifting the knowledge level within the manufacturing sector.

This thesis is the culmination of a rather unique opportunity to gain deep insight into many different Danish small and medium-sized enterprises (SMEs) that all had ambitions to advance their digitalisation as a stepping stone towards digital transformation. This was enabled through the research program called *Innovation Factory North* (IFN) (Møller, Hansen, et al., 2023b), which allowed us to dive into entire organisational systems.

We categorised important competence areas within *management, backend,* and *frontend* and linked them to the digitalisation process where a feedback loop is necessary to continuously adapt and improve. Such a feedback loop is currently not happening in the majority of manufacturing SMEs, and to understand why, we looked to the participating companies in the IFN program. Through an empirical case study, we pinpointed how Danish SMEs typically lack foundational knowledge in two main areas: *content knowledge* and *meta-cognitive knowledge*. Content knowledge was typically missing surrounding available digital technologies, how to handle and work with data, and a lack of knowledge related to integration of systems and knowledge sharing. Meta-cognitive knowledge was typically missing in areas such as how to plan or structure a digitalisation process and how to obtain the missing skills and competences that would help their digitalisation process.

To better understand how SMEs may overcome these foundational knowledge hindrances, we looked at two exemplary cases of SMEs that showed the capability to advance their digitalisation. We found that external knowledge plays a pivotal role through collaborations with universities, the integration of internships, and a strategic focus on new hires. These serve as invaluable conduits for injecting fresh perspectives and insights into the organisation. Moreover, a lack of long-term strategic planning towards digitalisation did not stop them in their digitalisation efforts. On the contrary, we noticed how their experimenting approach with a focus on new knowledge lent itself to an *effectuation* approach, which helped them get started, overcome disruptive *lightning strikes,* and experience incremental digital improvements. As time passed and their competences and experience grew, they started to display a more strategically focused approach, leaning towards a *causation* approach.

On a primary work systems level, we learned the significance of supporting the learning, e.g., through a learning scaffold – a progressive framework that initiates guidance at the learner's level, incrementally diminishing as complexity increases. This dismantling of the scaffold allows individuals to confidently stand on their own, equipped with the knowledge and skills needed to engage with modern production technologies. These findings were based on a specific operational technology (i.e., a collaborative robot) but are suggested to be transferrable to other enabling digital technologies.

Our exemplary cases underscored the significance of fostering a continuous learning mentality and pursuit of new knowledge to be brought into the companies. Particularly crucial for SMEs grappling with the urgent need for digitalisation to maintain competitiveness, human-centred production accommodates the challenges of attracting (or building) new competences and a skilled workforce. It not only aligns with the evolving technological landscape but also fosters an environment where employees are empowered as integral contributors to the digital evolution.

Digital technologies to enable digital transformation are available and evolving fast. Now, it is time to focus on how we better integrate learning and competences from a human-centred production perspective to ensure progress and to support sustainable work environments.

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APPENDED PAPERS

Paper A: Hansen, A. K., Lassen, A. H., Larsen, M. S. S., & Sorensen, D. G. H. (2023). Competence Considerations for Industry 4.0 and Future Trends. In O. Madsen, U. Berger, C. Møller, A. Heidemann Lassen, B. Vejrum Waehrens, & C. Schou (Eds.), *The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs* (pp. 379–389). Springer International Publishing. https://doi.org/10.1007/978-3-031-15428-7_35

Paper B: Hansen, A. K., Christiansen, L., & Lassen, A. H. (2024). Technology isn't enough for Industry 4.0: On SMEs and hindrances to digital transformation. *International Journal of Production Research. Accepted/In press.* https://doi.org/10.1080/00207543.2024.2305800

Paper C: Hansen, A. K., Stoettrup Schioenning Larsen, M., & Lassen, A. H. (2021). *The Role of Absorptive Capacity and Employee Empowerment in Digital Transformation of SMEs* (SSRN Scholarly Paper 3859277). https://doi.org/10.2139/ssrn.3859277

Paper D: Hansen, A. K., & Lassen, A. H. (n.d.). Enhancing Knowledge Creation in Manufacturing SMEs: A Digital Transformation Imperative. *Journal of Manufacturing Technology Management, Unpublished / In process to be submitted.*

Paper E: Hansen, A. K., Villani, V., Pupa, A., & Lassen, A. H. (n.d.). *Introducing novice operators to collaborative robots: A hands-on approach for learning and training. (In review)* Preprint available at TechRxiv: https://doi.org/10.36227/techrxiv.22762562.v1