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DESIGNING NEW WAYS OF WORKING IN INDUSTRY 4.0

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Bzhwen A Kadir

The transition towards Industry 4.0 and the increasing implementation of new digital technologies in industrial operations are creating new challenges and opportunities concerning human work and work organization. Overcoming these challenges and taking advantage of the emerging opportunities require new sociotechnical and human-centered design and engineering methods and approaches. This Ph.D. thesis investigates how the introduction of new digital technologies in industrial work systems affect human well-being and overall system performance. Also, this thesis presents implications, recommendations, and prescriptive frameworks for assisting practitioners in (re)designing work systems in connection with the implementation of new digital technologies. The overall focus of these prescriptive supports is to ensure human well-being and overall system performance.

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DESIGNING NEW WAYS OF WORKING IN INDUSTRY 4.0

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Bzhwen A Kadir

Ph.D. thesis

September 2020

Department of Technology, Management and Economics

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Preface and acknowledgments

This thesis is the results of a Ph.D. project, conducted by Bzhwen A Kadir at the department of Technology, Management, and Economics at the Technical University of Denmark (DTU). The project duration spanned from September 2017 to September 2020 and was fully funded by DTU. The main supervisor of this project was Associate Professor Dr. Ole Broberg, and the co-supervisors were Dr. Carolina Souza da Conceição (for the first two years of the project) and Professor Dr. Anja Maier.

But it is not true that I am self-made. Like everyone, to get to where I am, I stood on the shoulders of giants. My life was built on a foundation of parents, coaches, and teachers; of kind souls who lent couches or gym back rooms where I could sleep; of mentors who shared wisdom and advice; of idols who motivated me from the pages of magazines (and, as my life grew, from personal interaction). – Arnold Schwarzenegger (Ferriss, 2016)

While my accomplishments are nowhere near those of the seven-time Mr. Olympia bodybuilding champion, Hollywood action hero, and former governor of the state of California, Arnold Schwarzenegger, I too have stood and still standing on the shoulders of giants. Doing this Ph.D. project has been a fascinating, exciting, educational, and at times difficult journey. I dedicate this section to the people who have influenced, affected, and supported me throughout the past three years. Without these people, this Ph.D. project and thesis would not have existed.

First, I would like to thank my main supervisor, Associate Professor Dr. Ole Broberg, for being an exceptional mentor, instructor, guide, and friend. I appreciate the trust, respect, and compassion you have shown me over the past three years. Thank you for giving me the freedom to explore, learn, and fail on my own and for always being there when I needed support and guidance to get back on track. Also, I would like to thank Dr. Carolina Souza da Conceição, who was my co-supervisor for the first two years, for providing constructive feedback on the research activities related to the project.

I would also like to thank Professor Dr. Anja Maier and the rest of my colleagues at the Engineering Systems Design group at DTU Management for making these past three years enjoyable, fun, and unforgettable. A special thanks to Associate Professor Dr. Josef Oehmen and Dr. Pelle Lundquist Willumsen for including me in the Brightline project and inviting me to the MITsdm Conference in Boston, MA. Also, I would like to thank my co-authors and the companies that opened their doors and allowed me to conduct case studies and collect the essential empirical data I used in my research. Thanks to Associate Professor Dr. Cecilia Berlin, Professor Dr. Aasa Fast-Berglund, and Dan Li at the Chalmers University of Technology for accomodating me as an external researcher and showing exceptional hospitality.

Last but not least, I would like to thank my friends and family. I want to thank my beautiful wife, Mivan, for supporting my choice of coming back to DTU and pursuing a Ph.D. and for always being there, encouraging, and pushing me to continue and get things done. A very special thanks to my siblings and the best parents in the world. Without mom and dad, none of my accomplishments would be possible. Thank you for your love, trust, and support. Thank you for always believing in me and inspiring me to become the best version of myself.

Kgs. Lyngby, September 2020

Bzhwen A Kadir

Summary

The idea of a fourth industrial revolution and concept of Industry 4.0 presents a vision of highly digitalized and automated smart factories. This vision estimates that the future factories will mostly consist of interconnected Cyber-Physical Systems, which are systems that seamlessly connect and integrate virtual and physical components, thus, blurring the line between cyber and physical space. While such smart factories, for the most part, are still a vision, many industrial companies have begun their journey towards Industry 4.0. These companies are exploring, introducing, and working with new digital technologies such as Autonomous and collaborative robots, Automated Guided Vehicles, Augmented and Virtual Reality devices, and Big Data and Analytics. These novelties are creating new challenges and presenting new opportunities in the sociotechnical systems of industrial companies, and ultimately affecting human well-being and overall system performance.

This Ph.D. thesis applies a sociotechnical perspective to investigate the design of Industrial work systems in the transition to Industry 4.0 and how the introduction of new digital technologies affect human well-being and overall system performance. The thesis is a collection of four academic papers (three journal articles and one conference paper), which aim at answering the main research question of this thesis, which is "How to align humans, technology, and organization to ensure human well-being and system performance in industrial work systems in the transition to industry 4.0?". This main research question is dissected into four supplementing research questions, which are answered in the four pertaining papers. The empirical data used in these papers are from ten explorative, retrospective case studies conducted at ten industrial companies located in Denmark.

The first paper consists of a systematic literature review aiming at investigating research publications at the intersection between Industry 4.0 and Human Factors and Ergonomics (HF/E). The findings from this paper suggest that research at this intersection is minimal and that the majority of the publications are from non-HF/E outlets. This paper highlights that around 50% of the publications base their research on estimations and theories, rather than empirical data. This minimal empirical focus can limit the development of usable prescriptive actions and practices to ensure human well-being and system performance. Thus, this paper suggests that future research should focus on and include descriptive empirical data and increased collaboration between academia and industry.

Accommodating the call for further empirically-driven research presented in the first paper, the second paper presents empirical data on how the introduction of new digital technologies might affect perceived human well-being and overall system performance before, during, and after implementation. Based on these results, this paper presents factors that might impact human well-being and overall system performance as well as several implications and recommendations for practitioners on how to ensure human well-being and system performance before, during, and after the implementation of new digital technologies.

The third and fourth papers focus on work system design. Each paper presents a framework dealing with aspects of the design of industrial work systems in the transition to Industry 4.0. The third paper presents a conceptual framework for approaching work system (re)design projects, and the fourth paper presents a validated framework for Human-Centered Design of work system in connection to the introduction of new digital technologies and solutions. The framework from the third paper combines HF/E with Lean- and Design methods, while the framework from the fourth paper combines HF/E, work system modeling, and strategy design. The combined application of these frameworks can assist in ensuring human well-being and overall system performance in industrial work systems in the transition to Industry 4.0.

Thus, the contribution of this thesis is two-fold. On the one hand, it contributes to theory and research by quantifying a research gap, making recommendations for future research, and presenting descriptive data and conceptual models at the intersection of Industry 4.0 and HF/E. On the other hand, it makes contributions to practice by highlighting implications, making recommendations, and presenting prescriptive guidelines for designing work systems and assisting in ensuring human well-being and overall system performance in the transition to Industry 4.0.

Resumé (Dansk)

Idéen om en fjerde industriel revolution og konceptet for Industry 4.0 præsenterer en vision om højt digitaliserede og automatiserede smarte fabrikker. Denne vision estimerer, at de fremtidige fabrikker for det meste vil bestå af sammenkoblede Cyber-Fysiske Systemer, som er systemer, der forbinder og integrerer virtuelle og fysiske komponenter og dermed slører linjen mellem den virtuelle og fysiske verden. På trods af at sådanne 'smarte' fabrikker primært er en vision, har mange industrielle virksomheder påbegyndt deres rejse mod Industry 4.0. Disse virksomheder udforsker, introducerer og arbejder med nye digitale teknologier såsom autonome og samarbejdende robotter, førerløse køretøjer, augmenteret og virtual reality-enheder samt Big Data Analytics. Disse ny digitale teknologier skaber nye udfordringer og repræsenterer nye muligheder i industrielle virksomheders socio-tekniske systemer, som i sidste ende kan påvirke både menneskelige faktorer og system performance.

Denne ph.d. afhandlingen anvender et socio-teknisk perspektiv til at undersøge designet af industrielle arbejdssystemer i overgangen til Industry 4.0 og hvordan introduktionen af nye digitale teknologier påvirker menneskelig velvære og den samlede system performance. Afhandlingen er en samling af fire akademiske artikler (tre tidsskriftartikler og en konferenceartikel), der sigter mod at besvare det primære forskningsspørgsmål i denne afhandling, som er "hvordan tilpasser man mennesker, teknologi og organisation for at sikre menneskelig velvære og system performance i industrielle arbejdssystemer i overgangen til industri 4.0?". Det primære forskningsspørgsmål er opdelt i fire forskningsspørgsmål, som besvares i de fire inkluderede artikler. De empiriske data, der er brugt i artiklerne, er indsamlet i gennem ti eksplorative, retrospektive casestudier udført hos ti industrielle virksomheder i Danmark.

Den første artikel består af et systematisk litteraturstudie, der sigter mod at undersøge publikationer i området mellem Industry 4.0 og Human Factors and Ergonomics (HF/E). Resultaterne fra denne artikel antyder, at forskningen indenfor dette område er minimal, og at størstedelen af publikationerne kommer fra ikke-HF/E tidsskrifter og konferencer. Denne artikel fremhæver, at omkring 50% af publikationerne baserer deres forskning på skøn og teorier frem for empiriske data. Det meget begrænsede fokus på empirisk baseret forskning kan begrænse udviklingen af praksisnær forskning og præskriptiv praksis som kan sikre menneskelig velvære og systemets performance. På baggrund af forskningsresultaterne anbefaler forfatterene at fremtidig forskning skal fokusere på deskriptive empiriske studier og øget samarbejde mellem den akademiske verden og industri.

Den anden artikel præsenterer empiriske data om, hvordan introduktionen af nye digitale teknologier kan påvirke den menneskelige velbefindende og den samlede systemydelse før, under og efter implementeringen. Baseret på disse resultater præsenterer denne artikel faktorer, der kan påvirke menneskelige faktorer i arbejdssytemer og den samlede system performance. Forskningsresultaterne viser adskillige implikationer og anbefalinger til udøvende praktikere om, hvordan man kan sikre menneskelig trivsel og systemets performance både under og efter implementeringen af nye digitale teknologier.

Tredje og fjerde artikel fokuserer begge på selve designet af arbejdssystemer. Hver artikel præsenterer et framework, der adresserer forskellige aspekter af designet af arbejdssystemer i overgangen til Industri 4.0. Den tredje artikel præsenterer et konceptuelt framework til hvordan man kan gribe arbejdssystem (re)designprojekter an, og den fjerde artikel præsenterer et valideret framework for Human-Centered Design af arbejdssystemer i forbindelse med introduktion af nye digitale teknologier. Frameworket fra den tredje artikel kombinerer HF/E med

Lean- og Design-metoder, mens frameworket fra det fjerde papir kombinerer HF/E, modellering af arbejdssystemer og strategidesign. Den kombinerede anvendelse af disse frameworks kan hjælpe med at sikre menneskelig velvære og system performance i industrielle arbejdssystemer i overgangen til Industry 4.0.

Det forskningsmæssige bidrag fra denne afhandling er todelt. 1. Afhandlingen bidrager til teori og forskning ved kvantitativt at beskrive mangler inden for forskningsfeltet, fremsætte anbefalinger til fremtidig forskning og præsentere deskriptive data og konceptuelle modeller i området mellem Industry 4.0 og HF/E. 2. afhandlingen yder et bidrag til praksis ved at fremhæve implikationer, komme med anbefalinger og præsentere præskriptive retningslinjer for design af arbejdssystemer som kan hjælpe med at sikre menneskelig velvære og generel system performance i overgangen til Industry 4.0.

Publications

Publications included in this thesis

Journal articles

Paper A Kadir, B.A., Broberg, O., Conceição, C.S. da, 2019. Current research and future perspectives on human factors and ergonomics in Industry 4.0. Comput. Ind. Eng. 137, 106004. https://doi.org/10.1016/j.cie.2019.106004

Paper B Kadir, B.A., Broberg, O., 2020. Human well-being and system performance in the transition to industry 4.0. Int. J. Ind. Ergon. 76, 102936. https://doi.org/10.1016/j.ergon.2020.102936

Paper D Kadir, B.A, Broberg, O, 2020. Human-centered design of work systems in the transition to Industry 4.0. Appl. Ergon. (In review)

Peer-reviewed articles in conference proceedings

Paper C Kadir, B.A., Broberg, O., da Conceição Carolina, S., Jensen, N.G., 2019. A Framework for Designing Work Systems in Industry 4.0. Proc. Des. Soc. Int. Conf. Eng. Des. 1, 2031–2040. https://doi.org/10.1017/dsi.2019.209

Other publications, appended in this thesis

Peer-reviewed articles and extended abstracts in conference proceedings

Appendix A Kadir, B.A., Broberg, O., Souza da Conceição, C., 2018. Designing human-robot collaborations in Industry 4.0: Explorative case studies, in: International Design Conference. Design society, Dubrovnik, Croatia, pp. 601–610. https://doi.org/10.21278/idc.2018.0319

Appendix B Kadir, B.A., Broberg, O., da Conceição, S., 2019. A framework for aligning human, technology and organisation in Industry 4.0, in: Broberg, O., Seim, R. (Eds.), Proceedings of the 50th Nordic Ergonomics and Human Factors Society Conference. DTU Management, Technical University of Denmark, Denmark, Elsinore, Denmark, pp. 317–320

Appendix C Kadir, B.A., Broberg, O., 2019. Approaches for operationalizing digitalization strategies, in: Proceedings of the Society for Risk Analysis Nordic Conference. Copenhagen, p. 63.

Web publications

Appendix D Kadir, B.A., 2020. Digital transformation: Tilpasning af strategi, forretningsmodel, og organisation [Digital transformation – Aligning strategy, business model and organization]. SMV Guiden. URL https://smvguiden.dk/forretningskoncept/digital-transformation-tilpasning-af-strategi-forretningsmodel-og-organisation/

Appendix E Kadir, B.A., 2018. The six aspects of work in Industry 4.0. LinkedIn. URL https://www.linkedin.com/pulse/six-elements-work-industry-40-bzhwen-a-kadir/?published=t

Other publications, NOT appended in this thesis

Peer-reviewed posters at conferences

Willumsen, P.L., Kadir, B.A., Oehmen, J., 2018. How do you create buy-in in strategy implementation ?, in: MIT System Design & Management Symposium. Cambridge, MA, United States.

Willumsen, P.L., Kadir, B.A., Oehmen, J., 2018. What is the uncertainty profile of your strategy? - Sources of uncertainty in strategy implementation, in: MIT System Design & Management Symposium. Cambridge, MA, United States.

Web publications

Oehmen, J., Willumsen, P., Willumsen, P.L., Kadir, B.A., Andersen, T.J., 2018. Uncertainties and risks of strategy implementation-and-risks-of-strategy-implementation. LSE Business Review. URL https://blogs.lse.ac.uk/businessreview/2018/10/11/uncertainties-and-risks-of-strategy-implementation/

"The factory of the future will have only two employees, a man, and a dog.
The man will be there to feed the dog.
The dog will be there to keep the man from touching the equipment."

Warren Bennis

Content

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List of acronyms and abbreviations

AGV: Automated Guided Vehicles
AM: Additive Manufacturing
AR: Augmented Reality

BSC: Balanced Scorecard

Cobot: Collaborative Robot
CPS: Cyber-Physical Systems
CTA: Critical Task Analysis
CWA: Critical Work Analysis

DESI: Digital Economy and Society Index
DRM: Design Research Methodology
DS-I: Descriptive Study I
DS-II: Descriptive Study II

EU: European Union

HCD: Human-Centered Design
HF/E: Human Factors and Ergonomics
HitL: Human in the Loop
HitM: Human in the Mesh
HTA: Hierarchical Task Analysis

IEA: International Ergonomics Association
ILO: International Labour Organization
IIoT: Industrial Internet of Things
IoT: Internet of Things
IT: Information Technology

MVP: Minimum Viable Product
MVS: Minimum Viable Solution

NDA: Non-Disclosure Agreement

PDCA: Plan, Do, Check, Act
PS: Prescriptive Study

RC: Research Clarification
RQ: Research question

SME: Small and medium-sized enterprises
SOFT: Space, Organization, Finance, Technology
SOP: Standard Operating Procedure

VR: Virtual Reality

Reader’s guide

The purpose of the following section is to introduce the reader to the structure of this Ph.D. thesis and provide a brief reader’s guide. This thesis is not a monograph but a collection of articles consisting of three peer-reviewed journal articles (two published and one in revision) and one accepted peer-reviewed conference paper. This thesis includes the post-print (accepted papers) and the pre-print manuscripts (paper in review). It is also important to mention that each of the papers includes an elaborate discussion section. Thus to avoid repetition, the final discussion of this thesis focuses on highlighting the specific contributions and answering the main and supplementing research questions of the thesis. Lastly, where it is relevant, at the end of some sections and subsections, there is a blue-colored box with a brief summary.

Chapter 1: This chapter introduces the reader to the Ph.D. project and thesis. This introduction includes the motivation and aim, the research objectives, and the main and supplementing research questions. Also, this section provides an overview of the achieved results and contributions of all of the four papers, as well as an outline of the thesis.

Chapter 2: This chapter describes the theoretical background of Industry 4.0 (including the transition to- and human labor and work in Industry 4.0), Human Factors and Ergonomics, and work system design. Knowing the theoretical background is essential in getting a comprehensive understanding of the concepts explored and explained in the included papers.

Chapter 3: This chapter describes the overall methodology of the Ph.D. project, and the pertaining applied approaches and methods. The structure of this chapter follows the concept of the research “onion,” which covers research philosophy, research approach, overall research design, methodological choices, research strategy, time horizon, and applied research methods. However, this chapter does not include the description of the applied methods for data analysis, as I describe these methods in the included papers in Chapters 4, 5, and 6.

Chapter 4: This chapter is based on Paper A, which includes a systematic literature review that investigates to what extent, what type of and how academic publications on Industry 4.0 integrate HF/E in their research.

Chapter 5: This chapter is based on Paper B and includes empirical data on how the introduction of new digital technologies affect perceived human well-being and system performance in the transition to industry 4.0.

Chapter 6: This chapter includes Papers C and D and presents two different frameworks for the (re)design of work systems in the transition to Industry 4.0. The framework presented in Paper C aims at providing a general approach for work system (re)design projects, while the framework in Paper D proposes a comprehensive approach for (re)designing the work systems.

Chapters 7 and 8: Chapter 7 discusses the thesis’ contribution to research and practice, as well as providing explicit answers to the proposed research questions. This chapter also includes a discussion of the limitations, suggestions for further research, and the author’s reflection. Chapter 8 gives a summary of the thesis and provides concluding remarks.

1. Introduction

This chapter focuses on introducing the reader to the topic of the Ph.D. thesis. I begin with an explanation of the motivation and aim of the thesis and move on to describe the research objectives and the guiding research questions. Hereafter, I provide a short overview of the achieved results of the thesis. Lastly, I will present and describe the outline of the thesis and the remaining chapters.

1.1 Motivation and aim

In April 2013, as part of a joint initiative between the German government, academics, and industry, the German Academy of Science and Engineering (Acatech) published the report, “Recommendation for implementing the strategic initiative INDUSTRIE 4.0,” which was the final report of the “Industrie 4.0 Working Group”, established in connection with this joint initiative. This report presented a strategic vision for how Germany could strengthen its current competitiveness in the manufacturing equipment sector to ensure a future position as a global leader (Kagermann et al., 2013). Since the publication of this report, the term and concept of Industry 4.0 (translation of the German term “Industrie”), and the idea of a fourth industrial revolution has become increasingly popular in both industry and academia. Since the year 2013, countries such as the United States, France, United Kingdom, Japan, and China have also started similar strategic initiatives (Liao et al., 2017).

The main driver behind the concept of Industry 4.0 is the application of new digital technologies and capabilities. Already in the year 2013, Kagermann et al. (2013) estimated that the changes introduced in connection with Industry 4.0 would radically affect and transform the environment, organization, work content, and processes in the factories of the future. Kagermann et al. (2013) suggested that these emerging changes might result in more interesting work environments, more significant job enrichment, and increased autonomy of the workers, thus having a positive effect on the workers’ well-being. However, up until the start of this Ph.D. project (September 2017), there was still no common understanding of the human workers’ role in Industry 4.0 or how their work would change as the concept evolves and technological capabilities increase (Nelles et al., 2016).

L. Wang et al. (2015) argued that the majority of industrial companies would find themselves in unknown territory as they begin facing challenges related to the implementation of new technologies and the complexities involved when physical and virtual elements overlap and cooperate within the same work systems. Other academic publications such as Becker & Stern (2016), Roblek et al. (2016), Romero, Stahre, et al. (2016), Zhong & Nof (2015) had echoed this notion. These publications argued and estimated that the introduction of new digital technologies would present changes on technical, organizational, and individual levels across the different organizational layers of industrial companies.

To deal with the challenges and capitalize on the opportunities emerging as a consequence of these changes, publications such as Pacaux-Lemoine et al. (2017), Romero, Stahre, et al. (2016), Stern & Becker (2017) argued that there is a need for new human-centric engineering and design philosophies and methods. However, because of the novelty of the Industry 4.0 concept, the academic literature on the implementation of Industry 4.0-enabling technologies with particular focus on design-principles and factors related to human work seemed minimal (Hermann et al., 2016).

These practical implications and academic research gaps became the trigger for initiating this Ph.D. project. Thus, the motivation and aim of this Ph.D. were to make a positive contribution by addressing the limited academic research on the topic and constituting implications for practitioners on how to overcome organizational- and human-related challenges. Indeed, I wanted to take part in ensuring that industrial companies would avoid the pitfalls of the third industrial revolution in the 1970s, where machine-centered engineers had a bias towards automation, which in many cases lead to adverse effects on the workers' well-being (Kleiner, 2006).

Motivation and aim

Make a positive contribution to the limited academic research on the topic and constitute implications for practitioners on how to overcome organizational- and human-related challenges in their journey towards Industry 4.0.

1.2 Research objectives

The objective of this Ph.D. project became twofold. On the one hand, I wanted to investigate emerging challenges and opportunities related to human work and work organization in connection with the introduction and implementation of new digital technologies in industrial work systems. On the other hand, I wanted to use the results from this investigation to develop prescriptive frameworks and guidelines to assist industrial companies in ensuring human well-being and system performance in the (re)design of their work system in connection with the implementation of new digital technologies in their transition to Industry 4.0. The focus on human well-being and system performance in industry 4.0-enabled work systems scopes and places this Ph.D. project in the intersection between the research fields of Human Factors and Ergonomics (HF/E), Work System Design, and Industry 4.0. Figure 1 depicts the scope of this Ph.D. project.

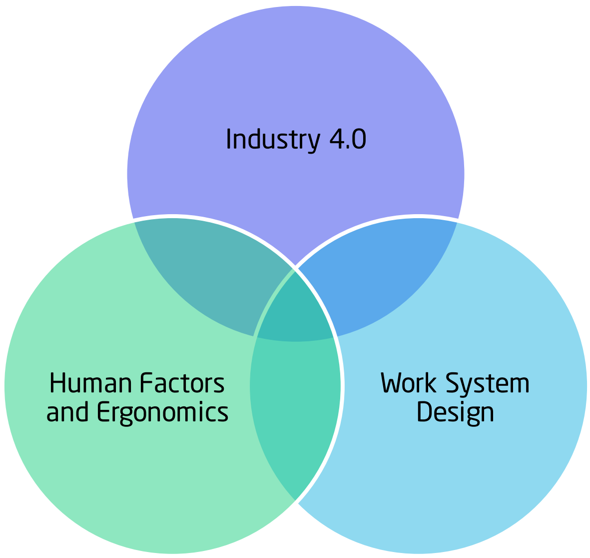

Figure 1 – The scoping of this thesis.

Achieving the research objectives required several supporting objectives that could assist with the development and formulation of the Ph.D. thesis' guiding research questions. These supporting objectives were:

- Establish an overview and baseline of the current knowledge and understanding of HF/E in the context of Industry 4.0.
- Collect empirical evidence to understand and document how industrial companies are dealing with the HF/E-related challenges and opportunities emerging in the introduction of Industry 4.0-enabled technologies and solutions.
- Use the collected empirical data to develop prescriptive guidelines and frameworks for how industrial companies can overcome HF/E related challenges in the (re)design of industrial work systems in connection to the introduction of new digital technologies.

Research objectives

1. Investigate HF/E-related challenges and opportunities in connection with the implementation of new digital technologies in industrial work systems.
2. Develop guidelines to assist in ensuring human well-being and system performance in the (re)design of work systems in connection with the implementation of new digital technologies in transition to Industry 4.0.

1.3 Research questions

To achieve the research objectives, it was essential to formulate a cohesive main research question (RQ1) that could encapsulate the underlying challenges of the topic. Thus the main research question of this Ph.D. thesis is

Main Research Question

RQ1: How to align humans, technology, and organization to ensure human well-being and system performance in industrial work systems in the transition to industry 4.0?

In addition to this main research question, I also formulated four supplementing research questions (RQ2 – RQ5). These four supplementing research questions are a dissection of RQ1, and each one deals with a different underlying aspect of RQ1. By answering these supplementing research questions, I was able to address and answer RQ1 adequately. The four supplementing research questions are

Supplementing Research Questions

RQ2: To what extent, what type of and how do academic publications on Industry 4.0 integrate HF/E in their research?

RQ3: How is the introduction of new digital technologies affecting human well-being and system performance in industrial companies?

RQ4: How might industrial companies ensure human well-being and system performance in connection to the implementation of new digital technologies?

RQ5: How should industrial companies approach the (re)design of work systems in connection with the implementation of new digital technologies

The purpose of RQ2 is to establish an understanding and a baseline of the currently available literature in the intersection between HF/E and Industry 4.0. By conducting a detailed literature review, it is possible to quantify the research gap and get qualitative descriptions of the different aspects of the topic. Such quantitative and qualitative data serve as the foundation for answering the remaining research questions. RQ3 focuses on investigating and providing descriptive data on how the introduction of new digital technologies affect human well-being and system performance in industrial companies. Such descriptive data are essential in answering the remaining research questions. Indeed, without descriptive data on the current situation, it will be challenging to provide prescriptive actions and recommendations and answering RQ1, RQ4, and RQ5. Lastly, RQ4 and RQ5 aim to build on the answers of RQ2 and RQ3 to understand how industrial companies might approach the introduction of new digital technologies and the (re)design of work systems in their transition to Industry 4.0. Figure 2 shows the connection between the research questions and the papers included in this Ph.D. thesis.

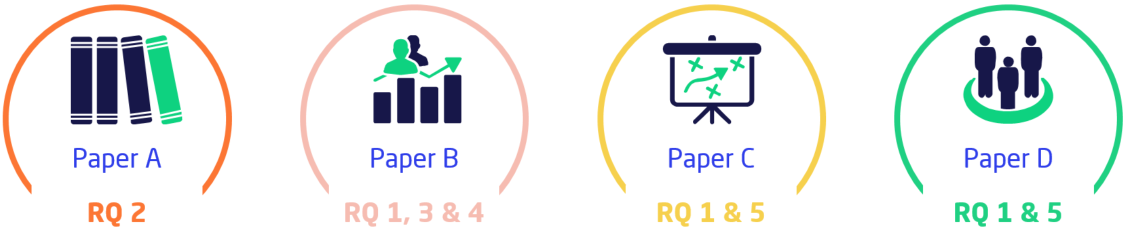

Figure 2 – The connection between the research questions and the papers included in this Ph.D. thesis.

1.4 Achieved results and contribution

This thesis has led to several academic and industrial contributions. In this subsection, I present an overview of the achieved results and contributions of these papers. Each paper had a specific purpose, achieved results, and contributions. Also, to a certain extent, the papers build on another, making the order of the papers highly relevant.

Paper A

Paper A serves as the foundation of this thesis, in that it presents an overview of the current landscape of academic research in the intersection between Industry 4.0 and HF/E. This paper includes an elaborative systematic literature study that aims at answering RQ2.

Achieved results

- The extent of Industry 4.0 research dealing with HF/E is minimal.
- Industry 4.0 research covers HF/E aspects much more compared to research within the HF/E discipline.
- The current research dealing with HF/E aspects is mostly theoretical/hypothetical and uses and incorporates minimal empirical research as a foundation.
- Most of the current research overlooks the importance of tactical and strategic organizational levels for the success of HF/E and mostly focuses on the operational level.

Contribution

- Establishing to what extent, what type of, and how academic publications on Industry 4.0 integrate HF/E into their research.
- Quantifying and highlighting research gaps and identifying areas of focus for future research on HF/E in Industry 4.0.

Paper B

Paper B presents empirical data on how Industry 4.0-enabling technologies affect perceived human well-being and overall system performance before, during, and after implementation, which aims at answering RQ3. Also, the paper includes implications and recommendations for practitioners on how to ensure human well-being and system performance throughout the three different phases of before, during, and after. This part of the paper aims at answering RQ4 and parts of RQ1.

Achieved results

- Understanding how new digital technologies might affect perceived human well-being and overall system performance before, during, and after implementation.
- During the implementation of new digital solutions, both perceived human well-being and overall system performance might be negatively affected.
- After a successful implementation, both perceived human well-being and overall system performance can improve.
- Identification of factors affecting perceived human well-being and overall system performance before, during, and after the implementation of new digital technologies.

Contribution

- Empirical evidence on how perceived human well-being and overall system performance change before, during, and after the implementation of new digital technologies.
- Implications for practitioners and recommendations for how to ensure human well-being and overall system performance in connection with the introduction of new digital technologies in the transition to Industry 4.0.

Paper C

Paper C presents a conceptual framework for approaching projects focusing on the (re)design of work systems and the development of new digital solutions in the transition to Industry 4.0, which aims at addressing and answering parts of RQ1 and RQ5.

Achieved results

- A framework that combines HF/E, Design- and Lean thinking for approaching work system (re)design projects on an operational, organizational layer.
- Illustrating the different aspects of the framework with examples from an industrial case study.

Contribution

- A general conceptual approach for how industrial companies might approach the (re)design of work systems in connection with the implementation of new digital technologies.
- A prescriptive tool, which practitioners can use in the process of (re)designing work systems in connection with the introduction of new digital technologies.
- An analytical tool for academics to apply when analyzing and trying to understand the (re)design process of a work system.

Paper D

While Paper C focuses on the overall method for approaching the (re)design of work systems in connection to the implementation of new digital technologies and development of new digital solutions, Paper D proposes a validated framework for Human-Centered Design (HCD) of work systems in the transition to Industry 4.0. The framework consists of seven steps, with each step having a specific purpose and objective. Paper D aims at answering parts of RQ1 and RQ5.

Achieved results

- Understanding of challenges related to the implementation of new digital technologies.
- A framework that combines HF/E, work system modeling, and strategy design for (re)designing industrial work systems in connection with the introduction of new digital technologies.
- Validation of the proposed framework through a prospective industrial case study.

Contribution

- Empirical data on implementation challenges of new digital technologies.
- A practical Human-Centered approach industrial companies can apply to (re)design work systems in connections with the introduction of new digital technologies.
- An analytical tool, which academics can use to analyze and understand how a newly developed industry 4.0-related concept and solution might affect the overall system performance and well-being of the humans working in the work systems.

1.5 Thesis outline

The outline and organization of the rest of this thesis are as follows: In Chapter 2, I will present the theoretical background of this thesis, i.e., Industry 4.0, HF/E, and work system design.

In Section 2.1, I will cover the topic of industry 4.0, which includes the origins and vision of Industry 4.0 (Section 2.1.1), the journey from Industry 1.0 – 4.0 (Section 2.1.2), the technological pillars of- (Section 2.1.3), the transition to- (Section 2.1.4), and human labor and work in Industry 4.0 (Section 2.1.5).

In section 2.2, I will cover the topic of HF/E, including its definition and application (Section 2.2.1), the three main domains of HF/E specialization (Section 2.2.2), and the primary purpose of HF/E, which is human well-being and system performance (Section 2.2.3).

Lastly, in Section 2.3, I will describe the definition of a work system and work system elements (Section 2.3.1), as well as the design of work systems (Section 2.3.2).

In Chapter 3, I will present the overall methodology of the Ph.D. project and the pertaining methodological considerations and decisions. Thus, Chapter 3 covers the applied research philosophy (Section 3.1), the research approach (Section 3.2), research design, as well as the applied research methods (Section 3.4).

Hereafter, Chapter 4, 5, and 6 will focus on presenting the research papers included in this thesis and provide answers to the research questions presented in Section 1.3. Chapter 4 includes Paper A and provides answers to RQ2. Chapter 5 includes Paper B and provides answers to RQ3 and RQ4 as well as parts of RQ1. Finally, Chapter 6 includes both Paper C and D and strives to answer RQ5 and parts of RQ1. These three chapters all start with a brief introduction, including a summary of the included papers, achieved results, and contributions.

In Section 4, I will provide an overall discussion and describe the contributions to literature and theory (Section 7.1.1), and practice (Section 7.1.2), provide explicit answers to the proposed supplementing research questions (Section 7.2) as well as the main research question (Section 7.3). In addition, I will discuss the limitations of this Ph.D. project in Section 7.4, present reflections on the overall Ph.D. project in Section 7.6, and make suggestions for further research in Section 7.5.

2. Theoretical background

As mentioned in Section 1.2 and shown in Figure 1, the scope of this Ph.D. falls within the intersection between three different topics, Industry 4.0, Human Factors and Ergonomics, and Work System Design. To ensure a cohesive understanding of the thesis content and results, the reader must get the basic knowledge about these three topics. Thus, this section focuses on presenting the theoretical background of Industry 4.0, Human Factors and Ergonomics, and Work System Design.

2.1 The fourth industrial revolution – Industry 4.0

This subsection will give the reader an overview of the theoretical background of the term and concept of Industry 4.0, which include the origins and definition of the term, historical context, technological pillars, current perspectives, and human labor and wok in Industry 4.0.

2.1.1 The origin and vision of Industry 4.0

The first use of the term "Industry 4.0" (or in its original German form, Industrie 4.0) was at the Hannover Fair in the year 2011, where a group of German industry, academic and governmental representatives used the term in connection with a presentation on a German manufacturing-related initiative. This initiative aimed at improving the German manufacturing sector's competitiveness through investments in new digital technologies and solutions (Kagermann et al., 2011; Vogel-Heuser & Hess, 2016). This same group would in two years, go on and publish the famous "Final report of the Industrie 4.0 working group" (Kagermann et al., 2013), which describes the concept of Industry 4.0 as well as a vision and recommendation for the future of the German manufacturing sector.

Kagermann et al. (2013) characterize the vision for Industry 4.0 by new levels of sociotechnical interactions between interconnected networks, manufacturing actors, and resources (e.g., machines, IT-systems, and facilities). This new level of interaction is driven by real-time data, which grants each resource the capability to control and make autonomous decisions independent of each other, thus creating highly digitalized smart factories. The concept of Industry 4.0 and smart factories are triggered by changes in the general social, economic, and political landscape, as well as an increasing technology push in industrial practices. With the increasing capabilities of digital technologies, Industry 4.0 is promising potential benefits such as shorter development time, flexibility, individualization on-demand, and improved resource utilization (Lasi et al., 2014).

2.1.2 From Industry 1.0 to Industry 4.0

The term Industry 4.0 indicates that the industrial sector has been through four industrial revolutions. Naturally, upon hearing about the term and concept, the first logical question most will ask is, "what were the other three Industries?" Using Kagermann et al. (2013) as a basis, in the following subsections, I will give an overview and shortly describe the journey from Industry 1.0 to 4.0. However, to get a comprehensive understanding, I believe that it is essential to clarify the meaning of the term "revolution," and more importantly, "industrial revolution."

While the term "revolution" has several different meanings, in a context relevant to Industry 4.0, I want to highlight the definition by The Oxford Learner's Dictionaries. A revolution is *a great change in conditions, ways of working, beliefs, etc. that affects large numbers of people* – (Oxford Learner's Dictionaries, 2020).

Regarding the term "industrial revolution," I believe that the online dictionary, Merriam-Webster, provides an excellent definition. This definition of an industrial revolution is

a rapid major change in an economy (as in England in the late 18th century) marked by the general introduction of power-driven machinery or by an important change in the prevailing types and methods of use of such machines. – (Merriam-Webster, 2020).

Refer to Figure 3 for an illustration showing an overview of the four industrial revolutions.

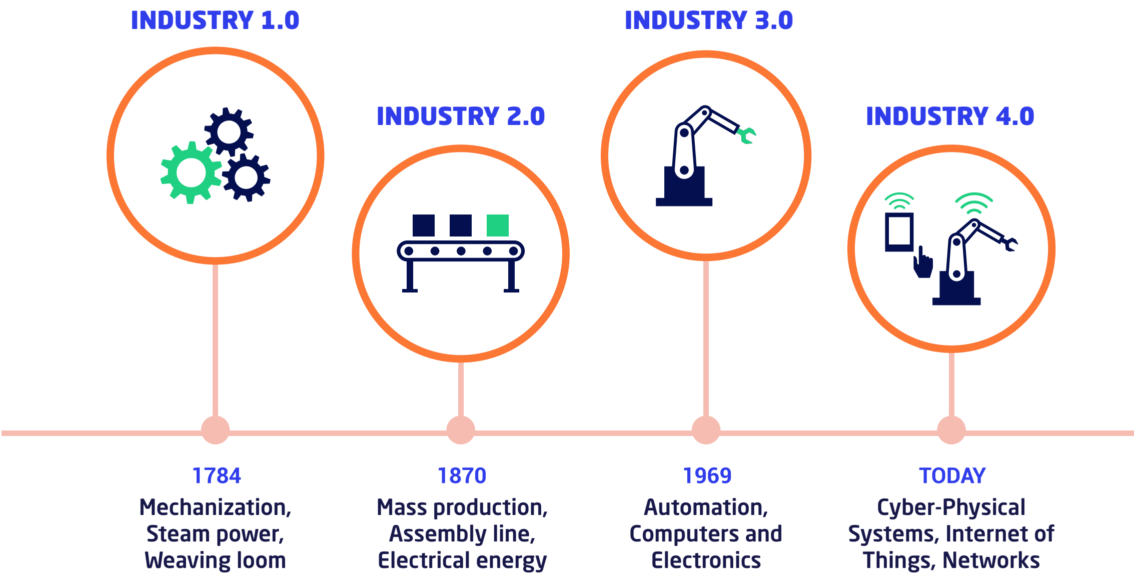

Figure 3 – From Industry 1.0 to 4.0

Industry 1.0 refers to the first industrial revolution (or the British Industrial Revolution), which happened around the end of the 18th century, leading to the creation of the first mechanical manufacturing facilities. The main characteristic of this revolution was technological innovations (e.g., the steam engine, weaving machines (the spinning jenny and water frame (Britannica, 2020a, 2020b)), and coke smelting), which had a lifespan of a century and a half before reaching the industrial revolution's natural limits (Allen, 2009).

The second industrial revolution was from the turn of the 20th century to the 1970s and began with the introduction of the first production and assembly lines, and mass production processes driven by electricity and division of labor. This era reached a significant milestone with the publication of Fredrick Taylor's monograph, *The Principles of Scientific Management*, which Henry Ford (Founder of the Ford Motor Company) and Taiichi Ohno (Creator of the Toyota Production System) greatly practiced, further developed, and extended (Y. Yin et al., 2018).

The third industrial revolution began around the 1970s, which has since evolved and is still continuing in the present day. The main characteristic of Industry 3.0 is the usage of electronics and Information Technologies (IT) to transform from analog to digital and to enable and attain further automation of manufacturing processes. Some of the main drivers of Industry 3.0 have been computers and the internet, industrial robots, biotechnology, and the progression of the Toyota Production System to Lean production, which most industrial companies have adopted to some extent (Taalbi, 2019; Y. Yin et al., 2018). Since the beginning of the third industrial revolution, digital capabilities have been continuously evolving and improving. Noticeable improvements and exponential growth of computing power (Moore's Law (Moore, 1965)), communication speed (Butter's Law of Photonics (Baxter & Straw, 2014)), and storage capacity (Kryder's Law (Walter, 2005)) are paving the way for the fourth industrial revolution and the transition to Industry 4.0.

With the advancements made in the third industrial revolution, the industrial sector has begun transitioning into the fourth industrial revolution and the realization of the Industry 4.0 vision. At the center of Industry 4.0 is the concept of a highly digitalized smart factory, which consists of interconnected physical and virtual components that form Cyber-Physical Systems (CPS). While there are many definitions of CPS, in its core, CPS are physical and engineered systems that integrate cyberspace (e.g., IT and real-time control of subsystems) with parts of the physical world (e.g., physical components and human workers). Enabled by a computing and communication core, this integration allows monitoring, coordination, and control of the physical processes in the system's operations (Carreras Guzman et al., 2020; Rajkumar et al., 2010). Thus, CPS is changing and transforming how humans control and interact with physical system components.

The interconnectedness provided by the growing digital capability advancements are not limited just to the CPS in the smart factories. Indeed, these new digital capabilities stretch across the entire manufacturing supply chain as well as reaching aspects of society. These new digital capabilities are creating bigger systems comprising of smart- products, buildings, logistics, mobility, and power grids, which are all connected to the smart factories (Kagermann et al., 2013).

Definition of Industry 4.0

Industry 4.0 describes the fourth industrial revolution, which is transforming how industrial companies operate and use new digital technologies and capabilities to create highly digitalized and interconnected smart factories and supply chains consisting of Cyber-Physical Systems.

2.1.3 The technological pillars of Industry 4.0

While there are many different concepts and technologies related to Industry 4.0, Rüßmann et al. (2015) provide a relatively comprehensive overview of some of the most prominent technologies that are transforming industrial production and creating and enhancing CPS. Rüßmann et al. (2015) refer to these technologies as the pillars of Industry 4.0. In this subsection, I will briefly describe these technological pillars using Rüßmann et al. (2015) as a basis. Figure 4 shows an overview of these nine technological pillars.

The first pillar is Big Data and Analytics. Analytics based on Big Data sets enables companies and organizations to gain a better understanding of the environment of their operations at a more granular level. Using a continuous flow of data and analytics capabilities, companies can react promptly to changes in data patterns and reduce costs, make faster and better decisions, and create new products and services (Davenport et al., 2012; Davenport & Dyché, 2013). In the context of Industry 4.0, Big Data can originate from sources as products, production-equipment, and systems, as well as customer- and enterprise management systems (Rüßmann et al., 2015).

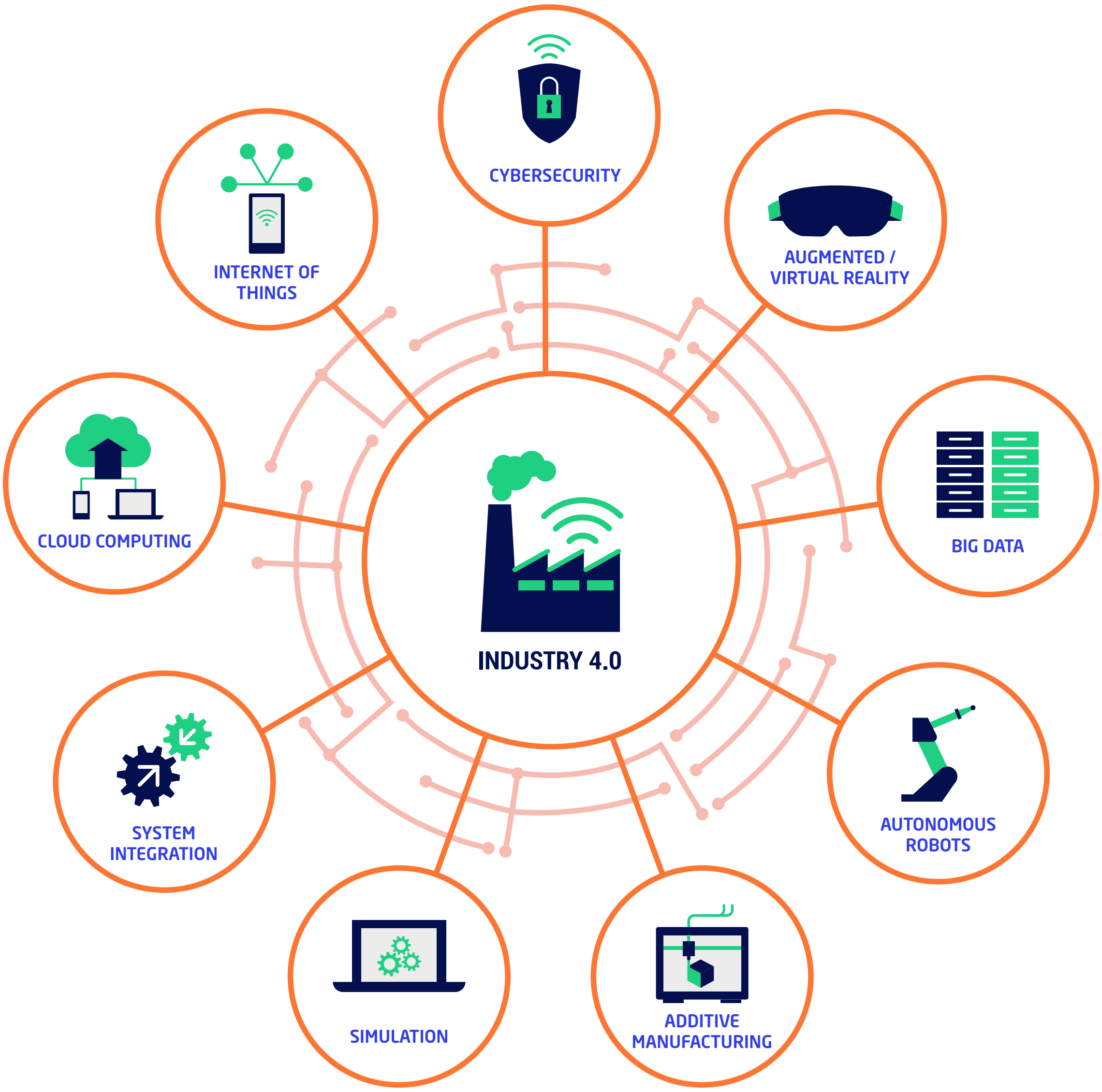

Figure 4 – Overview of the nine technological pillars of Industry 4.0

The second pillar is Simulations and Digital Twins. The availability of Big Data and Analytics, combined with continuously increasing computing power, is expanding the application of 3D simulations from the general engineering phases of products and production processes to plant operations (Grieves, 2014). The main driver of these new types of simulations is a Digital Twin (Zhang et al., 2017). A Digital Twin is an exact digital copy of a physical product, plant, or manufacturing facility that can simulate real-time system performance. A Digital Twin has three components, a physical product existing in real space, a virtual copy of this product in virtual space, and a data component that connects the real and virtual products (Grieves, 2014).

The third pillar is Autonomous Robots. The use of industrial robots is not new and has been around for several decades. Indeed, the first commercial use of industrial robots was in the early 1960s, and since the late 1970s, commercial use has rapidly increased, with a yearly sales growth exceeding 30% (Wallén, 2008). Traditionally, manufacturers have used industrial robots for tackling complex tasks and assignments. However, the advancement of technological capabilities is enabling a new generation of robots that can function autonomously, take on increasingly complex and challenging tasks, and the ability to work alongside humans or even in human-restricted workspaces (Graetz & Michaels, 2018).

The fourth pillar is horizontal and vertical System Integration. The integration of IT systems is an essential part of Industry 4.0, smart factories, and the creation of Cyber-Physical Systems (Schlechtendahl et al., 2015). However, Rüßmann et al. (2015) highlight that most of today's IT systems are not fully integrated and that there are minimal connections between companies, suppliers, and customers. The definition of horizontal and vertical integration can vary, depending on the context and the topic. In the context of Industry 4.0, vertical integration refers to the connection of internal IT systems across the different hierarchical levels of a company. Horizontal integration refers to the digitalization and connection of the various systems across a company's entire supply- and value chain. This connection aims at creating value networks between different companies and deliver end-to-end solutions (S. Wang et al., 2016).

The fifth pillar is the Internet of Things (IoT). IoT refers to the concept of networked systems consisting of interlinked physical objects and devices connected to the internet. These objects and devices include most things that are surrounding us, which we use in daily life. IoT is often portrayed as the essential technology that can lead to solving society-related challenges, e.g., the transition to smart cities, intelligent transportation, and connected healthcare (Gubbi et al., 2013). A subsection of IoT, referred to as the Industrial Internet of Things (IIoT), focuses on applying IoT capabilities for industrial purposes. IIoT is an essential premise for the concept of Industry 4.0 as it enables companies to continuously collect information from machines, sensors, products, and devices and use this information to detect failure, monitor quality, and initiate maintenance procedures (Wan et al., 2016).

The sixth pillar is Cybersecurity. While the transition to Industry 4.0 offers many benefits, it also poses an increasing concern regarding Cybersecurity. Indeed, the integration of systems and implementation of IIoT, Big Data and Analytics, and Cloud Computing increase the risk of cyber-attacks (Flatt et al., 2016; Wu et al., 2018). Corallo et al. (2020) argue that Cybersecurity and cyber-attack threats are some of the biggest challenges most companies will face in their transition to Industry 4.0. While the threat of cyber-attacks may vary, their impact on business can be severe. Business impact can include life-threatening situations for workers, theft of industrial trades and intellectual properties, safety and pollution compliance violations, denial of service to networks, and sabotage to critical infrastructure, machines, and components (Lezzi et al., 2018).

The seventh pillar is Cloud Computing. Cloud Computing refers to the sharing of IT resources and computing power over the internet. This new way of sharing resources has centralized and translocated software, platforms, and IT infrastructure from local into the cloud (Matt, 2018). The term cloud computing includes both the service of delivering applications over the internet and the system software and hardware in the centers that delivers the services (Armbrust et al., 2010). Cloud Computing services include servers, storage, databases, networking, software, analytics, and intelligence (Microsoft Azure, 2020). In the context of Industry 4.0, Cloud Computing can facilitate production and manufacturing activities across internal departments and company boundaries, thus paving the way for more collaborations, work flexibility, delivery of services, and creation of new products (Hardy, 2018; Xu et al., 2018).

The eighth pillar is Additive Manufacturing (AM). AM refers to a process, which includes 3D printing technologies that create parts by adding material. This process is different from conventional manufacturing processes such as milling and turning (creating products by removing material) or injection molding (creating products by injecting materials into a mold) (Rutkofsky & Banu, 2018). Up until now, most companies use AM mainly to prototype and produce individual parts and components (Rüßmann et al., 2015). However, as AM technologies are evolving and maturing, industrial companies are increasingly using them to transition from mass production of identical products to smaller, low-volume batches of customized and sophisticated products with advanced attributes (Dilberoglu et al., 2017; Paritala et al., 2017).

The ninth pillar is Augmented Reality (AR) and Virtual Reality (VR). AR refers to the integration of computer-generated information into the real-world environment by projecting a layer of graphical information into the user's view through devices such as tablets, smartphones, and smart-glasses (Paelke, 2014; Romero, Stahre, et al., 2016). This additional layer of information can assist workers in bridging the gap between the digital/virtual and physical environment, supporting operational tasks and decision-making (Masood & Egger, 2019). Virtual Reality (VR) is a step beyond AR. Instead of graphical layers of information projected on to the real-world environment, VR devices generate a virtual replica of a real-world environment, allowing users to interact with virtual elements and evaluate and perform activities in a virtual environment (Chryssolouris et al., 2000).

The technological pillars of Industry 4.0

The transition to Industry 4.0 is connected to the following nine digital technological concepts

1. Big Data and Analytics
2. Autonomous Robots
3. Simulation and Digital Twins
4. Horizontal and Vertical System Integration
5. The Industrial Internet of Things (IIoT)
6. Cybersecurity
7. Cloud Computing
8. Additive Manufacturing and 3D Printing
9. Augmented- and Virtual Reality

2.1.4 The transition to Industry 4.0

Since the publication of Kagermann et al. (2013), the concept of Industry 4.0 and the pertaining technological concepts have evolved. However, the majority of industrial companies have yet begun their digital transformation journey. The companies that have started this journey have yet to implement the new pertaining digital technologies and concepts entirely and are still in initial or piloting phases (KPMG, 2017; PwC, 2018; Wyck et al., 2019). Thus, while the fourth industrial revolution is underway, the industrial sector is in a transitional phase similar to the previous three industrial revolutions described in Section 2.1.2. Chien et al. (2017) propose an appropriate term for this transition, which they define as "Industry 3.5".

While the term "Industry 3.5" might be the most appropriate definition to describe the current state of the fourth industrial revolution, others are taking the rhetoric in another direction. Several publications from both academia and industry are proposing the concept of Industry 5.0. These publications include but are not limited to academic research papers, e.g., Özdemir & Hekim (2018) and industry-focused white papers, e.g., Østergaard (2018). On the one hand, Özdemir and Hekim (2018) build on the concept of Industry 4.0 and define Industry 5.0 as an incremental but necessary advancement that supports symmetrical innovation ecosystem design. On the other hand, Østergaard (2018), which is a white paper by the collaborative robot (cobot) manufacturer, Universal Robots, defines the concept of Industry 5.0 as the move from mass customization to mass personalization, which is only achievable with "the human touch."

However, it is essential to clarify that this thesis and the pertaining research questions view the current perspective on Industry 4.0 as being in a transitional phase, as proposed by Chien et al. (2017). Thus, the remaining chapters of this thesis will not include or deal with the concept of "Industry 5.0".

Current perspective on Industry 4.0

The industrial sector is currently in a transitional phase, going from Industry 3.0 to Industry 4.0. Thus, most companies have yet fully realized the full capabilities of Industry 4.0-enabling concepts and technologies.

2.1.5 Human labor and wok in Industry 4.0

European Commission (2020) ranks Denmark in third place on its Digital Economy and Society Index (DESI), which monitors Europe's overall digital performance and tracks the progress in the digital competitiveness of European Union (EU) countries. This report also highlights that even though Denmark is amongst the most well-performing countries, over the past five years, Denmark's progression has been relatively low. However, while Denmark is one of the more digitally advanced countries in the EU, the Danish industrial sector is currently in the beginning stages of the transition to Industry 4.0.

In a detailed study on Industry 4.0 in the Danish industry, Stentoft et al. (2017) highlight that in general, Danish companies are only to some extent ready or willing to work with Industry 4.0-enabling technologies and begin their transition to Industry 4.0. This study highlights that the uppermost barriers to Industry 4.0 in the Danish industry are lack of knowledge, more focus on operations than development, lack of understanding of the strategic importance, and lack of human resources. Other prominent barriers to a certain extent include continued education of employees, lack of understanding of the interplay between humans and technology, lack of qualified workforce, and lack of employee readiness.

While the Danish industrial sector might not be ready to embrace the concept of Industry 4.0 fully, Danish companies are continuously introducing new IT equipment and software, which are changing work tasks and job content. A study by the central authority on Danish statistics (Danmarks Statistik) from 2018 highlights that over 12 months, about 25% of all workers have experienced changes in their jobs, and about 50% have needed to learn using new software and IT equipment (Danmarks Statistik, 2018).

Finally, Holsbo et al. (2019) present the findings from a Danish report, focusing on how Industry 4.0-enabling technologies are affecting the work environment in the Danish industry. This report highlight that the most applied digital technologies in Danish production are automation with robots and advanced material technologies. Besides, Holsbo et al. (2019) mention that the most significant barriers regarding the utilization of digital technologies and artificial intelligence in the next 4-5 years will be the lack of the necessary skills and competences. This limitation is similar to the argument of the European Commission (2020) in regards to Denmark's staggering digital growth over the past five years.

Looking beyond Denmark, there seems to be a shared view of how the transition to Industry 4.0 will affect human work. Automation and digital technologies are increasingly replacing jobs that require a low degree of technical skills. Acemoglu & Restrepo (2020) extrapolate their results from a mathematical model based on empirical data and predict that the increase of robots in the US industrial sector will by the year 2025, result in a 0,94-1,76 percentage point lower employment to population ratio. These numbers suggest that lower employment levels will mostly affect low-skill workers in the routine manual, blue-collar, assembly, and other related occupations. Using the same dataset as Acemoglu & Restrepo (2020), Graetz & Michaels (2018) make similar estimations using data from 17 countries with developed economies.

Working in Industry 4.0 might require new competencies such as technical (e.g., IT and coding skills, and state-of-the-art knowledge), methodological (e.g., creativity, decision-making, and problem-solving), social (e.g., intercultural, communication, and leadership skills), and personal (flexibility, motivation to learn, and ability to work under pressure) (Sony, 2020). Fareri et al. (2020) argue that while technical competences will be necessary, horizontal competences, i.e., methodological, personal, and social, will become the essential competencies in Industry 4.0.

These new requirements are already becoming barriers to entry for many organizations. Indeed, in an industrial survey from 2020, Deloitte (2020) report that 80% of executives (respondents) do not believe that their organization is currently ready for a transition to Industry 4.0, and only 10% think that they are making significant progress in identifying, attracting, and retaining the essential talents. Besides, the findings for this report suggest that 60% of executives have yet to understand the skills needed for Industry 4.0. However, for many organizations, training, and development of employees have become top priorities. Deloitte (2020) highlights that 80% of the executives have developed or are currently developing corporate cultures focusing on lifelong learnings and an additional 17% mentioning that they have plans to do so in the near future. Thus, it is evident that the transition to Industry 4.0 is creating profound changes in jobs, work tasks, organization, and the necessary competencies required of human workers.

Change in human labor is not new. Throughout history, human labor has continuously developed, and humans have used technical progress to limit the amount of physical labor in their daily life. Cordes (2009) presents a taxonomy to analyze the long-term development in human labor, which divides human labor into "physical work" and "mental work." Refer to Figure 5 for an illustration of this taxonomy. Cordes (2009) explains that before gaining the ability to use non-human energy sources, humans relied on using mechanical work. However, as humans started developing technological creativity, the nature of their work and labor demand and characteristics started changing. To explain these changes, Cordes (2009) presents the following three propositions.

Proposition 1: Upskilling, deskilling, or polarization of workforce in economic developments depend on the possibilities of using non-human energy sources, and the attained technical knowledge about the transferability of certain types of labor to artificial devices.

Proposition 2: The possibility of easing or replacing certain types of human labor with mechanical and electronic devices enabled a multiplication and acceleration of tasks formerly executed by humans. This development resulted in productivity gains, which enabled population growth and/or periods of robust economic advancement.

Proposition 3: Novel production knowledge enabled the delivery of the same output in a reduced time, thus freeing additional spare human time and effort. Humans could use this extra time for the systematic search and application of further innovations in energy uses, tools, and appliances, which again increased the productivity and shortened working times.

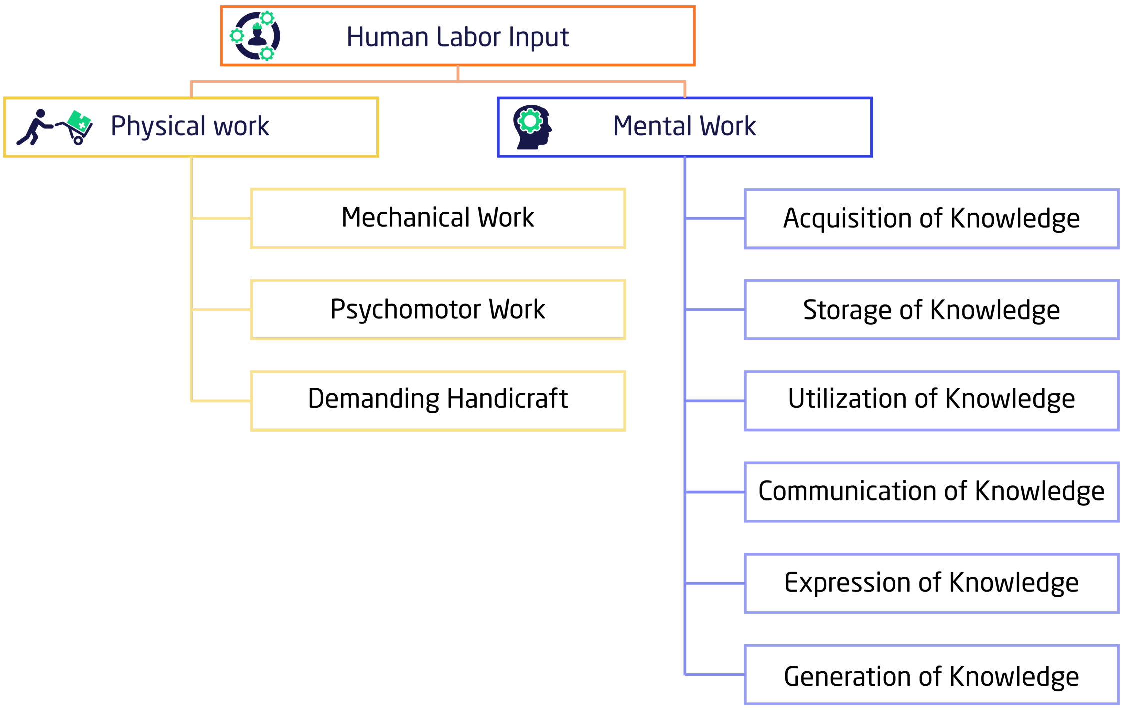

Figure 5 – A taxonomy of human labor inputs by Cordes (2009) recreated for this thesis.

Human labor and wok in Industry 4.0

- The transition to Industry 4.0 and the implementation of new digital technologies are affecting work content, organization, and the competencies required of human workers as well as increasingly replacing jobs that require a low degree of technical skills.
- Denmark ranks in third place on the European Commission's Digital Economy and Society Index (DESI). However, Denmark's progression is challenged by limited skills and competencies within new digital technologies.

2.2 Human Factors and Ergonomics (HF/E)

This section provides an overview of the topics of Human Factors and Ergonomics. The terms "Human Factors" and "Ergonomics" refer to the same concept and discipline. Thus, they are synonymous and often used interchangeably. For the sake of continuity, and similar to most contemporary literature on the topic, I will use the term "Human Factors and Ergonomics" or in the abbreviated form "HF/E" when referring to the concept/discipline. Also, it is essential to mention that the topic of HF/E and work system design are highly interconnected and complementary to each other. However, to avoid confusion, I have dedicated a section (Sections 2.3 and 2.2) for each of these two topics.

2.2.1 Definition and application of HF/E

While the first use of the word "ergonomics" dates back to the year of 1857, HF/E, as a discipline, emerged during World War II. In this period, human operators were becoming the weakest link in advanced military systems, and human-errors linked to design flaws had caused human-machine incompatibilities. The establishment of an association dealing with HF/E came about almost a decade later, in the late 1940s, and started by focusing on human productivity, aviation, psychology, and work physiology. Eventually, as the discipline grew, the focus of HF/E grew to include provision for a safer and healthier working environment and improved work-life quality (IEA, 2000). As digital technologies have become a prominent part of most societies and workplaces, the HF/E discipline has also grown and matured, accounting for the increasing changes and striving to accommodate human needs and well-being (IEA, 2019).

HF/E is an interdependent systems discipline, which focuses on the interactions between humans and artifacts viewed from a unified systems-oriented perspective of science, design, engineering, technology, and management of human-compatible systems (Karwowski, 2005; Wilson, 2014). The International Ergonomics Association (IEA), which is one of the leading global authorities/societies considering HF/E, defines HF/E as

> *the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance* – (IEA, 2020)

Dul et al. (2012) highlight that this definition implies that HF/E has the following three fundamental characteristics. HF/E takes a systems approach, HF/E is design-driven, and HF/E focuses on the two related outcomes of performance and well-being. In most cases, the results from HF/E assessments and analysis end up as recommendations for designing work- or service/product systems, intending to optimize well-being and performance. HF/E addresses system issues on three levels. A micro-level (e.g., how people perform single tasks and use tools), a meso-level (e.g., humans being a part of organizations and technical processes), and a macro-level (e.g., humans being a part of networks of countries, regions, and organizations). Also, human well-being and performance are correlated and closely connected. Thus changes in one of them will potentially affect the other (Pot & Koningsveld, 2009).

2.2.2 The three main domains of HF/E specialization

There are three main domains of HF/E specialization, Physical, Cognitive, and Organizational (IEA, 2020; Wilson, 2000). As mentioned in Section 2.2.1, because HF/E takes a systems approach, it is essential not to view aspects of these domains in isolation, as they, in most cases, are interconnected and influence each other (Carayon et al., 2012).

Physical HF/E focuses on factors related to physical activities (e.g., human anatomical, anthropometric, physiological, and biomechanical characteristics). In simple terms, physical HF/E includes working postures, materials handling, repetitive movements, work-related musculoskeletal disorders, workplace layout, safety, and health (IEA, 2018; Vieira & Kumar, 2004).

Cognitive HF/E deals with factors related to interactions among humans and other elements of a system that affect mental processes. Such factors include information processing, memory, perception, motor response and reasoning, decision-making, skilled performance, human-computer interaction, human reliability, work stress, and training (IEA, 2018; Karwowski, 2005).

Organizational HF/E (also called Macro ergonomics) focuses on optimizing organizational aspects such as organizational structures, policies, and processes of sociotechnical systems. Topics within these aspects can also include management, teamwork, communication, crew resources, participatory work design, community HF/E, computer-supported cooperative work, virtual organizations, and quality management (IEA, 2018; Karwowski, 2005). Figure 6 shows an overview of the three main domains of HF/E (IEA, 2020), recreated for this thesis.

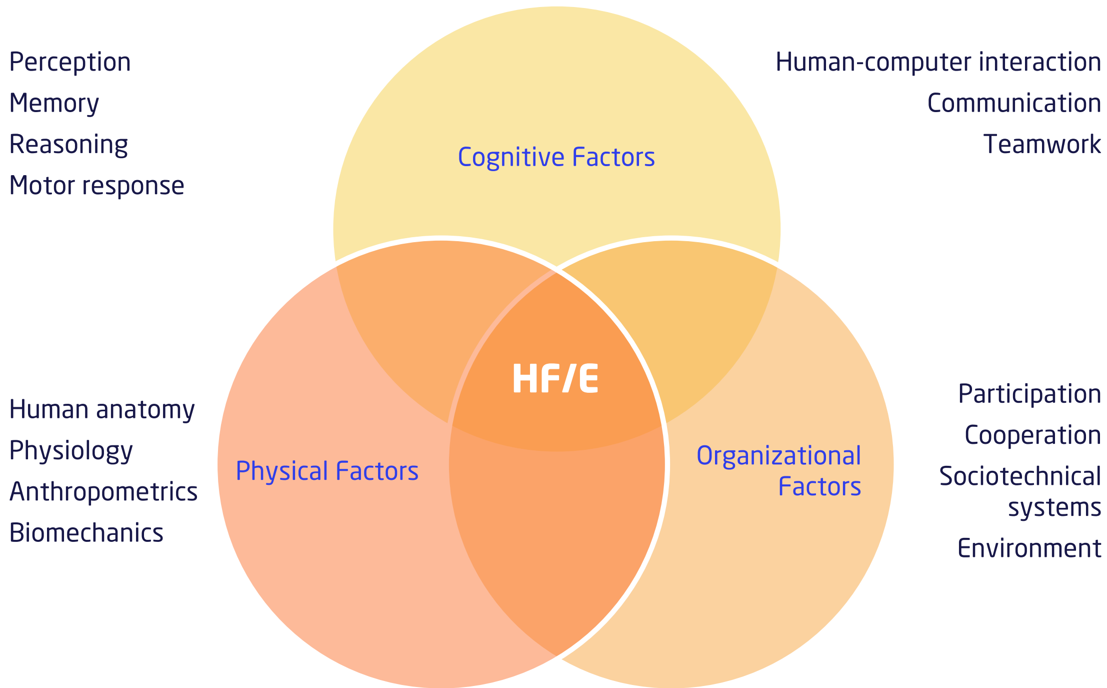

Figure 6 - Overview of the three main domains of HF/E by IEA (2020), recreated for this thesis.

2.2.3 Human well-being and System performance

As mentioned in Section 2.2.1, the main objective of HF/E is to ensure human well-being and overall system performance. Thus, it is essential to define what these two terms refer to in connection to HF/E. Dul et al. (2012) highlight that human well-being might include health and safety, satisfaction, pleasure, learning, and personal development. In comparison, system performance includes productivity, efficiency, effectiveness, quality, innovativeness, flexibility, (systems) safety and security, reliability, sustainability. In addition, Jenkins (2017), Jenkins & Baker (2015) provide a more elaborate framework for system performance, which includes effectiveness, efficiency, flexibility, safety, inclusiveness/compatibility, satisfaction/usability. Refer to Figure 7 for an overview of the System Performance framework by Jenkins & Baker (2015) recreated for this thesis.

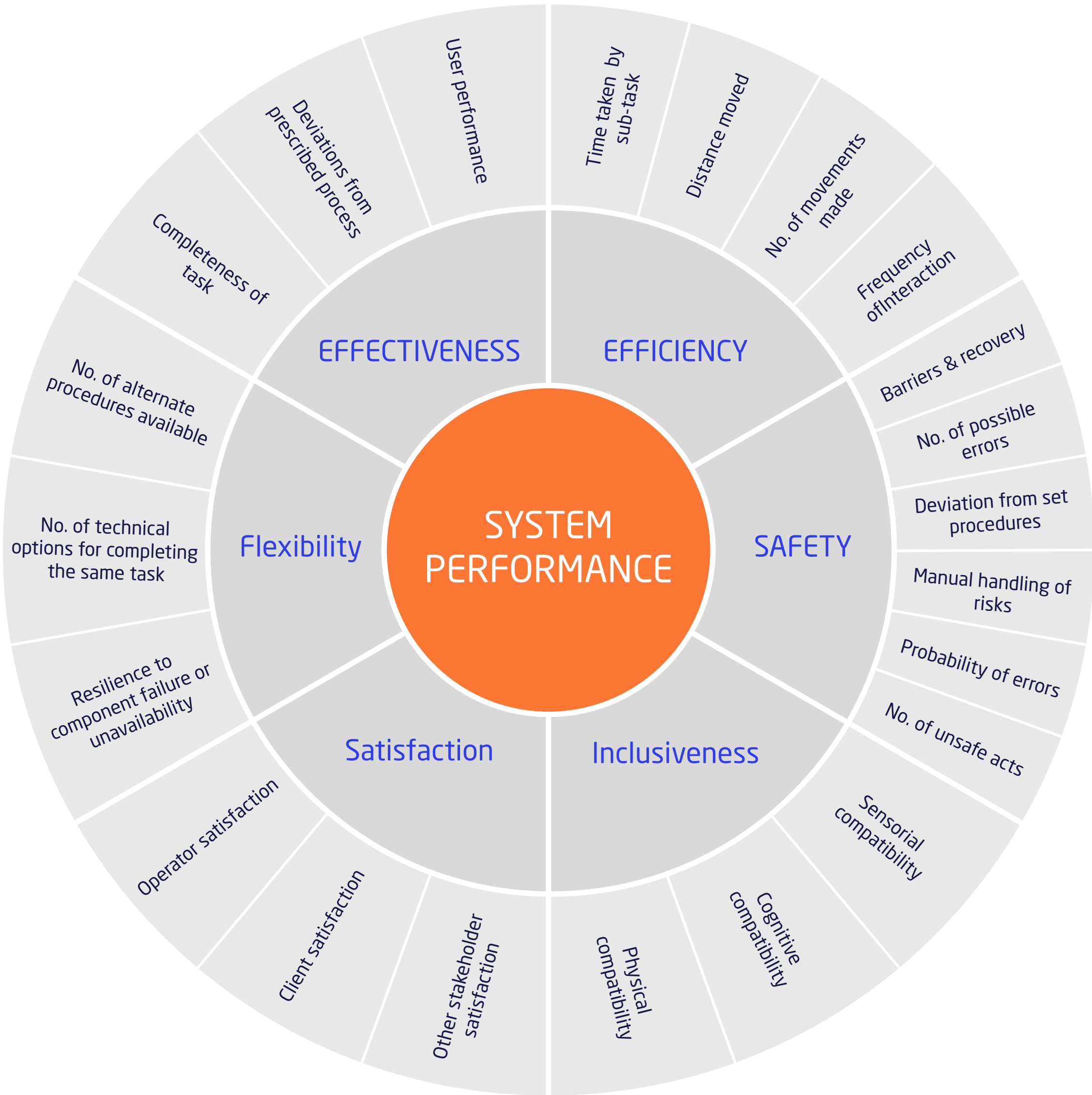

Figure 7 – System Performance framework by (Jenkins & Baker, 2015) re-illustrated for this thesis.

2.3 Work System Design

The fundamental knowledge of HF/E focuses on describing the best ways of designing tools, products, and machines, as well as to optimize interactions and compatibility between system components with the users (Bridger, 2018). When such systems include any type of work, we refer to them as work systems. This subsection focuses on the theoretical background and description of work systems and work system design.

2.3.1 Definition of a Work System and Work System elements

Over the past 50 years, practitioners and researchers from different fields of study have used the term "work system" in various ways and different contexts (Alter, 2013). This thesis mentions and includes several work system concepts and frameworks. However, the general definition of what a work system is and what it entails does not change. The definition I use in this thesis to describe the concept of a work system is the same as the definition of Alter (2006), who provides a relatively cohesive definition without being too broad or too specific. Alter (2006) defines a work system as

a system in which human participants and/or machines perform work using information, technology, and other resources to produce products and/or services for internal and/or external customers – Alter (2006)

This definition implies that a work system can be both a sociotechnical system (consisting of interactions between humans and technologies) as well as a fully automated system with no human interactions (Alter, 2013). Because the transition to Industry 4.0 can, in some case, result in fully automated systems with limited or no human interactions, makes Alter's definition more suitable in the context of this thesis. In addition, while there are many different frameworks and methods for designing work systems, most of these frameworks have similar fundamental elements. Drawing from relevant frameworks and methods such as Alter (2006), BSI Group (2016a), Horgen et al. (1999), Kleiner (2008), and Smith & Sainfort (1989), some of the fundamental elements of work systems include, Participants/Individuals, Workspace and environment, Organization, Technology, and Processes and Tasks. These elements are interconnected and work together to deliver an output, i.e., a product or service.

It is also important to mention that the scope of a work system can vary. A work system could be a small assembly station or an entire production or operations system, including aspects such as division of labor, strategies and management policies, infrastructure, material supply, and logistic systems (Alter, 2006; Neumann & Village, 2012). Figure 8 shows an illustration of a work system created for this thesis.

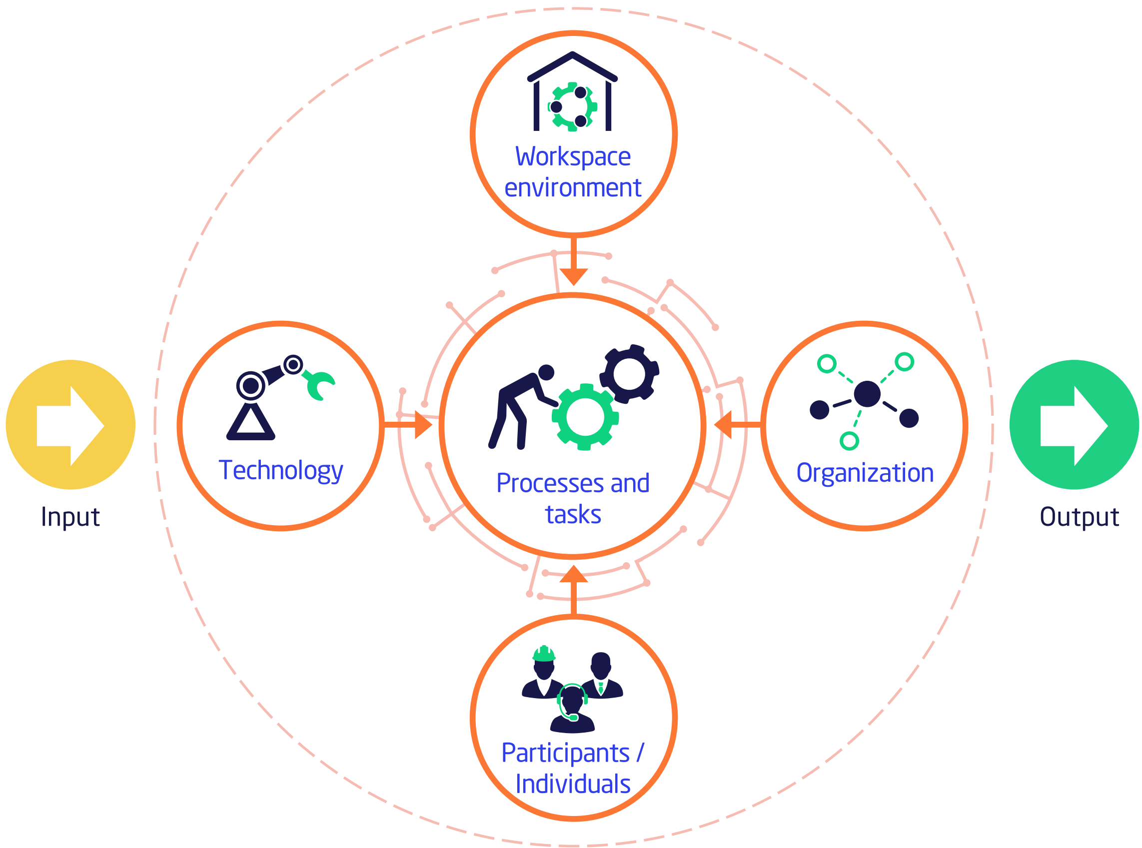

Figure 8 – Illustration of a work system, inspired by (Hansen & Møller, 2013) *created for this thesis.*

2.3.2 Design of Work Systems

A sociotechnical systems approach and incorporation of HF/E has since after World War II played an essential part in the design of work systems (Kleiner, 2008). Thus, the topic of work system design and HF/E are closely connected. Bridger (2018) argues that HF/E is never used on its own, but it is typically applied in conjunction with the design and creation of new and improved systems or management of existing systems. Besides, while the work system frameworks mentioned in Section 2.3.1 are descriptive, almost all of them have a pertaining method or principles for using the framework and designing work systems. For example, Carayon (2009) proposes several design principles to complement the Balance Theory and work system model, and Alter (2006) accompanying a highly cohesive method to complement his work system framework.

The incorporation of HF/E in work system design is quite essential. While most of the literature and guidelines on the topics are from academic publications, there are also practice-oriented guidelines. Examples of such guidelines include BSI Group (2016) (ISO 6385:2016(E)) and a highly recent publication made in a collaborative effort by the International Ergonomics Association (IEA) and the International Labour Organization (ILO) which proposes five foundational principles, accompanied by six guidelines for HF/E design and management of work system (IEA & ILO, 2020). These five foundational principles are

1. Ensuring the workers' safety, health, and well-being should be the top priority when optimizing a work system.
2. Design and manage work systems to ensure sustainability, alignment between organization and workers, and continuous evaluation and learning.
3. Use a holistic perspective and understanding to create a safe, healthy, and sustainable work environment that accommodate human needs.
4. Account for organizational contingencies and individual differences when designing work.
5. Use collective, transdisciplinary knowledge and full participation of workers when designing systems, detecting issues, and developing HF/E solutions in work systems.

These five principles of (IEA & ILO, 2020) are the most recent guidelines targeted at practitioners and bears a close resemblance to the principles described in ISO 6385:2016(E) (BSI Group, 2016a).

Definition of a work system

A work system is a system in which human participants and/or machines perform work using information, technology, and other resources to produce products and/or services for internal and/or external - Alter (2006)

A work system includes elements such as Participants/Individuals, Workspace and environment, Organization, Technology, and Processes, and Tasks.

Design of work systems

The design of a work system is usually closely connected to a sociotechnical systems approach and HF/E principles.

3. Methodology

This chapter focuses on introducing the reader to the overall research methodology and applied research methods. A methodology defines the overall approach of studying any phenomenon (e.g., choosing cases to study, methods of data gathering, forms of data analysis). In contrast, methods are specific research techniques, (i.e., quantitative techniques such as statistical correlations, and qualitative techniques such as observations and interviewing) for achieving specific research objectives (Silverman, 2014). To be more exact, in this, chapter I will describe the overall research- philosophy, approach, design (i.e., methodological choices, research strategy, and time horizon), and methods (i.e., techniques and procedures). Saunders et al. (2016) encapsulate all of the mentioned research topics, with what they call the research "onion." Figure 9 shows an example of the research onion recreated for this thesis.

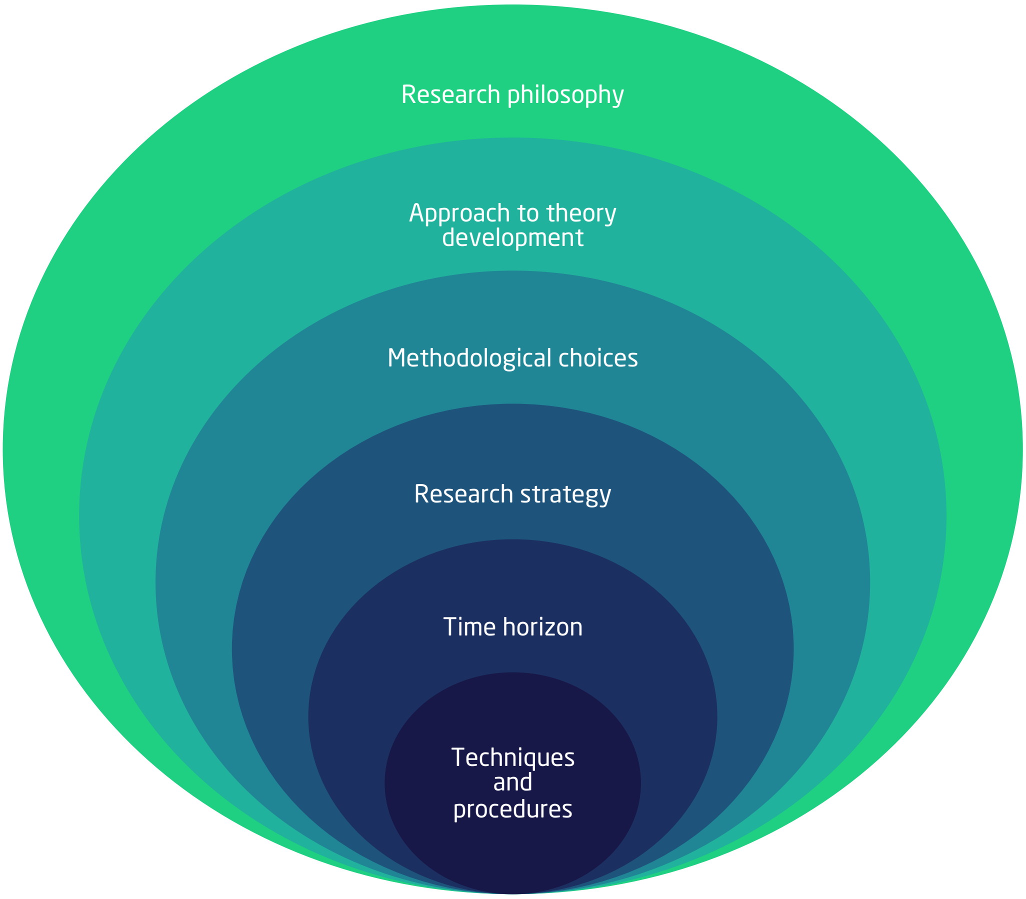

Figure 9 – The research "onion" by Saunders et al. (2016) recreated for this thesis

3.1 Research philosophy

Research philosophy refers to a system of assumptions and beliefs about knowledge development, which include ontological (the nature of reality), epistemological (what constitutes legitimate, valid, and acceptable knowledge), and axiological (role of values and ethics in a research process) assumptions (Saunders et al., 2016). These assumptions will usually shape the understanding of a research question, choice of methodological approach, and methods, which combined, ensure research credibility and convincing outcomes (Crotty, 1998).

While there are several major research philosophies (e.g., positivism, critical realism, postmodernism, and pragmatism), the research philosophy that I adhered to throughout this Ph.D. project was pragmatism. Tashakkori & Teddlie (2010) define pragmatism as

> *a deconstructive paradigm that debunks concepts such as "truth" and "reality" and focuses instead on "what works" as the truth regarding the research questions under investigation. Pragmatism rejects the either/or choices associated with the paradigm wars, advocates for the use of mixed methods in research, and acknowledges that the values of the researcher play a large role in interpretation of results –* (Tashakkori & Teddlie, 2010).

In contrast to most of the major research philosophies, which define fundamentally different ways of viewing the world and conducting research, pragmatism, claim that concepts are only relevant where they support action (Saunders et al., 2016). Saunders et al. (2016) highlight that for pragmatists, research starts with a problem and aims at developing or contributing to a practical solution in practice. Because this Ph.D. project focused on a specific challenge, i.e., ensuring human well-being and system performance in the transition to Industry 4.0, it was most appropriate to adopt pragmatism as the primary research philosophy. Thus, the epistemology focus on problems, practices, and relevance, as well as problem-solving and informed future practices. The Axiology focus on value-driven research determined by the researcher's doubts and beliefs (Saunders et al., 2016).

3.2 Research approach

There are three major research approaches to theory development, induction, deduction, and abduction. These approaches are forms of logical reasoning or ways of thinking used in every type of research and function as a means of generating and connecting ideas (Reichertz, 2014). Simply put, the difference between the three approaches is that abduction creates, induction explains, and deduction verifies (Tashakkori & Teddlie, 2010). Figure 10 shows a graphical illustration of these three approaches by Jokhio & Chalmers (2015), recreated for this thesis.

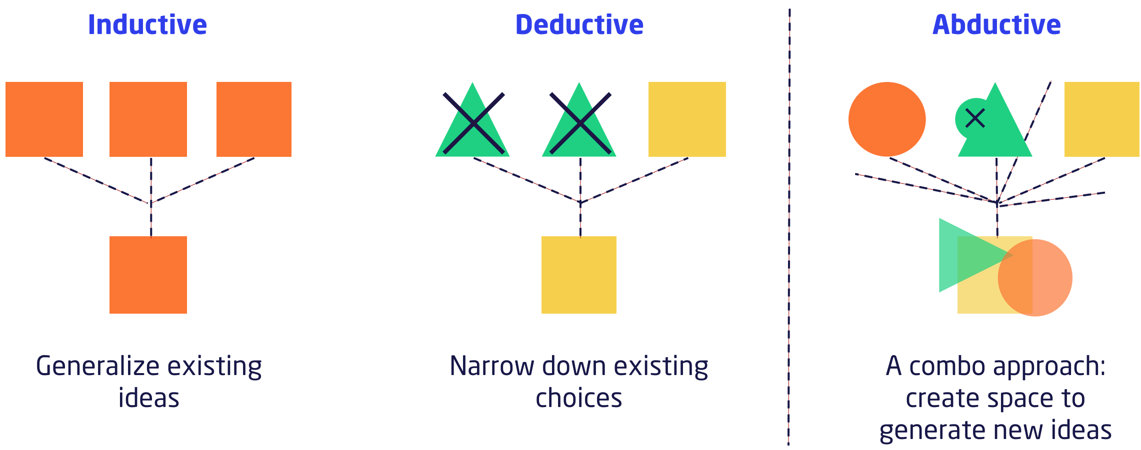

Figure 10 – Inductive, deductive, abductive by (Jokhio & Chalmers, 2015) *recreated for this thesis*

Deduction is most prominent in the natural sciences, where a researcher develops a theory and hereafter proceeds to test the theory through different sets of propositions to either validate or falsify the theory (Saunders et al., 2016). In deduction, conclusions logically arise from a set of premises and are only true when all of the premises are true (Ketokvi & Mantre, 2010). Inductive reasoning is, in some ways, the opposite of deductive reasoning because it argues from a particular observation to broad generalizations through inductive analysis (Tashakkori & Teddlie, 2010). An inductive analysis involves the discovery of patterns, themes, and categories in sets of data, whereas deductive analysis involves analyzing data following existing frameworks. Abduction tries to explain a surprising or unexpected event by moving back and forward between data and theory, thus combining deductive and inductive reasoning (Holmström et al., 2009). Abduction involves selecting or developing a provisional hypothesis that can both explain a specific empirical set of data better than any other hypothesis and be a worthy candidate for further research (Thornberg & Charmaz, 2014).

Because of the exploratory nature of this Ph.D. project, which required moving back and forward between theory, literature, descriptive empirical data, and development of prescriptive measures made abduction the most appropriate research approach. Indeed, the novelty of the topic and the limited yet continuously growing literature encouraged a highly iterative research approach and continuous switching between data collection, literature review, and idea development.

3.3 Research design

3.3.1 Overall research design

Design research methodology is an approach and collection of supplementing guidelines, and methods researchers can use as a framework for conducting design research (Blessing & Chakrabarti, 2009). The overall research design of this Ph.D. project followed the DRM method by Blessing & Chakrabarti (2009), which is a design research methodology that aims at supporting a more rigorous, effective, and efficient approach to design research. Because this project focused on the design of work system, and DRM focuses on assisting design-focused research, made the approach highly appropriate and compatible. DRM has four different stages, Research Clarification (RC), Descriptive Study I (DS-I), Prescriptive Study (PS), and Descriptive Study II (DS-II). Figure 11 shows the DRM framework including the four stages, as well as their basic means and main outcomes.

The RC stage aims at establishing a basic understanding of the research topic, research questions, and the scope of the project, thus supporting the researchers formulating a clear and realistic research plan. The purpose of the DS-I stage is to investigate the given topic by reading literature about empirical data, conduct empirical studies, and use reasoning. This investigation is to increase understanding of the topic and the current situation by identifying influencing factors and their impact on the preliminary criteria. The PS stage aims at using the understanding from the descriptive studies (DS-I or DS-II) to identify and address key factors that might improve the current situation. Besides, these stages also include developing actual supports (e.g., checklists, guidelines, frameworks, software, and tools) to reduce, eliminate, or enhance the influence of some of the key factors. The objective of DS-II is to evaluate whether the developed supports are applicable and have the expected effects on the key factors. Also, this stage entails identifying potential necessary development opportunities for the proposed supports.

Blessing & Chakrabarti (2009) emphasize that following DRM is not a linear process but rather an iterative process that allows parallel execution of the different stages. In Figure 11, the bold orange arrows between the different stages show the overall process flow, while the light orange arrows show the many expected iterations between the four stages.

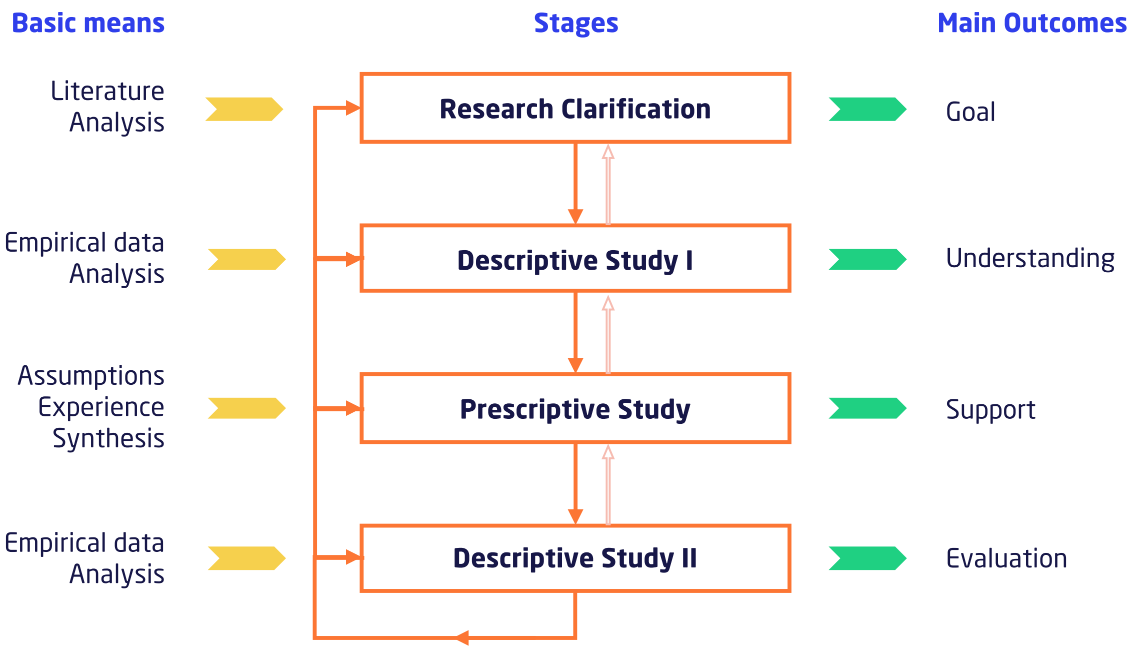

Figure 11 – The DRM method by Blessing & Chakrabarti (2009) *recreated for this thesis*

The DRM was an appropriate overall research design for this Ph.D. project since it allowed iterations and execution of the four stages in parallel with each other, which is also highly suitable with an abductive reasoning approach. Figure 12 shows an overview of the connection between the four DRM stages, and the research questions and papers included in this Ph.D. thesis.

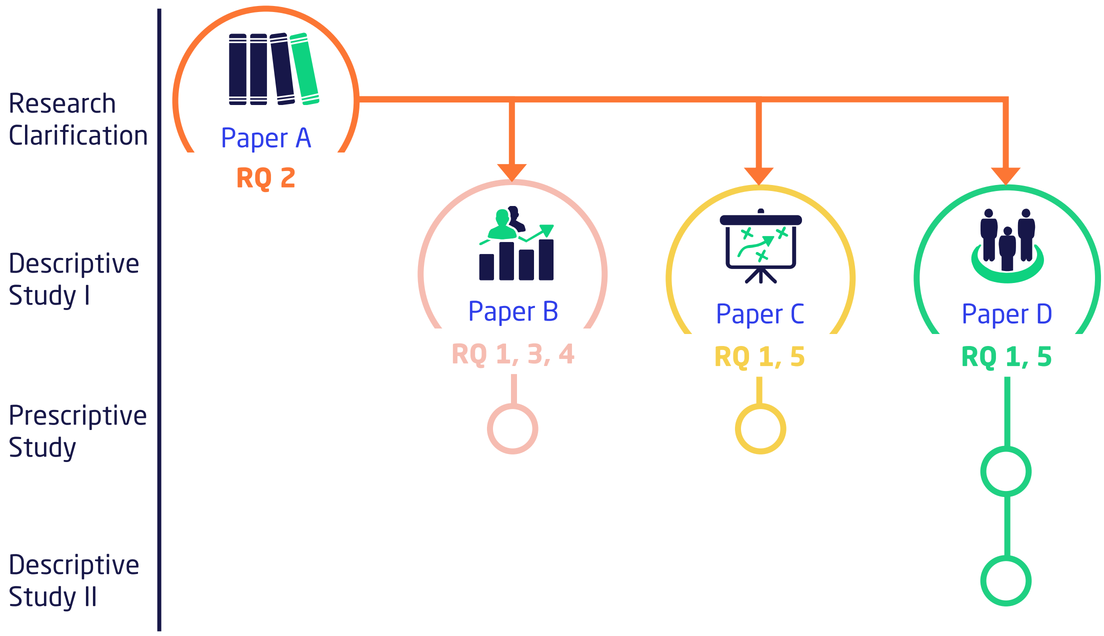

Figure 12 – Overview of the connection between the four DRM stages and the research questions and papers included in this Ph.D. thesis.

3.3.2 Methodological choices

Methodological choices refer to the type of study, i.e., quantitative, qualitative, or mixed-methods, which determines the data collection procedures and applied research methods. A quantitative study strives to test theories by specifying narrow hypotheses and seek explanations and correlations, using numerical data to analyze the relationship between variables (Creswell, 2013). In contrast, a qualitative research approach involves using empirical materials (e.g., case studies, interviews, artifacts, observations, and interactions) to study and describe things in their natural settings, striving to understand the meaning people assign to particular phenomena (Denzin & Lincoln, 2017). Lastly, a mixed-methods research approach, as the name suggests, involves both quantitative and qualitative approaches, advocating the application of whatever methodological tools necessary to answer a given research question (Teddlie & Tashakkori, 2009).

As described in Section 1.3, the research questions of this Ph.D. project mainly focus on understanding and investigating the phenomenon of Industry 4.0 from an HF/E perspective and answering "how" questions. Thus, the most appropriate methodological choice was to use qualitative methodologies to collect and analyze empirical data. However, to answer RQ2, I also used quantitative methods to analyze to what extent and what type of academic publications on Industry 4.0 integrate HF/E in their research.

3.3.3 Research strategy

A research strategy is a plan for how a researcher might tackle the task of answering a proposed research question and can shape the entire process of collecting, working, analyzing, and presenting the findings. This strategy is the methodological link between the overall research philosophy and the consequent choices of the proceeding methods in a research study (Denzin & Lincoln, 2017; Saunders et al., 2016). Because of the novelty and limited knowledge on the research topic, the main research strategy of this Ph.D. project was to conduct exploratory case studies at industrial companies that had started their transition to Industry 4.0 and started working with new digital technologies. R. K. Yin (2018) defines a case study as

> *an empirical method that investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident.* (R. K. Yin, 2018)

Case studies are an excellent strategy for answering "why and "how" questions with empirical data, which could potentially lead to novel exciting findings and the development of new theories. Besides, Flyvbjerg (2006) argues that even single-case studies can have benefits and play a central role in scientific development, using generalization as an alternative or supplement to other research methods and strategies. As the majority of the research questions deal with "how" questions and prompt the investigation of a contemporary phenomenon (the transition to Industry 4.0) in a real-world context made case studies an appropriate research strategy. The overall approach to these case studies was highly inspired and similar to the multiple-case study procedure of R. K. Yin (2018). Figure 13 shows an illustration of R. K. Yin (2018) case study approach, recreated for this thesis.

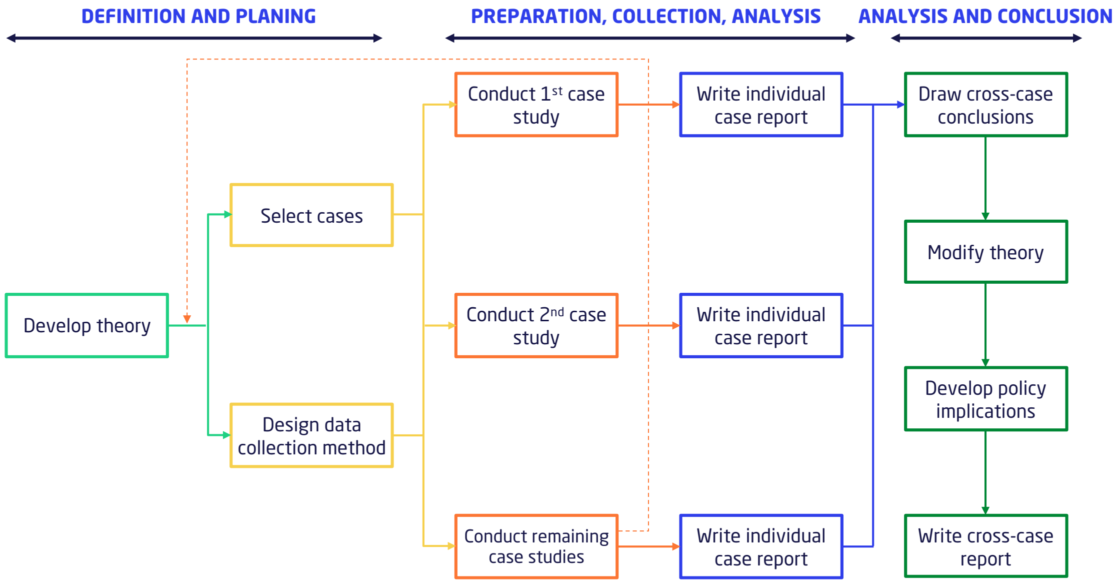

Figure 13 – Case study approach by R. K. Yin (2018), recreated for this thesis.

3.3.4 Time horizon

A research time horizon depends on whether a researcher wants to focus on a "snapshot" that captures a particular time/event or a diary that contains series of "snapshots" that represent events over a given period (Saunders et al., 2016). Saunders et al. (2016) refer to a snapshot time horizon as cross-sectional and the dairy perspective as longitudinal studies. Because of the relatively short time of the Ph.D. project, and difficulties of getting in contact with and access to industrial companies, it was only possible to conduct cross-sectional studies. Saunders et al. (2016) explain that while longitudinal studies allow studying of changes and development over a more extended period to explain how factors between organizations are related, many case study based research conduct cross-sectional studies that involve interviews over a short period.

3.4 Applied research methods

This section includes a description of the three main applied research methods I used to collect data, which were literature review, interviews, and observations.

3.4.1 Literature review

Machi & McEvoy (2016) explain that in general, there are two types of literature reviews, a simple and a complex. A simple literature review involves the critical review of relevant literature on a specific research topic and presentation of a logical case that establishes a proposition on the current knowledge about the topic. A complex literature review, on the other hand, aims at extending the work of the simple review to identify and state unanswered questions and uncover research problems that require further study.

Throughout this Ph.D. project, I conducted both simple and complex literature reviews. Indeed, to gain an understanding of the current state and development of the research topic and pertaining subjects and concepts, I conducted several simple literature reviews in connection to the writing of the research publication as well as in the initial stages of the Ph.D. project. However, I conducted a complex literature review in connection to answering RQ2 in Paper A (Kadir, Broberg, & Conceição, 2019a), which also included a presentation of future perspectives on research regarding HF/E in Industry 4.0 context.

3.4.2 Qualitative interviews

Qualitative interviews often refer to two types of interviews, unstructured and semi-structured interviews. An unstructured interview can be very similar to a conversation and usually involve the researcher asking a question and letting the interviewee answer freely and then only responding to the points that the researcher deems exciting and worthy of following upon. While in semi-structured interviews, the researcher has prepared an interview guide with a list of specific topic-related questions. However, the researcher will often use the interview guide, merely as a guide and not a definite list with a strict procedure. Thus, the researcher might choose not to ask questions in the original order or not to ask questions from the original list and ask new ones if they notice something interesting the interviewee said (Bryman & Emma, 2011).

Because of the exploratory nature of the research project and the methodological choices (e.g., conducting qualitative case studies) made semi-structured interviews an appropriate choice. I developed interview guides with several specific questions related to the research topic, with each question having several pertaining probes (to make the interviewee elaborate on a specific topic), and prompts (things or subjects to remind the interviewee about). The approaches for analyzing the collected interview data are described in the papers included in this thesis in Chapters 5 and 6.

3.4.3 Observations

A third method I used to collect data was through observations. Saunders et al. (2016) explain that observations involve a systematic viewing, recording, description, analysis, and interpretation of how people behave. While there are several observation types, I used a passive observation and a participant as observer type. Observations made as a passive observer entails that the researcher is present at the scene only as an observer, with minimal interactions with the participants (Spradley, 1980a). The participant as observer is similar to a passive observer. However, in contrast to the passive observer, while observing, the participant as observer might engage with and ask the participant relevant questions related to the activity at hand (Denzin, 1978).

Overview of all methodological aspects

Research philosophy	Ontology • Pragmatism. Epistemology • Focus on problems, practices and relevancy. • Problem-solving and informed future practices. Axiology • Focus on value-driven research motivated by the researcher's doubts and beliefs.
Research approach	Abductive approach, moving back and forward between theory, literature, descriptive empirical data and development of prescriptive measures.
Overall research design	The Design Research Methodology (DRM).
Methodological choices	Qualitative methodologies for collecting and analyzing empirical data, and the majority of the literature. Quantitative methodologies for parts of literature analysis.
Research strategy	Case studies
Time horizon	Cross-sectional studies
Applied research methods	Literature review • Simple and complex literature reviews. Qualitative interviews • Semi-structured. Observations • Passive observation and participant as observer type.

4. Current research on human factors and ergonomics in Industry 4.0

This chapter aims to establish a research clarification as in the first stage of the DRM and to answer RQ2. This chapter includes a summary of Paper A (Kadir, Broberg, & Conceição, 2019a), as well as the post-print version of Paper A.

RQ2: To what extent, what type of and how do academic publications on Industry 4.0 integrate HF/E in their research?

As mentioned in section 3.3.1, the main purpose of the DRM Research Clarification stage is to establish a basic understanding of the research topic, research questions, and the scope of the project, thus supporting the researchers formulating a clear and realistic research plan. The preliminary literature review I conducted at the start of the Ph.D. project (ultimo 2017) indicated that academic literature had paid limited attention to HF/E in the context of Industry 4.0. This limited research focus was despite the fact, several researchers (e.g., Romero, Stahre, et al. (2016) and (Pacaux-Lemoine et al. (2017)) highlighting the need for new human-centric design and engineering philosophies to deal with the human-related challenges emerging as industrial companies transition to Industry 4.0. Thus, to ensure the right research focus, objectives, and direction, it was necessary to establish a solid research foundation and clarify the research gap. Thus, this paper aimed to answer RQ2 as well as provide future perspectives on HF/E in Industry 4.0 by pointing to future research needs.

Summary of Paper A

Achieved results

- The extent of Industry 4.0 research dealing with HF/E is minimal.
- Industry 4.0 research covers HF/E aspects much more compared to research within the HF/E discipline.
- The current research dealing with HF/E aspects are mostly theoretical/hypothetical with minimal empirical research as foundation.
- Most of the current research overlook the importance of tactical and strategic organizational levels for the success of HF/E and mostly focus on the operational level.

Contribution

- Establishing to what extent, what type of, and how academic publications on Industry 4.0 integrate HF/E into their research.
- Quantifying and highlighting research gaps and identify areas of focus for future research on HF/E in Industry 4.0.

Paper A

Current Research and Future Perspectives on Human Factors and Ergonomics in Industry 4.0

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(Kadir, Broberg, & Conceição, 2019a)

Current Research and Future Perspectives on Human Factors and Ergonomics in Industry 4.0

Abstract

The journey toward Industry 4.0 and the increasing implementation of Cyber Physical Systems are evoking changes in human work and work organization, thus, creating new challenges and opportunities. To take advantage of these opportunities and deal with the challenges, we must gain a holistic understanding of the emerging socio-technical interactions and apply new human-centric approaches and methods when introducing new digital technologies and designing Industry 4.0-enabled work systems. In this paper, we present the findings of a systematic literature review, consisting of quantitative and qualitative data, focusing on investigating to what extent, what type, and how academic publications on Industry 4.0 integrate human factors and ergonomics in their research. Based on these findings, we point to future research needs, highlighting the need for further empirical evidence and improved collaboration between the academic fields of Industry 4.0, human factors, and ergonomics, as well as with practitioners.

Keywords

Industry 4.0, Cyber Physical Systems, Digitalization, Human Factors, Ergonomics, Literature review

1. Introduction

The final report of the Industrie 4.0 working group sponsored by the German Federal Ministry of Education and Research estimated that the changes introduced with Industry 4.0 will drastically transform work-content, processes, organization, and environments in the factories of the future (Kagermann et al., 2013). Kagermann et al. (2013) emphasized that work in Industry 4.0 will place greater demands on all members of the workforce in terms of problem-solving, abstraction, and managing complexity. Workers will also need to improve communication skills, become more independent, and take the responsibility of organizing their own tasks. These demands will have an increasing effect on the cognitive ergonomics of industrial work systems, thus, increasing the cognitive load of workers and changing the ratio between physical and cognitive load (Kong, 2019). However, Kagermann et al. (2013) suggested that these emerging changes will lead to benefits, such as greater job enrichment, more interesting working environments, and increased autonomy for the workers.

The catalyst behind these changes and the driving force of Industry 4.0, as well as the transformation of industrial production are new digital technologies, such as autonomous robots, augmented and virtual reality, the internet of things, additive manufacturing, and big data and analytics (Rüßmann et al., 2015). The implementation of these new digital technologies in manufacturing systems increase overall connectivity and bridge the gap between the physical and cyber computational space, resulting in the creation of Cyber Physical Systems (CPS) (Xu et al., 2018).

CPS are engineered systems that consist of humans and integrated computational and physical components, creating new levels of socio-technical interactions between humans, machines, materials, and objects (L. Wang et al., 2015). These new levels of socio-technical interaction between the physical and cyberspace include complex interdependencies among organization, production, and control facilities (Zhong & Nof, 2015), which introduce various technical, organizational, and human-related changes (Becker & Stern, 2016).

The implementation and integration of such complex socio-technical systems call for a holistic understanding of the changes in the roles and responsibilities of workers and approaches for designing work, and work systems in Industry 4.0. To attain this holistic understanding, it is important to identify and document the appertaining challenges and opportunities related to human work. However, because the topic of Industry 4.0 is relatively new, research on human work in this context is still limited. Moreover, the available research within this narrow field is mostly focused on the integration of human workers into manufacturing processes at a lower operational level and neglects the upper levels, which deal with decision-making, control, and scheduling (Pacaux-Lemoine et al., 2017). Thus, using a Human Factors and Ergonomics (HF/E) approach might be highly beneficial in terms of analyzing, understanding, and designing human work in Industry 4.0.

For decades, the field of HF/E has tested theories and developed tools, guidelines, and methods with the aim of ensuring the well-being of human workers. The International Ergonomics Association (IEA) defines HF/E as,

the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design to optimize human well-being and overall system performance – (IEA, 2018).

The IEA characterizes the field of HF/E into three domains of specialization: physical, cognitive, and organizational. Physical ergonomics focuses on the physical-elements, interactions, and activities. Cognitive ergonomics focuses on human mental processes and perception. Organizational ergonomics focuses on optimizing the surrounding organizational aspects of the system in which human workers operate. Table 1 shows an overview of the main domains of ergonomics and their content.

Table 1 – Overview of the main domains of ergonomics (IEA, 2018)

Physical Ergonomics	Cognitive Ergonomics	Organizational Ergonomics
• Working postures • Materials handling • Repetitive movements • Work-related musculoskeletal disorders • Workplace layout • Safety and health	• Perception • Memory • Reasoning • Motor response • Mental workload • Decision-making • Skilled performance • Human-computer interaction • Human reliability • Work stress • Training	• Organizational structures • Policies • Processes • Communication • Crew resource management • Work design • Design of working times • Teamwork • Participatory design • Community ergonomics • Cooperative work • New work paradigms • Virtual organizations • Telework • Quality management

Romero, Stahre, et al. (2016) suggest that the transformation into Industry 4.0 will require new design and engineering philosophies that are human-centric and focus on enhancing and augmenting the human's physical, sensorial, and cognitive capabilities, rather than unmanned autonomous factories. Using a human-centric approach to design Industry 4.0 work systems could improve the global performance of complex socio-technical systems and improve workers' well-being (Pacaux-Lemoine et al., 2017).

The aim of this paper is to investigate to what extent, what type of, and how academic publications on Industry 4.0 integrate HF/E in their research with the help of a systematic literature review; hereafter, pointing to future research needs, including better collaboration between HF/E and Industry 4.0 researchers as well as practitioners. Figure 14 illustrates the position of this paper in regard to research within HF/E and Industry 4.0.

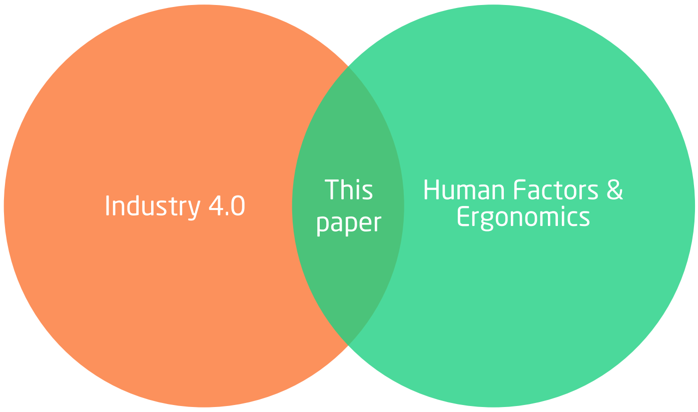

Figure 14 - The position of this paper in regard to research within HF/E and Industry 4.0

The organization of this paper is as follows: In Section 2, we describe the methodology and framework used to conduct the systematic literature review. In Section 3, we highlight the quantitative and qualitative results from the literature review and summarize the characteristics of HF/E research in Industry 4.0. In Section 4, we discuss the results and present a future perspective, as well as a research agenda for future research on HF/E in Industry 4.0. In Section 5, we highlight the limitations of this paper. In Section 6, we summarize the paper, provide final remarks, and draw a conclusion.

2. Methodology

To achieve the proposed aim of this paper, we conducted a systematic literature review. To answer the "what," we applied a quantitative data analysis approach focused on examining the extent of the overlap between the two academic research fields of Industry 4.0 and HF/E. This quantitative analysis included investigating characteristics of Industry 4.0 keywords associated with HF/E, the number of publications and publication types by year, types of data used in the publications, and publications in HF/E-related outlets. To answer the "how," we conducted a mix of qualitative and quantitative data analysis using the three broad HF/E domains characterized by and highlighted in Table 1, as a coding framework for analyzing the results from the literature review.

2.1. Literature Search Strategy

To ensure the literature search was as extensive and inclusive as possible, yet within scope, the search strategy included combinations of several keywords that are relevant to HF/E in Industry 4.0. The scope of this paper is research on HF/E in Industry 4.0 in general, thus, the Industry 4.0 related keywords only included the broadest keywords used to describe closely related connotations similar to those mentioned and clustered by Liao et al. (2017). In addition, due to the scope of this paper, the Industry 4.0 keywords did not include terms solely related to individual aspects of Industry 4.0 (e.g., Internet of Things, autonomous robots, big data, etc.).

In regard to the HF/E keywords, the keywords "human factors" and "ergonomics" are very broad and should capture most of the literature related to this research area. However, in accordance with recommendations of several experts within the HF/E research field, we added several other HF/E-related keywords. Table 2 shows an overview of the keywords used in the literature search. We did an individual search on each keyword(s) from Column 1 combined with each keyword(s) in Column 2 from Table 2, searching in titles, abstracts, and keywords using the electronic database, "Scopus."

Table 2 – Combination of keywords in the literature search

Industry 4.0-related keywords	HF/E-related keywords
• Industry 4.0 • Cyber Physical System • Smart manufacturing • Smart factory	• Human factors • Ergonomics • Work system • Work design • Work organization • Well-being

When searching the database, we also took into consideration the different variations of spelling the words (e.g., *organization* and *organisation*, or *cyber-physical system* and *cyber physical system)*. The literature search only included academic literature i.e. peer-reviewed journal articles and conference proceedings published in English after the year 2013. The reason for not including papers prior to the year 2013 is that the origin of the term "Industry 4.0" is associated with Kagermann et al. (2013) and almost no other peer-reviewed journal articles or conference papers exist prior to that year.

2.2. Review Method

To ensure consistency and transparency throughout the entire review process, this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), (Moher et al., 2009) modified to fit with the review criteria specific to this paper. Figure 15 illustrates the PRISMA flowchart highlighting the various stages of the systematic literature review applied in this paper.

The database searches in the identification stage resulted in 110 papers eligible for further screening. Because some publications included several of the Industry 4.0-related keywords, the 110 papers included several duplicates. After removing these duplicates, this number became 86. In the screening stage, we screened 86 papers by title and abstract with the intention of removing papers not relevant to the topic of HF/E in Industry 4.0. Examples of papers excluded were papers on autonomous street vehicles and smart cities. After the screening stage, 57 papers remained. Seven of the 57 papers were unavailable resulting in 50 papers included in the literature review. After reading and reviewing these 50 papers, we only deemed 40 papers as relevant, consequently only coding these 40 publications. We excluded the remaining 10 publications because they either did not include any relevant HF/E-related content or were conference papers published prior to a journal article by the same authors and with the same content. Therefore, the qualitative data analysis only included these 40 papers. However, to present a holistic picture of the current situation of the publication landscape in academic research on the topic, the quantitative analysis included all 50 papers.

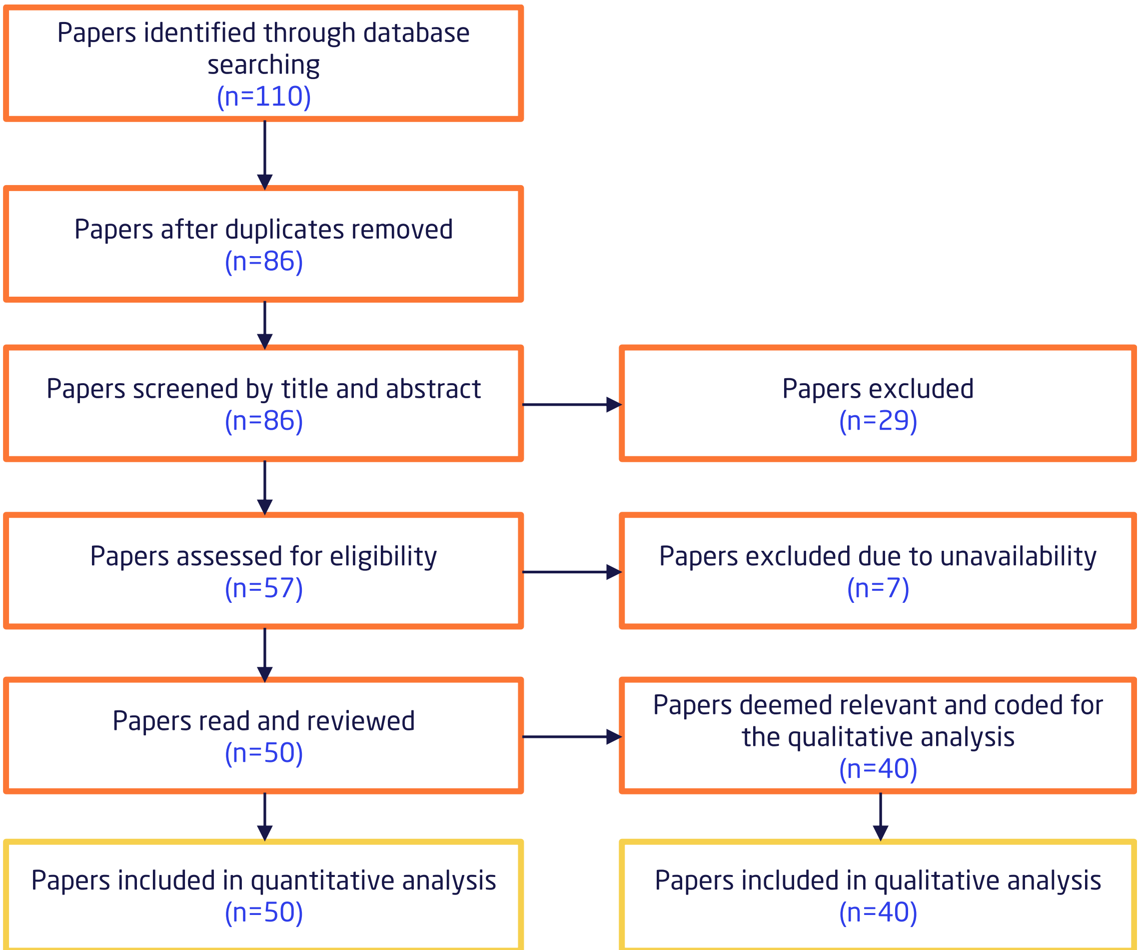

Figure 15 – The PRISMA flowchart specific to the systematic literature review of this paper

2.3. Data Analysis

We used the computer software Microsoft Excel to organize the quantitative data we collected for each publication, as well as for all the quantitative analysis we performed to investigate to what extent publications on Industry 4.0 are integrating HF/E in their research. To investigate how these publications are integrating HF/E in their research, we organized the papers and the qualitative analysis in the computer software Atlas.ti 8 and conducted the review following a systematic coding process of a template analysis (Brooks et al., 2015). We used the three broad types of HF/E categories, physical, cognitive, and organizational, as defined by (IEA, 2018) as a coding framework to characterize the findings from the literature review. Refer to Table 1 for an overview of the coding framework.

The coding of the literature and the analysis of the qualitative data were a three-phase process following an inductive analysis. The purpose of applying an inductive analysis approach is to allow themes inherent in the raw data to emerge as dominant, frequent, or significant without any constraint from structured methodologies (Thomas, 2006). In the first phase, we read all 50 papers included in the review, highlighting and coding statements, references, and results in accordance with the coding framework in Table 1. In the second phase, we revisited the codes and citations to validate and ensure coherency. During the third phase, we themed the codes across the publications and described and summarized the main points as shown in Section 3.2.

3. Results

The data analysis focused on characterizing the current research on HF/E in Industry 4.0 and building a holistic understanding through both the quantitative and qualitative data, thus, clarifying to what extent, what type of, and how the included academic publications integrated HF/E in their research. The results from the quantitative analysis provided important information on keyword and topic trends, the growth of the academic field over the years, and identified coverage of the three HF/E domains. Compared with the quantitative analysis, the qualitative analysis offered a more comprehensive perspective into the specific topics within HF/E that Industry 4.0 researchers have explored until now. By diving into the context of the papers, it was possible to highlight characteristics and focus of the current research within the topic of HF/E in Industry 4.0.

3.1. Quantitative Data Analysis

In this section, we present the findings from the quantitative data analysis and highlight characteristics of the current research on HF/E in Industry 4.0.

3.1.1 Characteristics of Industry 4.0 Keywords Associated with HF/E

Because of the variety of terms and definitions in this new field of research, searching for academic literature can be unproductive. To get an overview of the reoccurrence of the Industry 4.0 keywords used in the online database searches, we created a Pareto chart that shows the number of papers we found with each Industry 4.0 keyword and the cumulative percentage. Refer to Figure 16 to view this Pareto chart.

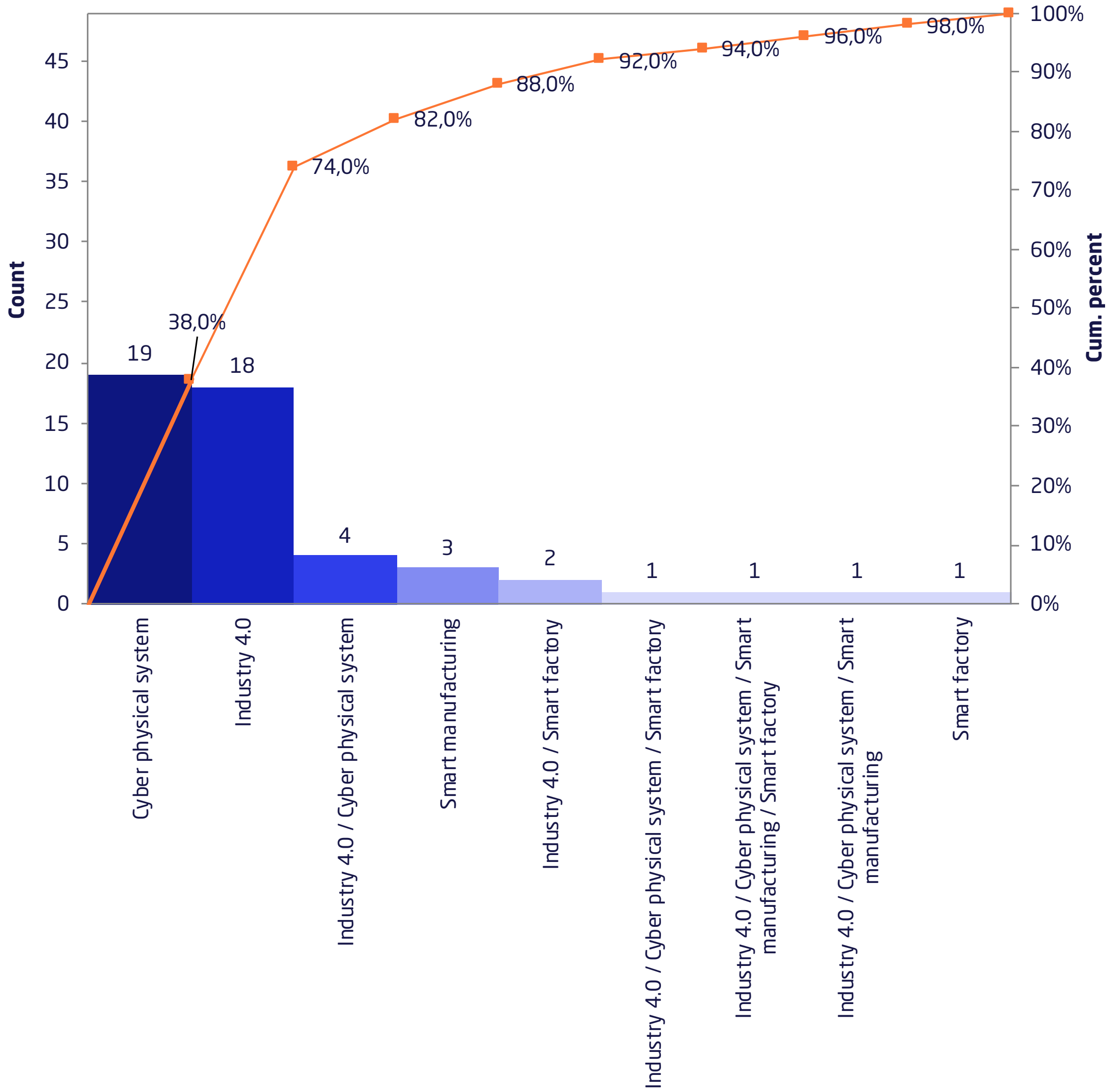

Figure 16 – Pareto chart showing the distribution of Industry 4.0-related keywords used to find the papers in the database searches

Each bar in the Pareto chart represents one or more combinations of Industry 4.0 keywords, meaning that some papers appeared with two or more keywords. Industry 4.0 and Cyber Physical System are the most reoccurring keywords, appearing alone in 19 and 18 papers, respectively. Looking across all of the keywords, these two appear in 47 of the 50 papers, which corresponds to 94%.

3.1.2 Number of Publications by Year

From the years 2013 to 2017, the number of academic publications dealing with HF/E in Industry 4.0 increased exponentially. At the time of this research, June 2018, the number of publications for the year was 11. To put these numbers in perspective, we did two additional searches in the online database Scopus, one with only the Industry 4.0 keywords and another only the HF/E keywords shown in

Table 2. *Well-being* is a very common keyword used in thousands of publications across many different research fields. To avoid any exaggeration of the search results, the HF/E keyword search did not include the keyword *well-being*.

Publications in both Industry 4.0 and HF/E fields have increased from 2013–2017, although publications related to HF/E have increased at a slower rate than Industry 4.0. Even though the number of publications on HF/E in Industry 4.0 is increasing, they still make up less than 2‰ of the total number of papers published related to Industry 4.0 and HF/E. Refer to Figure 17 to view the number of publications by years for Industry 4.0 keywords, HF/E keywords, and HF/E + Industry 4.0 keywords.

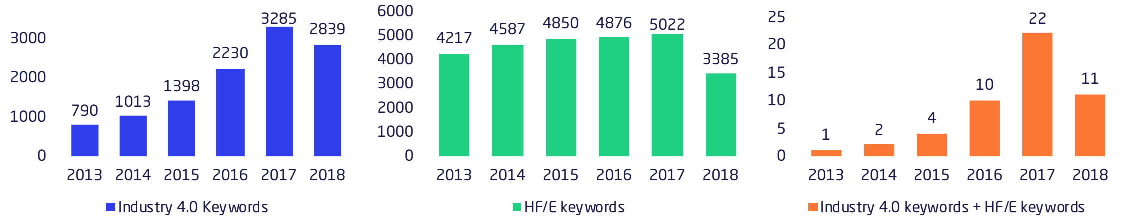

Figure 17 – Column charts showing the number of publications by year for Industry 4.0 keywords, HF/E keywords, and Industry 4.0 + HF/E keywords.

We categorized the publications into the two sources, conference proceedings and journal articles with respect to their original source. Thus, publications from outlets such as Procedia Manufacturing fell into the category of conference proceedings, even though the electronic database, Scopus, categorizes them as journal articles. Out of the 50 included publications dealing with HF/E in Industry 4.0, 37 are conference proceedings and the remaining 13 are peer-reviewed journal articles. Refer to Figure 18 for an overview of publication type by year for the 50 included papers.

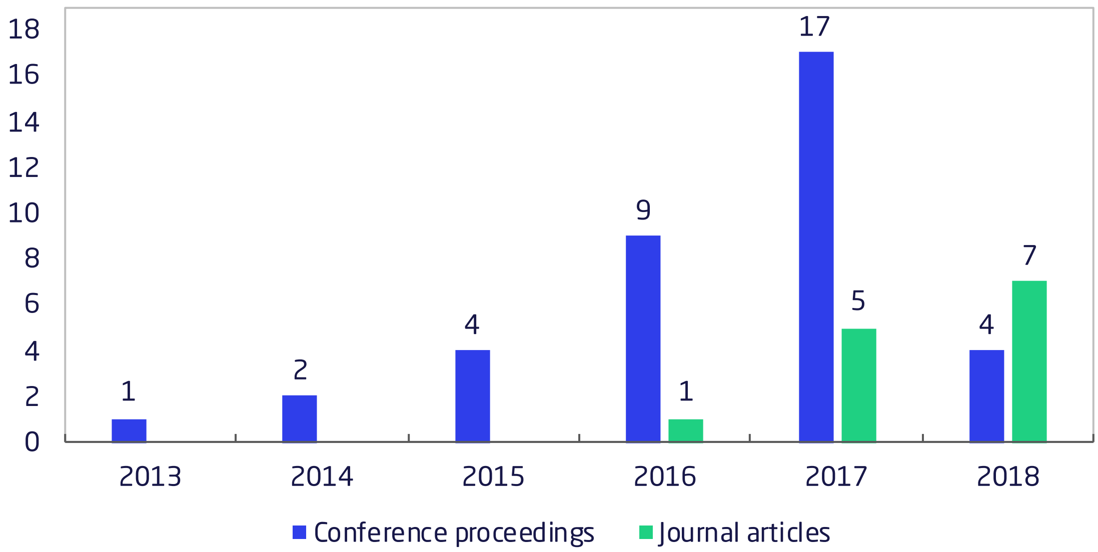

Figure 18 – Publication type by year

3.1.3 Publication Outlets

The 37 conference proceedings are associated with 29 different conferences, 22 of which have only one publication, six have two publications, while only one outlet has published three proceedings. In regard to the journal articles, of the 11 journal outlets, ten journals have each published one article, while one journal has published three. Figure 19 and Figure 20 give an overview of the conference proceedings and journal article outlets, respectively.

Figure 19 - Conference proceeding outlets

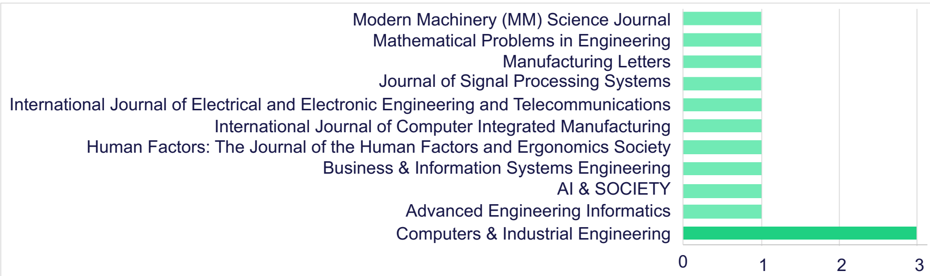

Figure 20 - Journal article outlets

3.1.4 Theoretical vs. Empirical Evidence

Out of the 50 publications included in this research, 26 contribute with theories, conceptual frameworks, and models. The remaining 24 publications contribute with empirical evidence through either case studies and industry data or simulations and laboratory experiments. We attribute the limited number of publications containing empirical data to the novelty of Industry 4.0. Figure 21 shows the distribution of data types in the 50 included publications.

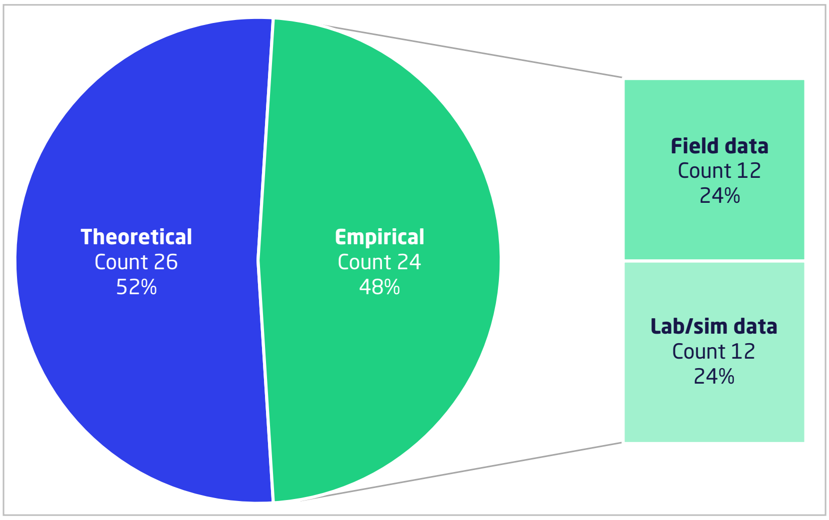

Figure 21 – Distribution of data types in the 50 included publications

3.1.5 Publication Outlets Dealing with HF/E

To get an overview of where academics publish research dealing with HF/E in Industry 4.0, we identified and categorized the publications published in HF/E-relevant outlets. We identified HF/E-related outlets by looking for keywords and terms related to HF/E in the outlets' names. In cases where it was unclear if an outlet was HF/E-related, we gained further information through the outlet's associated website. Refer to Figure 22 for an overview of the number of publications published in HF/E-related outlets.

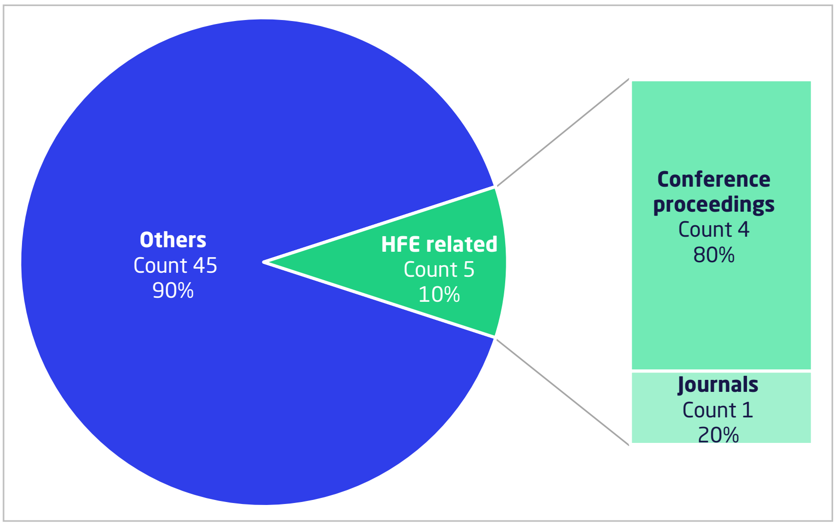

Figure 22 – Overview of the number of publications published in HF/E-related outlets

3.1.6 Categorizing the Current Research into the Three HF/E Domains

By the end of the third and final phase of the coding process, we were able to categorize the included publications into the HF/E coding framework. This categorization highlight which of the HF/E type categories researchers have focused on to date. Refer to Figure 23 for an overview of this categorization.

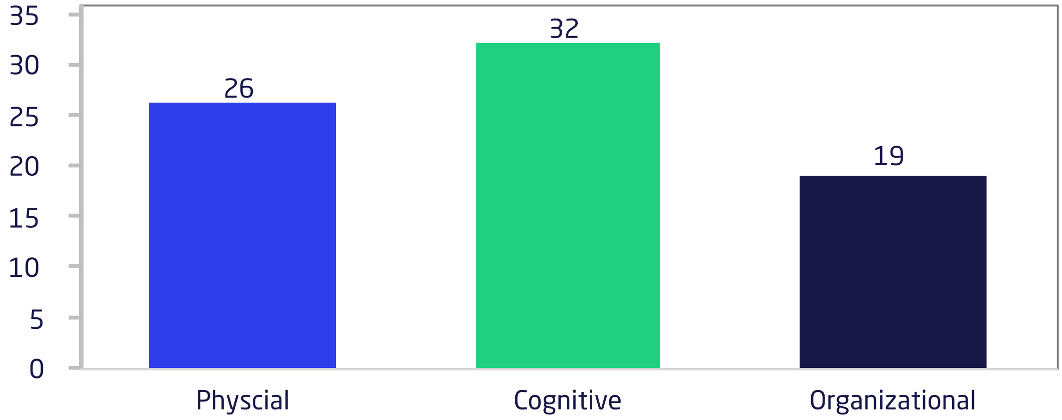

Figure 23 – Summary of number of publications coded in each category of the coding framework

The results in Figure 23 show the distribution between physical, cognitive, and organizational HF/E. Refer to Table 3 for an overview of the specific articles coded in each category of the coding framework.

Table 3 – The distribution of the included papers into the coding framework

Physical	Cognitive	Organizational
(Becker & Stern, 2016; Borisov et al., 2016; Dannapfel et al., 2018; De Felice et al., 2018; Dombrowski et al., 2017; Fantini et al., 2018, 2016; Gašová et al., 2017; G. Horváth & Erdős, 2017; Huber & Weiss, 2017; Hummel et al., 2015; Kadir et al., 2018; Kerpen et al., 2016; U. Müller et al., 2015; Paritala et al., 2017; Peruzzini et al., 2017; Peruzzini & Pellicciari, 2017; Richert et al., 2016b, 2016a; Richter et al., 2018; Römer & Bruder, 2015; Romero, Stahre, et al., 2016; Rylnikova et al., 2017; Scheuermann et al., 2016; Stern & Becker, 2017; Vysocky & Novak, 2016)	(Becker & Stern, 2016; Cohen et al., 2017; Czerniak et al., 2017; Dworschak & Zaiser, 2014; Fantini et al., 2018, 2016; Gašová et al., 2017; Gopalakrishna et al., 2017; Hummel et al., 2015; Kadir et al., 2018; Kerpen et al., 2016; Kim et al., 2013; Lazarova-Molnar et al., 2017; Ma et al., 2018; Mazali, 2018; Pacaux-Lemoine et al., 2017; Peruzzini & Pellicciari, 2017; Pinzone et al., 2018; Repta, Moisescu, Sacala, Dumitrache, et al., 2015; Repta, Moisescu, Sacala, Stanescu, et al., 2015; Richert et al., 2016b, 2016a; Richter et al., 2018; Romero, Stahre, et al., 2016; Rylnikova et al., 2017; Schlagowski et al., 2018; Singh & Mahmoud, 2017; Spichkova et al., 2015; Stary & Weichhart, 2017; Stern & Becker, 2017; Theis et al., 2014; Vernim et al., 2017)	(Becker & Stern, 2016; Cohen et al., 2017; Dannapfel et al., 2018; Dworschak & Zaiser, 2014; Fantini et al., 2018, 2016; Gurjanov et al., 2018; Hummel et al., 2015; Kadir et al., 2018; Kerpen et al., 2016; Mazali, 2018; U. Müller et al., 2015; Pacaux-Lemoine et al., 2017; Pinzone et al., 2018; Richter et al., 2018; Romero, Stahre, et al., 2016; Stern & Becker, 2017; Vernim et al., 2017; Vysocky & Novak, 2016)

3.1.7 Summary of the Quantitative Data Analysis

There are several terms related to the concept of Industry 4.0, and the results from the quantitative data analysis showed that the keywords *Industry 4.0* and *Cyber Physical System* are the most reoccurring in academic publications that deal with HF/E in Industry 4.0. The results also highlight the lack of attention HF/E has received in Industry 4.0 research. The number of publications focusing on HF/E in Industry 4.0 has increased since the introduction of the term *Industry 4.0* in 2013, yet this number is incremental in comparison with the total number of publications published since 2013 related to Industry 4.0 and HF/E separately. In addition, the distribution of the HF/E categories is similar, with cognitive HF/E being the most populated.

3.2. Results from Qualitative Data Analysis

In this section, we present some of the most important findings from the themes emerging within each of the HF/E categories with the intent of answering how the included publications integrate HF/E into their research. The qualitative data analysis focused on highlighting the prevailing results and discussions of importance to HF/E in Industry 4.0 coded in the three HF/E categories. The statements we present in this section are not estimations, predictions, or subjective views of the authors of this paper, but are the findings from the qualitative data analysis of the literature review. Refer to Table 4 for an overview of the qualitative data analysis results.

Table 4 – Overview of the qualitative data analysis results

Physical	Cognitive	Organizational
• Manual repetitive tasks are getting automated. • Close human–machine collaboration evokes safety concerns. • Wearable and handheld devices are improving ergonomic feedback. • New digital technologies are improving internal logistics and transportation.	• Virtual models improve perception and create timely interactions. • CPS are introducing new forms of human–machine interactions. • Problem-solving and IT skills will become a necessity. • Augmented Reality devices will contribute to the reduction of mental strain. • Changing demographics creates new demands for factories of the future • Data sharing across departments is improving cognitive ergonomics. • Technology forecasting can identify necessary skills early on.	• Hybrid production systems are bridging the gap between humans and machines. • New human–machine interactions will affect work organization and design. • Human-centered design will benefit workers. • Work organization is expanding across departments. • The combination of new technology and work organization will determine future skills' development.

3.2.1 Physical HF/E

3.2.1.1 Manual repetitive tasks are getting automated

A frequently mentioned aspect in regard to HF/E in Industry 4.0 was the automation of manual tasks, which is one of the most notable characteristics attributed to Industry 4.0. Numerous publications highlighted and mentioned a future scenario where companies will have automated, easy, repetitive manual tasks (Kerpen et al., 2016; Richter et al., 2018; Stern & Becker, 2017). However, it is also stated that most of the automation technologies in industry have limited flexibility (Dannapfel et al., 2018; Hummel et al., 2015; Kadir et al., 2018). Complex tasks that require flexibility and ad hoc problem-solving skills will still belong to human workers, making them a necessity in the factories of the future (Fantini et al., 2016; Richert et al., 2016; Romero et al., 2016).

Advancements in traditional industrial robots and collaborative robots (cobots) are considered as one of the more prevalent technologies in the automation of repetitive, monotonous, and physically straining tasks (Kadir et al., 2018; Romero et al., 2017). It is mentioned that hybrid teams of humans and robots will support demographic and diverse team structures, and the physical limitations of human workers are compensated through human–robot interactions, where robots help workers lift heavy items or take over other physical tasks. A step further in the direction of human–robot collaboration will be autonomous robots identifying and adapting to workers' individual strengths and taking on the role of an equal supportive workmate (Richert et al., 2016a).

3.2.1.2 Close human-machine collaboration evokes safety concerns

Several publications included in the literature review highlighted concerns regarding workers' safety when working in CPS. This was especially relevant in the case of cobots. Unlike traditional industrial robots, cobots are estimated to be highly reliable in terms of safety and can work side-by-side with humans without the need for any fencing or enclosure (BSI Group, 2016b). However, Vysocky & Novak (2016) highlight that cobots, as well as robots, are only as safe as the tools they operate. Everything that is fastened or attached to the cobot/robot can cause its safety to decrease. To overcome these safety concerns, it is suggested that companies use digital/virtual twins to simulate various scenarios to evaluate the human–robot collaboration and collision detection (G. Horváth & Erdős, 2017). Alternatively, it is proposed that companies could incorporate hands-free gesture control in human–robot interactions to accommodate operational safety, physical ergonomics, and efficiency (G. Horváth & Erdős, 2017; Scheuermann et al., 2016).

3.2.1.3 Wearable and handheld devices are improving ergonomic feedback

It is mentioned that wearable and handheld digital devices, such as smartphones and smart watches that are able to measure workers' exercise activity levels, heart rate, and other health-related metrics, as well as GPS location, will contribute to the improvement of physical ergonomics in the factories of the future (Romero, Stahre, et al., 2016). On the one hand, Borisov et al. (2016) argued that these devices raise the awareness of workers in regard to physical ergonomics and promote more sensible behavior while working. On the other, Hummel et al. (2015) and Peruzzini et al. (2017) mentioned that the data these devices produce while tracking the workers along with CPS data, creates a unique opportunity to drive process configuration, planning, and smart adaptation of manufacturing systems in accordance with workers' behaviors and stress conditions. However, using such personal and somewhat sensitive data may be rather complicated. Huber & Weiss (2017) highlighted that companies might face privacy issues if they start collecting data without consent from the workers.

3.2.1.4 New digital technologies are improving internal logistics and transportation

It was highlighted that the transition to CPS is happening across company departments and is not limited to individual workstations on the factory floors. It is estimated that considerations regarding physical ergonomics are a focus as companies increase automation of internal logistics and transportation between various locations on the factory floors, as well as across departments. Hummel et al. (2015) mention that the improvement of the science driving technologies such as Automated Guided Vehicles and intelligent continuous conveyors is now allowing these technologies to roam autonomously side-by-side and in the same area as workers.

3.2.2 Cognitive HF/E

3.2.2.1 Virtual models improve perception and create timely interactions

It is mentioned that virtual models, 3D drawings, and virtualization of entire supply chain processes are improving the perception and understanding of planned changes between different company departments and organization layers. This improvement of perception and understanding is estimated to enable timely interaction between different departments that need to collaborate in problem-solving and decision-making (Mazali, 2018).

3.2.2.2 CPS are introducing new forms of human-machine interactions

Lazarova-Molnar et al. (2017) highlight that regardless of the increasing tendencies of automation in industry, CPS' will still include humans, thus, some sort of human–computer/machine interactions will remain. The two most discussed human–computer/machine interactions prevailing in the literature are Human-in-the-Loop (HitL) and Human-in-the-Mesh (HitM).

HitL scenarios are described to involve human activities, such as overseeing and adjusting machines, directly commanding the system, and first in line to detect and report abnormalities (Fantini et al., 2016). This paradigm of HitL combines data and decision models with human knowledge and feedback, which promotes the development of machine intelligence (Ma et al., 2018). It is mentioned that in HitM scenarios, the role of humans is more focused on supporting the systems in activities such as receiving alerts, intervening when necessary, analyzing and changing planning, and observing and extracting knowledge (Fantini et al., 2016). However, Fantini et al. (2016) also mentioned that HitM still lacks a clear definition.

3.2.2.3 Problem-solving and IT skills will become a necessity

It is highlighted that the increasing automation of manual work will support and benefit workers, however, it will also change the skills and competence requirements demanded of workers. Several publications mentioned that the prevailing skills will include the capability to understand abstract information, solve complex problems, and have IT literacy (Becker & Stern, 2016; Dworschak & Zaiser, 2014; Fantini et al., 2016; Kerpen et al., 2016; Lazarova-Molnar et al., 2017). Of the 32 publications coded in the cognitive ergonomics category, 12 of them mentioned the changes in skills and competence requirements. However, most of the data presented were based on estimations and predictions for the future and did not provide any more specific details than the ones mentioned in this section.

3.2.2.4 Augmented Reality devices will contribute to the reduction of mental strain

Augmented Reality (AR) and its use on factory floors was mentioned to contribute to the reduction of mental strain of workers. AR provides a visual layer of information on top of the real-world factory environment through devices such as head-gear, smart glasses, smartphones and tablets, and spatial AR projectors (Romero, Stahre, et al., 2016). It was further noted that AR would have an important role in improving the cognitive ergonomics of workers. It was also estimated that AR technologies can support highly complex and stressful work by removing unnecessary information and provide the workers only with the information they need (Theis et al., 2014). Pinzone et al. (2018) highlighted that the information such technologies might provide could be item codes, names of components, or instructions to help workers remember maintenance and repair procedures. However, Czerniak et al. (2017) emphasized that it is important to not overload workers with information, thus, causing information overload and increasing mental strain instead of reducing it.

3.2.2.5 Changing demographics creates new demands for factories of the future

Peruzzini & Pellicciari (2017) mentioned that demographic changes and national regulations regarding late retirement, as well as improved health, are allowing workers to stay on the job market for a longer time. Thus, aging workers (45–64 years old) in the industrial sector are increasing in the EU, as well as worldwide. In addition, it was highlighted that political conditions have resulted in increased employment of workers with an immigrant background in European countries (Kerpen et al., 2016).

These new conditions were estimated to be creating new challenges in regard to training, competence development, and human–machine interactions. Therefore, it would be important to adopt a social perspective to improve the assistance of aging, disabled, and apprentice workers with the use of new digital technologies (Romero, Stahre, et al., 2016). Kerpen et al. (2016) used an example, which included an AR device that can automatically adjust its settings depending on the workers using it. In the case of an older worker, the font could enlarge or, in the case of workers with language barriers, the device could show pictograms to create better understanding.

3.2.2.6 Data sharing across departments is improving cognitive ergonomics

It was highlighted that the availability of data across various departments and layers of a company is promoting new ways of planning work with consideration for cognitive ergonomics. Digital planning systems are able to produce Key Performance Indicators that can describe the actual status of a production system and provide real-time individual ergonomics data showing the stress status of the workers. Hummel et al. (2015) mentioned that this kind of data provides quantitative measurements, which other departments in a company, such as planning, can use to plan work and activities, thus, being able to adjust their interactions with the workers on the shop floor accordingly.

3.2.2.7 Technology forecasting can identify necessary skills early on

It is mentioned that the changing requirements to workers' capabilities and skills mean that companies will need to invest in training and skill development (Pacaux-Lemoine et al., 2017). Before any training can take place, the companies have to identify the prevailing skills their workers will need in the near future. Dworschak & Zaiser (2014) suggested that already before companies invest in any new technologies, strategic level decision-makers could take preliminary steps in identifying the needed skills and training by performing technology forecasting.

Technology forecasting is a method for anticipating and understanding promising future technologies and evaluating their potential and application at an early point in time (Firat et al., 2008). Dworschak & Zaiser (2014) suggest that technology foresight can prepare companies for what capabilities and skills they may need 3–5 years into the future.

3.2.3 Organizational HF/E

3.2.3.1 Hybrid production systems are bridging the gap between humans and machines

CPS and the combination of human workers and automated production parts are said to be creating hybrid productions systems that rely on close human–machine collaborations and new tasks connected to computational devices (Becker & Stern, 2016). Mazali (2018) and Stern & Becker (2017) mentioned that this type of system may reduce organizational losses with mobile assistance systems, intelligent automation, expert knowledge, and workers' creativity. Furthermore, it is suggested that automated and collaborative communication between machines, humans, and systems might replace many aspects of traditional ways of managing, planning, and controlling activities. This will result in new activities that will affect social sustainability performance from a technological and management standpoint (Pinzone et al., 2018).

However, it is mentioned that most of these statements are merely estimates and predictions and do not provide enough depth to the underlying challenges related to this new way of working. Fantini et al. (2018) highlighted that current studies have yet to address challenges, such as how to understand and control interactions between CPS technologies and human workers, how to capture value-added work (decision-making and problem-solving, creative work, social behavior), and how to account for workers' skills and characteristics.

3.2.3.2 New human-machine interactions will affect work organization and design

It was mentioned that as the demand for new competencies changes, the current approaches toward work design and resource management would need to change too. (Stern & Becker, 2017) suggested that classic job design would need an upgrade to include other elements, such as usability, user interface, and human–machine interactions, in addition to new objectives. For example, in human–robot collaboration, it was mentioned that it is important to analyze the tasks and make a clear division between what activities robots and humans will perform (Dannapfel et al., 2018; Kadir et al., 2018). Furthermore, it was suggested that in the integration of HitM, human competencies and organizational factors would both have a relevant role. Fantini et al. (2016) suggest that due to the complexity, variability, and unpredictability of HitM integration, companies must consider organizational factors to influence positive human behavior and performance.

However, Richter et al. (2018) suggest that there is a need for research on the process of studying and designing tools and digital environments, how companies can introduce digital support for workers, and in which context digital work design is happening. Thus, it is still unknown how the combination of technology and work organization will evolve in the factory of the future.

3.2.3.3 Human-centered design will benefit workers

It is estimated that CPS will directly affect workers and create new interactions between humans and machines and the digital and physical world. Therefore, transformation into Industry 4.0 will require new design and engineering philosophies that are human-centric and focus on enhancing and augmenting the human's physical, sensorial, and cognitive capabilities, rather than unmanned autonomous factories (Romero, Stahre, et al., 2016). There were two proposed scenarios for designing CPS: the techno-centric perspective states that human work will be determined by technology, while in the anthropo-centric scenario, workers will be in control and make decisions supported by the CPS (Pacaux-Lemoine et al., 2017).

The techno-centered design is estimated to require workers to behave flawlessly, have a suitable response time, and react perfectly when facing unexpected situations, which is an overstatement of the workers' abilities. Whereas, using a human-centered design when designing intelligent manufacturing systems would improve the global performance of complex and conflicting production objectives and reduce workers' workload (Pacaux-Lemoine et al., 2017).

3.2.3.4 Work organization is expanding across departments

Automated and collaborative communication between machines, humans, systems, and departments is estimated to replace many aspects of traditional ways of organizing, managing, planning, and controlling activities. Pinzone et al. (2018) suggest that this will result in new activities that will affect social sustainability performance from a technological and management standpoint. Furthermore, it is suggested that shared responsibility, proactive positions, and participatory roles across the company are a part of the Industry 4.0 paradigm, and they are restructuring the work relationship on a collective and individual level. Mazali (2018) mentioned that responsibility and decision-making will not be exclusive to the managers in charge, but also include the workers.

3.2.3.5 The combination of new tech. and work organization will determine future skills development

While it is mentioned that the integration of CPS and the increase of new digital technology implementation will demand new skills and competencies, it is also highlighted that it will not be the only determining factor. Dworschak & Zaiser (2014) argue that the combination of new digital technology and work organization chosen in a company will have a determining role in further skills and competence development.

3.2.4 Summary of the Qualitative Analysis

The results from the qualitative analysis provide a fair idea of how the included academic publications dealt with HF/E. In this section, we give a short summary of the results obtained through the qualitative data analysis and highlight the prevailing topics mentioned to have an effect on the physical, cognitive, and organizational ergonomics related to human work in Industry 4.0.

In regard to the domain of physical ergonomics, we highlighted four topics. These four topics covered the increasing automation of manual tasks, safety concerns evoked by close human–machine interactions, how wearable and handheld devices are contributing to the improvement of ergonomics, and how new digital technologies will improve internal logistics in Industry 4.0 companies.

In the domain of cognitive ergonomics, we highlighted the following six topics: Upgrading the workers' problem-solving and IT skills will become a requirement in Industry 4.0. CPS will introduce new forms of human–machine interactions. AR devices could help reduce workers' mental strain. Data sharing across company departments and virtual models could have positive effects on workers' perception and decision-making. Finally, yet importantly, how using technology forecasting could help with the identification of future skills.

In the domain of organizational ergonomics, we highlighted the following five topics: Hybrid production systems are bridging the gap between humans and machines. New human–machine interactions will have an effect on work organization and design. Using a human-centered design in CPS would benefit the workers. Work organization is expanding across departments. The combination of new technology and work organization will determine future skills' development.

Finally, while conducting the qualitative analysis, we noticed that the included publications predominantly favored pinpointing and highlighting opportunities and benefits over challenges and downsides of Industry 4.0 and the implementation of new digital technologies.

4. Discussion

4.1. Contribution

The contribution of this paper is the establishment of to what extent, what type of, and how academic publications on Industry 4.0 integrate HF/E into their research. Thus, highlighting research gaps and areas of focus for future research on HF/E in Industry 4.0. The following are some of the main findings of this paper. The extent of Industry 4.0 research dealing with HF/E is small. Surprisingly, Industry 4.0 research has covered HF/E aspects much better in comparison with research within the HF/E discipline. In addition, the research dealing with HF/E aspects were often theoretical/hypothetical and not developed on empirical research. Most focus on the operational level—overlooking the importance of tactical and strategic levels for the success of HF/E.

4.2. Current Research on HF/E in Industry 4.0

The results from the systematic literature review and the quantitative analysis confirm that Industry 4.0 research dealing with HF/E is limited. While the number of publications on Industry 4.0 research dealing with HF/E has been increasing from 2013 to 2018 (going from one in 2013 to 22 and 11 publications in 2017 and mid-2018, respectively), it is still relatively low. As highlighted in Figure 17 in Section 3.1.2, these numbers are a fraction of the number of publications published on the topics of Industry 4.0 and HF/E separately during the same time span. The initial recommendations for implementing the strategic initiative of Industry 4.0 in Germany (Kagermann et al., 2013) included a focus on research on human work and work organization. From the findings presented in this paper, it is clear that academic research published in English does not accommodate this recommendation very well. Thus, the extent of research in the overlap between the research field of Industry 4.0 and HF/E is limited.

An important element to highlight is the limited empirical evidence that accommodates statements and predictions on how the move toward Industry 4.0 might affect HF/E in industrial companies. As highlighted in Section 3.1.4, around 52% of the publications included in this paper covered the topic of HF/E in Industry 4.0 with theories, estimations, and predictions. In addition, very few of the topics we presented in Section 3.2, which were highlights from the findings of the qualitative data analysis, included empirical evidence. When discussing HF/E in Industry 4.0, the included publications focused on presenting future scenarios, challenges, and opportunities, rather than current findings related to the current state of industry. The following are some examples of such statements.

The estimations of future scenerios where easy tasks are automated (Section 3.2.1.1). Change in skills and competence requirements demanded of workers (Section 3.2.2.3). Automated and collaborative communication between machines, humans, and systems may replace many aspects of traditional ways of managing, planning, and controlling activities (Section 3.2.3.1). Because the publications do not have a foundation of descriptive empirical evidence to support their claims and predictions, they lack the necessary power to present any strong prescriptive actions to overcome the emerging challenges and opportunities.

The qualitative analysis also showed that current research on HF/E in Industry 4.0 is more concerned with lower operational level topics and put a limited focus on the topics related to upper organizational levels. This is in coherence with Pacaux-Lemoine et al. (2017), who also make similar statements. Finally, the majority of research on HF/E in Industry 4.0 is from non-HF/E focused publication outlets, thus, our evaluation is that the majority of the researchers behind the publications are not highly familiar with the HF/E domain, thus, their research approach and perspectives may differ from the typical HF/E researcher. This was evident in many of the included publications in their ways of describing and referring to HF/E. A recurring example was the term "ergonomics," which in many non-HF/E publications outlets was used solely in reference to physical ergonomics and physical strain.

4.3. Future Perspectives for HF/E in Industry 4.0

The findings from the qualitative analysis indicate that researchers, for the most part, are in conformity regarding their predictions and estimations on how Industry 4.0 and new digital technologies might affect humans and work in industry. However, as mentioned in Section 4.2, descriptive empirical evidence is scarce, thus most prescriptive actions and recommendations are untested and lack practical application. Having this lack of empirical data in mind, we propose the following agenda for research on HF/E in Industry 4.0.

4.3.1 Increasing Focus on Empirical Data

To provide practitioners with valid prescriptive actions that enable them to tackle the changing demands of HF/E in Industry 4.0, there is a need for descriptive empirical evidence and tested hypotheses. In addition, empirical evidence is highly important in the creation of a solid foundation that can carry future research within this field in academia. From our perspective as researchers, we find it of great importance to have a sufficient understanding of the HF/E challenges and opportunities that are emerging with the implementation of new digital technologies. This information is paramount in dictating the direction of future research in academia as well as driving HF/E-related solutions and strategies in industry. The results of this paper are a clear indication of how limited this type of empirical evidence in HF/E research is in academia.

Industrial case studies are a great way of collecting empirical data, which could lead to new interesting findings and fresh theories that connect qualitative evidence to mainstream deductive research (Eisenhardt & Graebner, 2007). Flyvbjerg (2006) argues that even single-case studies have their benefits and are a sufficient method for certain important research tasks. Extensive industrial case studies with rich data presentation could be a step in the right direction in validating or rejecting many hypotheses on the changes in human work in Industry 4.0.

Furthermore, we suggest that researchers strive to test conceptual tools, methods, and designs outside of the enclosed walls of controlled laboratories. Rigorous testing in real-life industrial scenarios may highlight the shortcomings of a concept and provide insights and further development. However, this is a two-way street, which is why we suggest and encourage closer collaboration between academia and industry.

4.3.2 Adopting a Holistic Research View on HF/E in Industry 4.0

As we highlighted in Section 4.2, much of the HF/E research in Industry 4.0 focuses on the emerging changes on the operational level and pays little attention to the tactical and strategic organizational levels. Dul & Neumann (2009) highlight the importance of incorporating HF/E in company strategies, which we assess to be ever more important in the transition to Industry 4.0. While the strategic level of a company makes decisions related to the investment of new digital technologies and implementation of CPS, the tactical level focuses on the (re)design of work systems and implementation of new solutions. To ensure sufficient attention to HF/E in Industry 4.0, it is our belief that it is essential to consider HF/E aspects on all three organizational levels.

To accommodate this need, it is important to widen the scope of research on HF/E in Industry 4.0 to include all three organizational levels spanning across the three main domains (physical, cognitive, and organizational) of HF/E, as well as the interplay between them. In addition, due to the novelty of Industry 4.0 and the current limited understanding of the appertaining changes in human work, it might be necessary to explore new territories outside of these three HF/E domains. We suggest that a new research scope should serve to provide a holistic view of HF/E in Industry 4.0 and the effects of pertaining changes on the different aspects in the domains of HF/E. Furthermore, it might be beneficial for researchers exploring HF/E in Industry 4.0 to follow an existing holistic approach such as or similar to the Work System Method (Alter, 2006).

5. Limitations of the Paper

Identifying what terms to include in the literature search was one of the initial aspects we had to consider while working on this paper. On the one hand, the term "Industry 4.0" is popular and commonly used to describe the current digitalization agenda in industry, however, there are other terminologies and words academic publications might use to describe the same concept. On the other hand, some publications might solely focus on one technological aspect and refrain from using any terminologies related to the overall concept associated with Industry 4.0. This different use of words and terminologies might leave room for overlooking relevant publications. Even though we have been very careful in selecting the search terms and did the utmost to be as inclusive as possible without making the search too wide, it is difficult to eliminate the probability of having overlooked publications.

6. Conclusions

Using a Human Factors and Ergonomics (HF/E) approach to analyze, understand, and design human work and Cyber Physical Systems in Industry 4.0 could be highly beneficial. However, due to the novelty of the Industry 4.0 concept, further research within this narrow field is in high demand. In this paper, we conducted a systematic review on HF/E research in Industry 4.0 with focus on investigating the manner and to which extent academic publications on Industry 4.0 integrate HF/E aspects into their research. On the basis of these findings, we present future perspectives for research on HF/E in Industry 4.0.

Our findings show that academic publications dealing with this specific topic are scarce. The majority of the publications are conference proceedings and a low percentage of the publications come from HF/E-related publications outlets. The data from these publications are very heavy on estimations and predictions on future scenarios and present limited novel descriptive empirical data. Thus, many of the prescriptive actions and recommendations these publications suggest are unfounded and untested. In addition to these findings, we present a future perspective for HF/E in Industry 4.0, which includes recommendations for future research approaches to HF/E in

Industry 4.0. Such recommendations include increased focus on empirical evidence to establish a baseline for the challenges and opportunities emerging with new digital technologies and Industry 4.0 and widening the research scope to include all three organizational levels (strategic, tactical, and operational), rather than the current situation, which is primarily focused on the operational organizational level.

5. Human well-being and system performance in the transition to industry 4.0

The objective of the chapter is twofold. On the one hand, it contributes to the second DRM stage (Descriptive Study I) with descriptive empirical data to answer RQ3. On the other hand, it also contributes to the third DRM stage (Prescriptive study) aiming at answering RQ4 and parts of RQ1. This chapter includes a brief summary of Paper B (Kadir & Broberg, 2020b), as well as the full version of Paper B

RQ3: How is the introduction of new digital technologies affecting human well-being and system performance?

RQ4: How might industrial companies ensure human well-being and system performance in connection to the implementation of new digital technologies?

The main purpose of the Descriptive Study I stage in the DRM is to conduct empirical studies and using empirical data to investigate the research topic and to get an enhanced understanding. This focus on empirical data was well aligned with the findings from Chapter 4. Indeed, as highlighted in Chapter 4 and Paper A (Kadir, Broberg, & Conceição, 2019a), the current research on HF/E in Industry 4.0 are mostly theoretical/hypothetical with minimal empirical research as a foundation. Thus, the main recommendation for future research included an increased focus on descriptive empirical data, documenting how new digital technologies are affecting humans and human work. Besides, as mentioned in Section 2.2.1, the purpose of HF/E is to ensure human well-being and overall system performance. Thus, it made great sense to focus the descriptive study on establishing an understanding of how the introduction of new digital technologies might affect these two factors in the transition to Industry 4.0.

The purpose of the Prescriptive Study stage of the DRM is to use the findings from the descriptive studies to identify and address key factors that can improve the existing situation. In line with the DRM stage Thus, Paper B (Kadir & Broberg, 2020b) also includes several recommendations for how industrial companies might ensure human well-being and overall system performance as they transition to Industry 4.0.

Summary of Paper B

Achieved results

- Understanding of how new digital technologies might affect perceived human well-being and overall system performance before, during, and after implementation.
- During the implementation of new digital solutions might negatively affect both human well-being and overall system performance.
- After a successful implementation, both well-being and overall system can performance improve.
- Identification of factors affecting perceived well-being and overall system performance before, during, and after the implementation of new digital technologies.

Contribution

- Empirical evidence on how perceived human well-being and overall system performance change before, during, and after the implementation of new digital technologies.
- Implications for practitioners and recommendations for how to ensure human well-being and overall system performance in connection to the introduction of new digital technologies in the transition to Industry 4.0.

Paper B

Human well-being and system performance in the transition to industry 4.0

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Human well-being and system performance in the transition to industry 4.0

Abstract

The transition to Industry 4.0 and the introduction of new digital technology in industrial companies are evoking profound changes in their work systems. It is estimated that the emerging changes will affect both the overall performance of systems and the well-being of the humans working in and interacting with systems elements. However, descriptive empirical evidence focusing on the pertaining effects of these emerging changes is minimal. Moreover, without the support of such empirical evidence, it will be challenging to provide prescriptive actions for how industrial companies might navigate through the transition to Industry 4.0.

In this paper, we address this research gap and present empirical evidence collected through ten industrial case studies illustrating how the introduction of Industry 4.0-enabling technologies may affect human well-being and system performance before, during, and after implementation. Hereafter, we provide several implications and recommendations for practitioners.

Relevance to industry: The results serve to assist organizational decision-makers, and Human Factors and Ergonomics experts with prescriptive guidelines and recommendations for dealing with and overcoming challenges related to human well-being and system performance in the transition to Industry 4.0.

Keywords

Cyber-physical systems; Human factors; Digital transformation; Change Management; Digitalization

1. Introduction

The introduction of new digital technologies in industrial companies is creating new socio-technical interactions between physical and virtual elements, leading to human-related, technical, and organizational changes (Becker & Stern, 2016). In order to deal with these changes and the related emerging challenge, there is a need for descriptive empirical data that can serve as the foundation for prescriptive, e.g., theories, models, and frameworks that can guide future research as well as practitioners in their journey towards Industry 4.0. However, such empirical data is currently minimal (Hoffmann et al., 2019; Kadir, Broberg, & Conceição, 2019a; Schneider, 2018). In this paper, we address this gap and present empirical evidence that illustrates how new digital technologies affect human well-being and system performance before, during, and after implementation. In addition, we introduce Carroll & Fidock's (2011) model of technology appropriation as a means to understand the change process and put forward recommendations on how to stage the process of transitioning to Industry 4.0.

Optimizing human well-being and overall system performance is the main objective of the scientific discipline of Human Factors and Ergonomics (HF/E) (IEA, 2018), which makes it a highly appropriate approach for designing and implementing new digital solutions. Indeed, researchers such as (Pacaux-Lemoine et al., 2017; Romero, Stahre, et al., 2016) suggest that overcoming challenges emerging with the changes evoked by new digital technologies might require new human-centric design and engineering philosophies. Such approaches can create a holistic understanding of the complex relationships and interplay between the various organizational elements and could have an essential impact on overall system performance and human well-being in all of the transitioning phases leading to Industry 4.0.

1.1. The current state of HF/E research on Industry 4.0

In a literature review focusing on the intersection between Industry 4.0 and HF/E, Kadir, Broberg, & Conceição (2019a) highlight that the majority of the limited academic research publications in this area are from non-HF/E related publication outlets. Most of the empirically driven research in this intersection are focusing on technical or isolated aspects of the new digital technologies. Thus, they do not manage to explore the emerging changes and identify relationships and interdependencies between system elements (Schneider, 2018). In addition, HF/E publications also seem to have a narrow scope and mostly focus on conceptual frameworks, simulations, and laboratory experiments. The following are some examples of such research. A human factors taxonomy to model workers' behavior developed on experts' opinions (Longo et al., 2019), and testing digital twins to enhance the integrations of ergonomics in workplace design with experiment (Caputo et al., 2019b). While such research studies are highly valuable and necessary for the development of new novel solutions and the research field in general, they fall short of addressing the socio-technical changes and support claims and predictions on how work and work organization is changing (D. Horváth & Szabó, 2019).

Over the past few years, the number of academic publications from non-HF/E outlets that use case studies to research HF/E in Industry 4.0 has increased. Similar to this paper, publications such as Cagliano et al. (2019), Ghobakhloo & Fathi (2019), Hoffmann et al. (2019) apply an inductive approach using industrial case studies to create new theories and generate new theoretical implication. The majority of the remaining publications (e.g., Fantini et al. (2018), Kaasinen et al. (2019), Peruzzini et al. (2019), Peruzzini & Pellicciari (2017), Stern & Becker (2019)) use case studies as part of a deductive approach to test and validate novel conceptual frameworks and methodologies. However, it is essential to highlight that, in general, theoretically driven research dealing with the topic of Industry 4.0 outweighs empirical driven research (Cagliano et al., 2019; Frank et al., 2019; Kadir, Broberg, & Conceição, 2019a).

One of the reasons for the limited empirical data might be a symptom of the current level of digitalization and implementation of industry 4.0-enabling technologies in industrial companies. The futuristic vision of an interconnected, highly digitalized, and automated smart factory is still just a vision for most companies. While most industrial companies are aware of the potential benefits of achieving such a vision and are investing in Industry 4.0 capabilities and technologies, the majority are still in a transitioning phase, experimenting and piloting standalone solutions and working on establishing a digital foundation. Thus, most industrial companies have started their Industry 4.0 journey, but have yet to successfully apply the newly gained capabilities across their operations (KPMG, 2017). Chien et al. (2017) describe this transition phase as Industry 3.5. While this transition is predominantly focusing on upgrading technical aspects and ensuring compatibility between new and old systems, there is also another aspect, which is the impact on the organization and the individuals in it.

1.2. Organizational transition and technology appropriation

In the past, digital technologies in the context of work have predominantly been information technologies (IT) (which have often mostly affected knowledge and administration workers) and secluded automation technologies such as fenced industrial robots (which have had limited direct contact with human workers and other organizational elements.) Still, it is relevant and useful to look back at some theories and models dealing with organizational and human-related challenges in the introduction of new digital technologies from before the concept of Industry 4.0. Such a look back might enable a better understanding of the similarities and differences between past efforts and the current transition to Industry 4.0.

Because the journey to Industry 4.0 is a transition that industrial companies are going through, it might be beneficial to clarify the meaning *transition* in this context. Bridges (2003) describes a transition as a multiphase psychological process that organizations and individuals go through as they come to terms with a new situation, which new changes have created. Change without transition will usually lead to disappointing results, and end up costing a lot of money (Bridges, 2003). In the context of IT projects, Markus (2004) argues that the implementation of new IT solutions that trigger organizational changes needs a more human-centric approach that combines IT project management and organizational change management and proposes an approach called *technochange*. A technochange approach is an iterative process spanning over three phases (before, during, and after implementation), which involves both IT functionality and related organizational changes, e.g., training, new performance metrics, and (re)design of business processes (Markus, 2004). While Markus (2004) is more than a decade old and solely focuses on IT projects (which often have a limited effect on shop-floor workers), an approach such as technochange might still be relevant and useful in the context of Industry 4.0. The approach has similarities with an HF/E approach since it considers both technical, organizational, and human aspects.

How humans use and react to new technologies is not a notion unique to Industry 4.0. Indeed, user resistance is a crucial factor in the successful implementation of information systems and has been an essential theme in information systems research (Beaudry & Pinsonneault, 2005). Another concept related to user acceptance and user resistance is technology appropriation. Similar to resistance models, technology appropriation deals with the process of how users “take possession” of new technology and incorporate them into their existing work over time (Carroll, 2004). Often, users end up using new digital technologies in unexpected ways, less than expected, or not using them at all (Janneck, 2009).

When organizations introduce new digital technologies, three types of organizational changes emerges; Anticipated changes (the changes that are planned and prepared for ahead of time), emerged (change that arises unexpectedly, which were not anticipated initially), and opportunity-based (unplanned changes that are introduced intentionally) (Orlikowski & Hofman, 1997). Thus, the successful implementation of new digital technologies and type of related changes depend on the process from introduction to the usage of the technologies Janneck (2009). The users need to make sense of how the new technologies fit with their work tasks and routines and receive support on how to use and work with the new technologies. If the new technologies do not accommodate the users' needs, the users might end up disappropriating the technology or aspects of it Carroll & Fidock (2011). Carroll & Fidock (2011) argue that disappropriation of new technology might not be an act of resistance, but are instead a reaction to the failure of gaining any value of the technology. Figure 24 shows the appropriation process developed by (Carroll & Fidock, 2011).

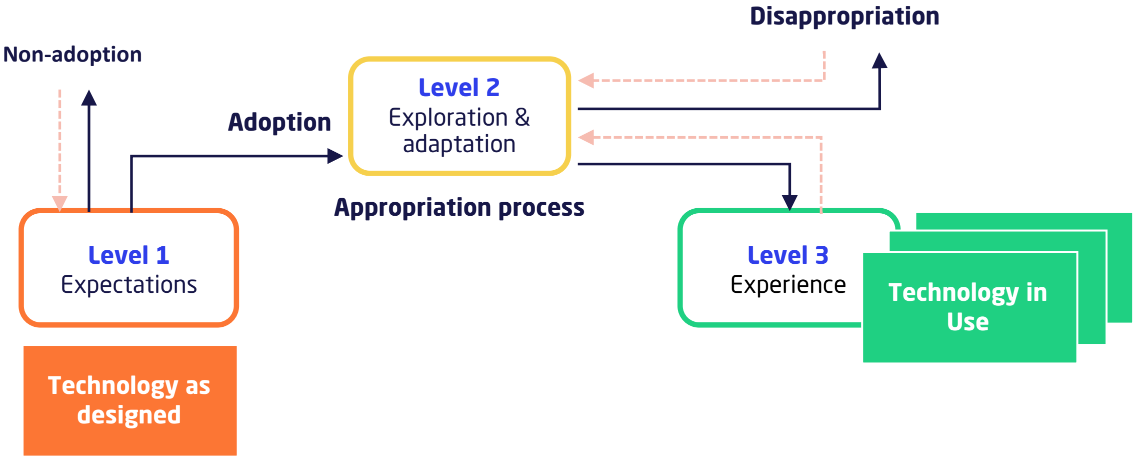

Figure 24 – Carroll & Fidock's (2011) Model of Technology Appropriation recreated for this thesis.

As mentioned at the beginning of this section, compared to IT projects, the changes emerging with the implementation of new digital technologies have more significant implications on human-work and organization, which makes the application of an interdisciplinary approach that accounts for humans as well as technologies useful (Pacaux-Lemoine et al., 2017). The increasing implications amplify the benefits of viewing the journey towards Industry 4.0 as an organizational transition with multiple phases. Thus it is essential to understand the appropriation process and of how new digital technologies affect human well-being and overall system performance before, during, and after implementation. Such an understanding is especially important when considering that organizational factors such as lack of appropriate competences and skill, inadequate organizational structure and processes, and organizational resistance to change might be some of the barriers of the transition to Industry 4.0 (D. Horváth & Szabó, 2019).

In this paper, we use empirical data to present industrial experiences of implementing and working and appropriating with new digital technologies. We highlight how new digital technologies affect human well-being and overall system performance before, during, and after implementation. We have conducted several retrospective industrial case studies and collected empirical data documenting work and work organization changes, as well as the appropriation of new digital technologies in connection with the transition to Industry 4.0. Understanding these changes could serve as a foundation for the development of new theories, practical frameworks, and prescriptive principles for aligning humans, technology, and organization in Industry 4.0 work systems.

We present the empirical findings by highlighting positive and negative effects on perceived well-being and perceived performance throughout the transition phases of before, during, and after implementation. In addition, we provide a summary of factors that positively and negatively affect perceived well-being and overall system performance, as well as several implications and recommendations for practitioners.

The organization of this paper is as follows: In Section 2, we present the methodology used to collect and analyze the empirical data. In Section 3, we showcase the results from the analysis and present the factors affecting perceived well-being and performance in the three transition phases. In section 4, we discuss the findings from Section 6; see how they relate to the technology appropriation model, as well as present implications and recommendations for practitioners. In Section 5, we discuss the limitations of the paper. Lastly, in Section 6, we summarize the paper, give final remarks, and draw a conclusion.

2. Methodology

Case studies are an efficient method for using qualitative data to develop theories inductively and bridging these theories to popular deductive research (Eisenhardt & Graebner, 2007). Thus, in this paper, we used qualitative data collected through exploratory retrospective case studies following the approach of R. K. Yin (2009), at ten different sized industrial companies, all located in Denmark. The data collection included observation of the work systems in operations, demonstration of work with new digital technologies, and semi-structured interviews with employees on strategic, tactical, and operational organizational levels. We use the results of these case studies to highlight the variety and range of possible effects on well-being and performance.

2.3. Case studies

To get a heterogeneous sample, the case companies were of various sizes and operated in different industries. However, they were all similar in that they had started focusing on digitalizing work systems and investing in new digital technologies. Most of the companies had been public around their strategy of implementing new digital technologies and had shown a positive attitude toward the changes associated with industry 4.0. Some of the companies had been the center-point of articles in Danish newspapers, discussing the changes new digital technologies were creating in their companies, while others had representatives giving keynote speeches about their industry 4.0 and digitalization initiatives at industrial seminars.

The digital technologies the companies had introduced in their work systems differed from company to company. However, the similarity between them was the novelty of the technologies in the work systems and the companies' lack of experience in working with them. In most cases, the companies aimed at either automating or digitalizing parts of processes in their work systems. However, it is important to note, that not all of the cases had been through all of the three transition phases, and some were still in the During phase at the time of the case studies. Refer to Table 5 for an overview and description of the digital technologies included in the case studies and Table 6 for an overview of the case companies and implemented digital technologies.

Table 5 – Overview and description of the digital technologies included in the case studies.

Tech ID	Digital technologies	Description
T1	AGV	Automated Guided Vehicles that roam around in the same area as human workers and other vehicles manually driven by workers
T2	Digitalized paper flow	Replacement of all papers in and between work systems with digital solutions, i.e., mounted and handheld touch screens such as tablets and smartphones.
T3	System integration	Integrating new digital systems and solutions with existing IT systems and machines. A prerequisite to digital solutions, e.g., Digitalized paper flow and AGV.

T4	Industrial robots	Replacing and automating parts of manual labor with industrial robots
T5	Collaborative robots	Replacing and automating parts of manual labor with collaborative robots.
T6	Advanced computing and vision systems	Replacing and automating parts of manual labor new machines that utilize advanced computing and vision systems.
T7	Data visualization	Generating and visualizing operations and customer-related data to shop floor workers.
T8	Additive manufacturing	Using 3D printers to produce and prototype plastic components.

Table 6 – Overview of case companies and implemented digital technologies.

Company	Size	Industry	T1	T2	T3	T4	T5	T6	T7	T8
A	Large	Manufacture of light metal packaging	X	X	X	X		X	X	
B	Large	Manufacture of games and toys				X		X		
C	Large	Manufacture of electric motors, generators, and transformers		X	X				X	
D	Large	Manufacture of fluid power equipment	X	X	X		X			X
E	Large	Manufacture of loaded electronic boards		X	X	X	X			
F	Large	Manufacture of builders' ware of plastic				X	X			
G	Large	Manufacture of other pumps and compressors				X	X			
H	Medium	Other printing		X	X		X			
I	Small	Manufacture of metal structures and parts of structures		X	X	X	X			
J	Small	Machining					X			

2.4. Data collection

The primary source of the data was semi-structured interviews. In total, we interviewed 35 participants (15 workers and 20 decision-makers) across the ten case companies, where the interview durations ranged between 30 – 90 minutes. The interviews were face-to-face interviews that were audio-recorded and transcribed in Danish. The only exception was Company E and two of the interviews at Company D. In Company E, it was not possible to record due to company policies and the Non-Discloser Agreement. In the case of the two interviews at Company D, it was not possible to record interviews, due to technical issues with the audio recording equipment. Thus, we stored the data from these cases in the form of hand-written notes taken during the interviews. In addition, we note that due to NDAs with the case companies and to ensure the promise of complete anonymity to the interviewees, we refrain from using third-person pronouns (e.g., he or she and his or hers) and use the third plural pronoun (e.g., they and their) when mentioning specific interviewees. Refer to Table 7 for an overview and division between workers and decision-makers interviewed at each case company.

Table 7 – Overview and division between workers and decision-makers interviewed at each case company.

Company	Workers	Decision-makers	Total
A	3	4	7
B	1	2	3
C	-	2	2
D	2	3	5
E	2	3	5
F	1	1	2
G	-	2	2
H	3	1	4
I	1	1	2
J	2	1	3
Total	**15**	**20**	**35**

These interviews focused on uncovering how the introduction of new digital technologies had affected the workers' well-being and overall performance before, during, and after implementations. In addition, the interview guide included probes and prompts for how the changes affected the three main domains of HF/E (physical, cognitive, and organizational), change management, and organizational learning. Because of the retrospective nature of the case studies, the interviewees had to recollect from memory the effects on well-being and performance during the different transition phases. In addition, we used passive participation as described by Spradley (1980a) when observing how the workers used and interacted with the new digital technologies. Passive participation entails that we were present at the scene as observers, but did not participate or interact with the workers to any great extent.

2.5. Data analysis

We organized all of the collected data in the computer software *Atlas.ti 7* and followed a systematic coding process comparable to a template analysis as described by (Brooks et al., 2015). We used the framework shown in Table 8 to code all of the data collected data. The *Before* phase is the initial phase where a company has decided to invest (and possibly has chosen) in new digital technologies but has yet started implementing. The *During* phase is the phase where a company is implementing and testing out the new digital technologies. Lastly, the *After* phase is the final phase when a company has implemented the new digital technologies and has decided to continue using them.

Table 8 – The coding framework we used to code the collected data.

Before	During	After
After the decision to invest in the new digital technologies but before implementation. • How was the perceived well-being and performance before implementation? • Which aspects did the interviewees perceive as positive, and which as negative?	During the implementation of the new digital technologies. • How did the perceived well-being and performance change during implementation? • Which aspects did the interviewees perceive as positive, and which as negative?	After the implementation of the new digital technologies. • How was the perceived well-being performance after implementation? • Which aspects did the interviewees perceive as positive, and which as negative?

We used the three main domains of HF/E (Physical, Cognitive, and Organizational) defined by (IEA, 2018) as a guiding framework for coding human well-being related aspects. For system performance-related aspects, we used a framework that covers five measures of performance, which we adopted from (Jenkins, 2017). These five measurements are; Efficacy (the ability to meeting the needs of the employees and organization), Flexibility (the ability to do more and adapt to changes faster), Usability (the ease of use and understanding), Efficiency (the ability to work faster), Safety (the level of safety-related risks).

We divided the coding and analysis of the data into five phases that followed a general inductive approach, as described by Thomas (2006). In the first phase, we read all of the data highlighting and coding statements related to well-being and performance. In the second phase, we categorized the codes into the three categories of before, during, and after implementation. In the third phase, we categorized and analyzed the codes using a bottom-up approach and building affinity diagrams (Holtzblatt & Beyer, 2016) for each of the three categories of before, during, and after implementation. The purpose of the affinity diagram was to identify the various themes that had a negative or positive effect on well-being and performance. In the fourth phase, we summarized the main themes emerging in the affinity diagram, which we present in the following section (Section 3). Lastly, in the fifth phase, we identified several factors impacting perceived well-being and performance before, during, and after implementation of new digital technologies, which we present in Section 3.13.

Refer to Table 9 for an overview of the overall procedure from data analysis to the results presented in Section 3. Furthermore, Table 9 also includes a detailed description and outcome of each of the mentioned five phases.

Table 9 – Overview of the overall procedure from data analysis to the results presented in Section 3.

Phase	Description	Outcome
1	Organized all of the collected data (i.e., interview transcriptions and field notes) and for each case study.	A well-organized dataset with a transparent structure to improve transparency.
	Read the interview transcriptions once case by case for each case study.	An understanding of the themes and discussed topics of the interviews.
	Re-read each interview transcription immediately after the first read-through, highlighted, and coded relevant statements related to well-being and performance using the software Atlas.ti 7.	A list of unique codes that summarized statements related to well-being and performance discussed during the interviews. The result included about 200 different codes divided into two groups of well-being and performance. Example of a code: *Well-being – Received limited information on upcoming changes.*
2	Identified the context of each statement in each code from the previous phase, to categorize the codes into the three categories of before, during, and after implementation of new digital technologies.	An organized code structure where the codes were divided into the three categories of before, during, and after. At this point, each of the three categories had two groups of codes, well-being, and performance. Example of a code in this structure: *Before: Well-being – Received limited information on upcoming changes.*
3	Developed six two-level affinity diagrams, one for each of the two groups (well-being and performance) within each of the three categories (before, during, and after). On the first level, the codes were clustered into groups, and on the second level, the groups clustered into themes.	Six different affinity diagrams, each with a list of emerging themes consisting of grouped codes. These themes describe the effects on well-being and performance.
	The emerging themes were categorized into the two categories of "positive" and	Overview of the effects on well-being and performance before, during, and after the implementation of new digital

	“negative” effects on perceived well-being and performance.	technologies, which are highlighted in Table 10 and Table 11 in section 3.
4	Summarized and described the effects highlighted in Table 10 and Table 11 to create a better understanding of their content, context, and how they were expressed in the case studies.	A detailed description of the positive and negative effects on perceived well-being and performance before, during and after implementation of new digital technologies, as described in sections 3.1 – 3.12.
5	Clustered the effects affecting perceived well-being and performance before, during, and after implementation of new digital technologies (Table 10 and Table 11 from Phase 3) into groups. Hereafter, we identified the underlying factors that might have an impact on the effects of each group.	A list of factors that have an impact on perceived well-being and performance before, during, and after the implementation of new digital technologies, as shown in Table 12.

3. Results

In this section, we present the results from the case studies and answer how the introduction of new digital technologies affect perceived human well-being and system performance before, during, and after their implementation. In the parts on well-being, we highlight notions on how the well-being of the workers was affected, while in the parts on performance, we highlight notions that had affected performance. Furthermore, we have divided the results into two categories, positive and negative effects. It is essential to mention that the results we present in this section are the variety and range of possible effects impacting perceived well-being and performance that emerge in conjunction with the introduction of new digital technologies. Thus, not every presented effect had occurred in all of the case studies. Refer to Table 10 for an overview of the results related to perceived well-being and Table 11 for perceived performance.

Table 10 – Overview of the effects on well-being before, during, and after the implementation of new digital technologies.

Phase	Well-being (positive)	Well-being (negative)
Before	• Workers like being informed and engaged by management on upcoming changes. • Workers are excited about working with new technologies. • Workers look forward to learning new skills and competences.	• Workers are worried about working with new digital technologies. • Workers question their skills and competences. • Workers fear they will have to work faster. • Workers worry about health and safety. • Workers fear they will lose their job.
During	• Workers like being involved in the design and implementation process.	• Workers get frustrated with limited information on upcoming changes.

	• Workers like learning new skills and competences. • Workers like working with new digital technologies.	• Workers become reluctant to work with new digital technologies. • Workers worry about working with new digital technologies. • Workers get frustrated with partially developed solutions. • Workers get stressed because of changes in the work division. • Workers get stressed because of red numbers and alarms.
After	• Workers are contempt with improved physical and cognitive ergonomics. • Workers like new ways of working. • Workers worry less about health and safety. • Workers worry less about losing their jobs.	• Workers are frustrated with the lack of management's commitment. • Workers are frustrated with the lack of standardized operating procedures and training material.

Table 11 – Overview of the effects on performance before, during, and after the implementation of new digital technologies.

Phase	Perceived performance (positive)	Perceived performance (negative)
Before	• Companies assume that new digital technologies will increase competitiveness and assist with meeting increasing customer demand. • Companies assume that informing and involving workers will reduce resistance to upcoming changes. • Companies assume that involving workers in the design process will increase the success rate and the performance of the final developed solution.	• Decision-makers find it challenging to assess organizational maturity. • Decision-makers find it challenging to get all employees to support digital transforming initiatives. • Some workers need training in using simple IT and digital technologies.
During	• Decision-makers state that workers' involvement and feedback are essential in developing successful new digital solutions with high performance. • Decision-makers state that software-based digital solutions are more straightforward to develop.	• Companies find it challenging to find appropriate tasks and use-cases for some new digital technologies. • Decision-makers and workers state that limited process understanding can prolong the development process of new digital solutions. • Decision-makers state that system integrations limit the full utilization of new digital technologies.

		• Decision-makers state that some workers do not use the new technologies as intended. • Decision-makers and workers state that partially developed solutions decrease overall system performance. • Decision-makers and workers state that unreliable new digital technologies lead to uncertainty.
After	• Decision-makers and workers state that efficiency, and process and information flow improves. • Decision-makers and workers state that relevant information becomes more transparent and enables better decision making and faster communication. • Decision-makers state that customer satisfaction increases.	• Decision-makers and workers state that all work becomes dependent on the new digital technologies. • Decision-makers and workers state that new digital solutions need to be continuously improved even after full implementation. • Decision-makers fear that in the long run, an increase in employee turnover rate is inevitable.

3.1. Before – Positive effects on well-being

Before the implementation of any new digital technologies, the majority of the companies had informed their workers on the upcoming changes to some degree. This information had both created excitement as well as some uncertainties. Regardless, informing the workers and engagement from the management team seemed to play an essential role in how workers had perceived the upcoming changes. All companies had different approached and degrees for informing and engaging their workers. Nevertheless, the workers all expressed their appreciation for receiving the information before the implementation of any new digital technologies.

Workers were generally excited about working with new digital technologies. When asked, almost all of the workers expressed that they were excited about working with new digital technologies when they initially received the information. This excitement was especially apparent in the cases of tangible technologies such as industrial robots, cobots, and AGVs. Several of the workers mentioned that after hearing of the news, they spend time reading about and watching videos on the technologies in their own spare time.

In addition, the workers also perceived the need for learning new skills and competences as positive. While some of the workers believed the new skills could help them perform better at their current jobs, others viewed it as an opportunity to grow and improve their job profile in case of future hiring outside of their current company. One of the workers at Company H mentioned that they were highly aware of the benefits of learning to work and operate new digital technologies and solutions.

> *I know that the more I learn about these new digital technologies and robots, the more competences I will gain. And having these competencies will not hurt if my boss one day decides that the company does not need me anymore.* – Worker (Company H)

3.2. Before – Negative effects on well-being

The information on the upcoming implementation of new digital technologies might also lead to uncertainties affecting well-being. While many workers might be excited about working with the new digital technologies, others might find it worrying. Several of the interviewed workers explicitly expressed that they initially were worried about working with the new digital technologies, and the majority mentioned they had at least one colleague who had been very worried.

While most of the interviewed workers perceived the possibility to gain new knowledge and learn new skills positively, several expressed they also had feared that they would not be able to keep up with the new requirements demanded of them. Some workers feared that they would not be able to keep up working with the new digital technologies, while others feared that they would not have the capacity to learn new skills and competences. Besides, several decision-makers and workers across the cases expressed that this fear was predominantly shared by their aging (>45 years old) colleagues and workers. All of the aging workers we interviewed expressed that they had experienced this fear to a certain degree.

The questioning of own skills and competencies becomes even more prominent in cases when the decision-makers promote the new digital technologies as performance improving tools. This definition puts pressure on the workers even before the workers have started working with the new digital technologies. Company A, C, and E, all had experienced workers directly expressing their lack of enthusiasm to work in new ways if this meant that they had to work faster or increase the number of outputs. Several workers at Company E had been very vocal against working in a new setup that would include an industrial robot, which would increase the work cell's output by 100%. Similarly, before the digitalization of a work cell, the decision-makers at company C had to address several workers that had been worried about the increase of workload resulting from working in new ways.

> *Before we had even started implementing anything, several of the workers told us [the management team] that they would quit if the number of items they currently produced were to increase.* – Decision-maker (Company C)

In the case of cobots and AGVs, workers might initially become worried about personal health and safety because of the technologies' autonomous nature and ability to share the same physical workspace as the workers. The majority of the workers who had experienced working with such tangible technologies mentioned that, before working with the new technologies, they were worried about being hit and getting hurt. To overcome this worry, a decision-maker at Company G mentioned that their company had made the experience of getting hit by a cobot a mandatory part of the training the workers had to go through before they could start working with the cobots.

With the information about investments in new digital technologies combined with the mentioned uncertainties, some workers had become worried about their future as workers at their company. While few of the workers we interviewed mentioned that they had feared for their jobs, all of them highlighted that they at least knew of at least one worker that have had concerns in this regard. In the extreme case of company A, because they believed that getting fired was inevitable, several workers had decided to quit just after the management team had announced that they would invest in AGVs.

> *I understand if people are afraid (of being fired). I know that several of my colleagues quit their jobs when they heard we were getting AGVs. I believe they feared for their future at the company.* – Worker (Company A)

3.3. During – Positive effects on well-being

Involving the workers in the implementation of the new digital technologies were mentioned in all of the case studies. The decision-makers emphasized the workers' satisfaction with being actively involved, and the interviewed workers who had been actively involved confirmed this notion. Several of these workers mentioned that having influence and contributing to how the final solution ended up, gave them great pleasure and motivation in their daily work.

This active participation and involvement meant that some workers had to learn and gain additional non-technical skills, such as project management and systematic problem-solving skills. Thus, while the workers were excited about getting the opportunity of gaining new knowledge and competences in the *Before* phase, they seemed equally happy once the learning and competence upgrade had started in the *During* phase.

> *I gained a lot of knowledge on how to manage projects. I was able to get an active role in the project management part… I had no previous experience in project management, so it took time to learn, and I also made some mistakes along the way, but I learned a lot. It was a great experience.* – Worker (Company I)

The excitement about working with the new digital technologies from the *Before* phase tended to continue for some workers into the *During* phase. Besides, some of the worries from the previous phase (e.g., getting fired) had decreased when the workers had started working with the new technologies and begun to understand the technologies' limitations. One of the workers at company A emphasized their relief as they slowly became accustomed to working with the company's newly acquired AGV as they realized how many limitations the new technology had in comparison to the human forklift drivers.

3.4. During – Negative effects on well-being

While in some cases, the workers had played an active role in the redesign of the work system and implementation of the new digital technologies, in other cases, they had not. In the latter cases, and in instances where the workers had not received adequate information on the changes, the level of frustrations had increased tremendously for some workers.

In some cases, the workers' frustration had resulted in a reluctance to work with the new digital technologies. Company A had digitalized and automated a significant part of a process in a work system, without involving and informing the workers as well as not eliminating the old ways of working. Thus, because they had not removed the ability to work in the old way, several workers had directly refused to work with the new digital technologies and had continued to operate using the old manual process. The consequence of several workers refusing to use the new digital technology and comply with the new ways of working had created a division between the team members as well as with the decision-makers. Both workers and decision-makers mentioned that this division had resulted in a decrease in morale and performance. Ultimately, the reluctant workers had received written reprimands with the threat of being fired if they did not comply.

Working with new digital technologies can evoke different types of worries. Several workers expressed that they initially were apprehensive about causing errors or breaking the new digital technologies. Knowing the high price of the new digital technologies and being unfamiliar with using them had created a certain level of cautiousness and nervousness. Such cautiousness and nervousness were especially relevant when workers had received limited training in using the new digital technologies and working in new ways. Several decision-makers mentioned that such worries might ultimately lead to real, costly, and irreversible errors and mistakes.

> *We have observed that our workers typically make more mistakes when they feel unsafe and uncertain. It is one of the reasons we push automation and digitalization in the first place*. – Decision-maker (Company A)

Partially developed new digital technologies and solutions had also resulted in frustrations for the workers. Because the new digital technologies are continuously developed and implemented throughout this phase, technical errors are almost unavoidable. Several workers and decision-makers mentioned this issue and highlighted the frustrations it caused. Such issues were mentioned to cause a break in the workflow, errors, and worsen cognitive and physical strain. To avoid such issues, Company B makes a great effort to develop any new digital solution as much as possible before testing them in their shopfloor operations.

> *We know that immature technologies that create more complexity for our operators lead to frustration and the operators not using the new technologies at all.* – Decision-maker (Company B)

In the case of automation, the organization of work and division of labor between workers and new digital technologies had lead to stressful situations, where the workers had ended up having additional roles and taking on additional tasks. One of the workers at Company A explained that the new industrial robot, which had replaced his coworker, was only able to take on 50% of his coworker's tasks. Thus, the worker had to perform all of his tasks as well as the remaining 50% of his former colleague’s tasks. The worker expressed that the extra tasks had created much stress and negatively affected his well-being.

The increase of alarms and red numbers introduced with new digital technologies that serve to give warnings and alerts might result in frustration and stress, especially when the warnings and alerts are a result of technical and system errors, which the operators have no control over. One of the new digital solutions at company A had been programmed with a countdown timer that indicated how long the workers had to complete a maintenance task. If the worker did not complete the task within the set time, the software would automatically notify the worker's manager with a direct email. As a worker explained, both the countdown and notification to the manager felt very demoralizing and stressful, mainly because the time the software developers had accounted for was not enough. Thus, the workers were never able to finish the task in the set time.

3.5. After - Positive effects on well-being

In almost all of the cases, once a solution had been fully implemented and standardized in operations, the workers experienced that there had been an improvement in their well-being. Thus, the workers had become much happier with the new ways of working in comparison to the *During* phase. Almost all of the workers and decision-makers expressed this notion of improved well-being. Tangible automation technologies were mentioned in all of the cases to have improved physical ergonomics. Besides, the majority of workers working with digitalization solutions expressed similar notions concerning cognitive ergonomics.

In general, the workers seemed fond of working with the new digital technologies in the *After* phase. Despite ongoing challenges, and the new digital technologies not being flawless, the majority of the workers expressed that they were satisfied with the new ways of working and use of the new digital technologies. While in several of the cases, the final implemented solution had still contained errors and not optimized, the workers expressed that they were still pleased with the new digital technologies and felt that the benefits outweighed the challenges.

It is what it is. You learn to accept and live with it (referring to the flaws of the companies implemented digital solution). That is how new technology works. Nothing is perfect. – Worker (Company H)

As mentioned in Section 3.2, some workers had been worried about their health and safety before the implementation of their new digital technologies. However, this worry seemed to disappear as the workers got used to the new ways of working. No workers expressed that they had any worries in this regard in the *After* phase.

Most workers tended to view the new changes in a positive light in the *After* phase and were less worried about losing their jobs to the new digital technologies. Indeed, the majority of the workers mentioned that they did not believe that they would lose their jobs in the near future because of their company's investment in new digital technologies. The reason for this notion was often related to the workers' understanding of how limited the new digital technologies are regarding flexibility and adaptability in comparison to human workers.

Losing our jobs is not something we the workers fear here in our company… These machines cannot do everything by themselves. Someone has to take care of them, work around them, and make sure that they are operating as they are supposed to. – Worker (Company F)

The above statement is highly representative of how the majority of the workers expressed their feelings on the idea of being replaced by new digital technologies and machines.

3.6. After - Negative effects on well-being

Decision-makers' commitment to anchor the new digital technologies and new ways of working in the work systems, might affect workers' wellbeing. For example, while the decision-makers at Company H had been very good at information the workers on the upcoming changes, they had not been equally efficient at following up on the emerging changes. The management team had spent little time on adjuring and setting up the necessary frameworks for support and feedback after the implementation of the new digital technologies. This limited follow up had resulted in frustration for the workers.

Several workers expressed frustration concerning limited training in the new ways of working, usage of the new digital technologies as well as lack of standard operation procedures (SOP). In several of the cases, limited training and lack of SOPs had lead to workers performing tasks and using the new digital technologies in various ways, thus resulting in errors, misalignment, and reproducibility issues.

3.7. Before - Positive effects on performance

The majority of the decision-makers agreed that performance-related factors drive investment in new digital technologies. The companies had invested in new digital technologies because they believed that their investments would increase competitiveness and place them in a better market position. Also, several decision-makers mentioned that they believed new digital technologies could assist them in meeting increasing customer demands. However, all the decision-makers from the small and medium companies highlighted that the decision to invest in new digital technologies was a necessity for the survival of their company.

We are facing constant competition from companies all around the world. We knew that our company would not survive if we did not change from serial production to order production… We could only achieve this [surviving] by investing in these new digital technologies. We

> *would not have been here today if we had not taken this decision.* – Decision-maker (Company I)

Informing and involving the workers in the upcoming changes might reduce organizational friction and ease the transition. The majority of the decision-makers shared this notion and believed that their initiative in this regard had positively affected the performance of the new implemented digital solutions. Besides, the majority of the companies had relied heavily on the workers to come up with ideas for how their company could use new digital technologies. In company D, the senior management team had started an internal competition within their company, looking for innovative ideas for using additive manufacturing technologies. The workers/departments with the best ideas had received a small 3D printer, which they had used to test their ideas. In 12 months, the management team had, in total, distributed 35 3D printers. This initiative had been received so well by the organization that Company D had created a new department focusing on servicing all departments with 3D printed prototypes of components and products.

Several decision-makers mentioned that involving workers early on in (re)designing the work system might result in better solutions. The notion was that the workers are usually very familiar with how the different elements of the work systems operate and interact with each other, thus having their involvement is essential in creating the best solutions.

> *The workers had an essential role in the redesign of the work system. They designed the workflow based on how they were actually working and not how we thought they were.* – Decision-maker (Company C)

However, several decision-makers and well as workers mentioned that it is highly essential to involve the “right” workers and not just any worker. In this context, the decision-makers described the “right” workers as someone who has an exceptional understanding of how the given work system operates and interacts with other work systems, the capability to provide constructive feedback, and does not have a negative attitude towards changes and new digital technologies.

3.8. Before – Negative effects on performance

Several decision-makers highlighted that assessing organizational maturity and readiness to adapt to- and work with new digital technologies can be very challenging. Company D had previously failed with the implementation of several new digital technologies in their operations because of worker's limited understanding and technical maturity to work in new ways. To overcome this challenge and ensure that it did not repeat, a decision-maker at Company D explained that they had hired an external consultancy to assess their organizational maturity and identify the necessary competencies before deciding to move forward with any new digital technologies.

While informing and involving workers early on might have a positive effect on well-being and performance, it is challenging to get all employees on board with the emerging changes. The decision-makers all agreed that, while it is an essential element, getting organizational buy-in and reducing organizational friction is a great challenge. One of the decision-makers at Company E highlighted the difficulties their company faced in getting buy-in from the employees in regards to digitalization and implementation of new technologies. This decision-maker mentioned that it is difficult to convince people to get on board with a digitalization strategy, especially when the decision-makers have limited data supporting the claim that working with the new digital technologies will be better than the “old” ways of working.

While some workers find it easy to use and work with new digital technologies, others do not. Several decision-makers and workers mentioned that aging workers find it more challenging to work with new digital technologies compared to younger workers. Several workers and decision-makers mentioned that this challenge was usually due to the aging workers having limited experience with computers in general. Having many aging workers, the decision-makers at Company H team had decided to provide every worker with training in basic computer use. Basic computer use had included simple tasks such as turning computers on and off, and opening and closing basic computer programs.

3.9. During – Positive effects on performance

As mentioned in section 3.7, involving workers in the design process in the *Before* phase was considered to have a positive effect on not only well-being but also performance. Similarly, involving workers and receiving their continuous feedback as they work and test the new digital technologies in the *During* phase was mentioned to be constructive and essential in developing successful high performing solutions. Almost all of the large case companies had, to a certain degree, involved the workers and considered their feedback while developing and implementing their new digital solutions. In the small case companies, not only had the workers been involved, but they had also been in charge of almost every aspect of the development and implementation of the new digital technologies.

Several decision-makers mentioned that in most cases, the development of new digital solutions and implementation of the new digital technologies had been quick and straightforward. The notion of quickness and straightforwardness was especially emphasized in the case of digital solutions that were solely software-based in comparison to solutions that included both software and hardware. Thus, depending on the complexity of the chosen new digital solutions, a company could rather quickly start developing, testing, and working with the new digital technologies. Several decision-makers expressed that this relative quickness was highly valuable because they could evaluate the usefulness of the new digital solution in a short period without wasting too many recourses.

3.10. During – Negative effects on performance

In several of the cases, the decision-makers had decided upon which technology to invest in and implement before having identified how they were going to use it. Thus, once they had acquired the new digital technology, they found it challenging to find appropriate tasks and use-cases. This challenge was especially relevant in the case of cobots. Several decision-makers from different companies mentioned that they had invested in cobots because they found the idea of the technology exciting; however, after acquiring the cobots, they struggled to find appropriate tasks the cobots could partake. One of the decision-makers at Company D explained that upon learning about cobot, they believed the technologies sounded interesting had the potential of being in their department.

> *I asked my manager if we could get a cobot to see if we could find some use for it in our department. My manager replied that we already had one stored away somewhere. Apparently, another department had bought it one year ago but had not able to find any use for it.* – Decision-maker (Company D)

Limited understanding of work system elements and processes can prolong the development and implementation process. This understanding includes, e.g., how work is planned and performed

in the work system, how departments communicate with each other, how inputs are processed, and output delivered. Almost all decision-makers noted that they had experienced particular challenges because they overlooked or not accounted for some elements or interactions within and between their work systems. In the case of company C, the digitalization of paper flow in a shop floor work cell had resulted in communication challenges and information error
s with the planning department. These challenges and errors had occurred because the decision-makers in charge of the redesign of the work cell had overlooked how the new changes might affect the particular way the work cell processed and used inputs.

Most of the decision-makers mentioned that they had experienced several drawbacks and challenges related to integration between the new digital technologies and the existing IT system infrastructure. It was highlighted that system integration was both technically challenging and resource-consuming and had limited full utilization of their new digital solutions. Several decision-makers had avoided connecting the new digital technologies with the current systems to bypass the challenges of system integration. These companies had initially used the new digital solutions as stand-alone solutions and had not connected them to the rest of the existing IT systems. For example, Company E had invested in a new, highly digitalized solution for picking-lists that could potentially vastly increase performance. However, due to challenges with IT system integration, the workers could not use the majority of the features of the solution. Thus, the workers had resorted to taping a piece of A4 paper on the machine’s screen and a pen hanging on an elastic band, which they used to document the items they picked.

Because the *During* phase is a transitioning phase between the old and new ways for working, in some cases, the old and new had overlapped. As mentioned in section 3.4, in such scenarios, some workers had been reluctant to use the new digital technologies and chosen to keep working in the old ways. A decision-maker from Company A mentioned that when the workers had not used the new digital technologies, the performance of the entire work system had drastically decreased, and resulted in poor product quality and lost profits.

> *One of the workers who refused to use the new solution had a large order worth around €55.000. At the end of the line quality control, we realized that everything this worker had produced in that order had to go straight into the trash.* – Decision-maker (Company A)

As mentioned in section 3.4, partially developed solutions can have a negative effect on the workers’ well-being in the *During* phase. Similarly, partially developed solutions can also negatively affect performance in this phase. Several workers mentioned that the general workflow and work efficiency had initially decreased because of technical errors and deficiencies. In some of the cases, the new technologies had added new tasks, steps, and sub-processes the workers had to account for while the new digital solution was taking its final form. While developing and testing their AGV solutions, Company A had experienced several challenges that had negatively affected both the workers' well-being and overall system performance.

> *We have had several stops in the operations because of technical error. These errors and stops created an annoyance for the workers and were also very time-consuming. In busy periods, we observed that the workers would push the AGVs to the side and not use any time on restarting them.* – Decision-maker (Company A)

Several workers mentioned that they viewed partially developed solutions as unreliable and felt an increase in uncertainty regarding their tasks and operation of the new digital technologies. Consequently, such uncertainties had resulted in longer lead times and decreased deficiency. A worker at Company H expressed that initially, they did not find their new digital paper flow system very reliable, and at times, felt very uncertain when using it. In many instances, the received information had seemed wrong, which had resulted in the worker being forced to go around the entire shop floor and find the people responsible for the provided information to ensure the validity of the received information. This additional task had required much effort and, in several instances, taken hours to complete.

3.11. After - Positive effects on performance

While system performance might decrease in the initial stages of the *During* phase, it tends to increase once the companies have fully developed the new digital solutions and implemented the new digital technologies and transitioned into the A*fter* phase. The Efficiency and workflow improved as new digital solutions mature and are sufficiently developed and implemented. The majority of the decision-makers, as well as several workers, highlighted this notion and expressed contentment with the new ways of working. In the case of digital paper flow at Company C, one of the decision-makers mentioned that once they had developed and implemented one of their new digital solution, the changeover time for that specific work system had vastly decreased. This improvement had been a great accomplishment because the mentioned work system had never managed to live up to the targeted changeover time as defined in the protocols. However, the new digital paper flow had enabled them to reach and go beyond the target changeover time.

Digital technologies that grant access to existing or newly created data had, in some cases, increased transparency in the process and information flow within as well as between work systems. Such transparency had had a positive effect on performance across the majority of the companies' supply chains. In the cases of digital paper flow, i.e., case company C and company H, both the decision-makers and workers mentioned how the new digital solutions had created such transparency.

> *In the past, I could not follow the orders, but today I can look and see where in our facility the order is. This is highly valuable information because we usually have very tight deadlines with customers all over Scandinavia… Knowing where an order is at all times ensures that I can react timely if something goes wrong.* – Worker (Company H)

Thus, data availability and transparency had made it easier to communicate and identify problems and challenges within and across the work systems as well as enabling better decision-making. Several decision-makers and workers mentioned and highlighted such notions as positive effects on system performance.

The implementation of new digital technologies was also mentioned to have had improved production lead times, and product quality and uniformity as well as reducing error rates and customer claims. Several decision-makers highlighted that such improvements had had a positive effect on customer satisfaction, which they had experienced through direct communication with their customers and customer claim. One of the decision-makers at Company A mentioned that after a few months, their investment in automation with advanced vision systems had decreased customer claims, as well as product waste by a noticeable amount.

3.12. After - Negative effects on performance

The development of the new digital solutions seemed to be continuous, which in some cases had continued even after the final digital solution has been developed. Over time, as the workers work with the digital solutions and use the new digital technologies in various ways, new errors and technical issues can emerge that need to be handled and solved. Such challenges can have a negative effect on system performance, and dealing with them can be highly resource consuming. In cases where it is not possible to change back from the new way (working with new digital technologies) to the old way of working, technical issues and errors can bring the entire work system into a halt. Also, because the individual work systems become increasingly dependent on each other's input and output, technical issues in one work system might have an impact on other work systems across the supply chain. While none of the decision-makers or workers let to believe that such scenarios had occurred, several decision-makers expressed that they feared it would eventually happen.

Several decision-makers highlighted that their company had invested in new digital technologies to grow without hiring any additional workforce. However, most decision-makers expressed that ultimately, an increase in employee turnover is inevitable. All but one of the decision-makers at company A mentioned that they had initially not believed that their investment in new digital technologies would result in workers being laid off. However, once they had fully implemented the new digital technologies, they had been forced to lay several workers off because they could not find new tasks suitable tasks for them.

> *We have laid off several forklift drivers because of our new AGVs. It is a way of rationalizing our investments. This is given, because we have to pay for the AGVs in one way or another, and in this case, we had to optimize our staffing to justify our investment.* – Decision-maker (Compay A)

3.13. Summary of the results

In the results presented in the previous sub-sections of section 3, we highlighted how new digital technologies affected perceived performance and well-being before, during, and after implementation. Based on these results, we have identified several factors that impact the perceived well-being and performance in the three phases. Refer to
Table 12 for an overview of these factors.

Table 12 – Factors impacting perceived well-being and performance before, during, and after the implementation of new digital technologies.

Phase	Well-being factors	Performance factors
Before	• The level of information on the upcoming changes and planned digitalization initiatives. • Clarity on how upcoming changes might impact current roles, tasks, and responsibilities. • Job security	• The organization's maturity and readiness to work with new digital technologies. • The level of support and buy-in from all stakeholders and employees. • The current IT skills and worker's capacity to learn new ones.
During	• The Level of information on the ongoing changes related to the digitalization initiatives. • The level of workers' involvement in the development and implementation process.	• The level of knowledge and understanding of the elements and interactions within and between the work systems. • The level of workers' involvement in the development and implementation process.

	• Work division between workers and new digital technologies. • The design and maturity of the new digital solutions.	• Training and updating workers' skills and competences. • The design and maturity of the new digital solutions.
After	• The decision-makers' commitment and allocated resources. • Training materials and Standard operating procedures. • The impact on physical and cognitive ergonomics. • Job security.	• The level of dependence on new digital technologies. • The decision-makers' commitment and allocation of resources. • The success rate of the new digital technologies.

4. Discussion

The contribution of this paper is twofold. On the one hand, it provides empirical evidence collected through case studies on how perceived human well-being and overall system performance changes before, during, and after the implementation of new digital technologies. On the other hand, it highlights implications for practitioners as well as giving recommendations for how to ensure human well-being and performance.

4.1. Results discussion

The way new digital technologies affect human well-being and system performance are subject to change before, during, and after implementation. Indeed, the results indicate that each of these three phases evokes different positive and negative perceptions of how well-being and performance changes.

In the *Before* phase, well-being is almost equally affected both negatively and positively. While the workers tend to have some fear regarding the upcoming changes and their particular situation in their company, they also tend to showcase some excitement about the new digital technologies and working with them. In regards to performance, the perception of how new digital technologies might affect performance is in some ways similar to how they affect well-being. While there are some positive perceptions and expectations on how the new digital technologies are going to affect performance positively, there are almost the same amount of negative perceptions and expectations.

In the *During* phase, the negative aspects affecting well-being and performance tend to outweigh the positive ones. Because most of the new digital technologies are not fully developed and might have errors and flaws when used in the *During* phase, the workers might view them as unreliable. Thus, new digital technologies become a source of uncertainty. Unreliable digital technologies and increased uncertainty might result in stressful situations and scenarios that will have a negative impact on both performance and well-being. Besides, the development of a new digital solution and successful implementation requires a holistic understanding of elements and interactions within, and between work systems Thus, limited knowledge in this regard might become a contributing factor to some of the other negative aspects such as finding an appropriate use for new digital technologies, providing limited training, and poor work division.

In comparison to the *During* phase, in the *After* phase, after the new digital technologies have been implemented, both perceived well-being and performance tend to improve. Performance improves in the form of efficiency, workflow, and transparency, which also play a contributing factor to the improvement of well-being in the form of physical, cognitive, and organizational ergonomics. However, not every negative aspect disappears in this phase. Limited standardization and insufficient management involvement tend to negatively affect perceived human wellbeing, while dependency on- and continuous improvement and development of the new digital solutions can negatively affect performance.

In summary, perceived well-being and performance are in a neutral position in the *Before* phase, worsen in the *During* phase, and improve beyond the neutral *Before* phase in the *After* phase. Figure 25 shows this simple overview of how perceived well-being and overall system performance changes in the three transition phases.

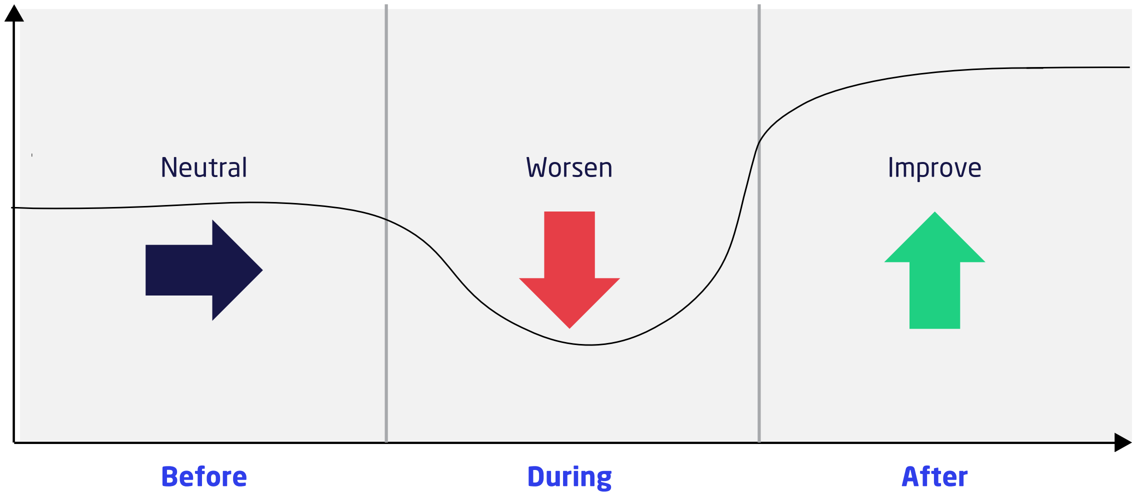

Figure 25 – Simple overview of how perceived well-being and overall system performance changes before, during, and after the implementation of new digital technologies.

How perceived well-being and performance change throughout these three phases are not surprising. These findings fall well within popular change and organizational transition concepts and models such as "Bridge's model of transition" (Bridges, 2003), which we introduced in section 1.2. Such models can explain the process organizations, as well as individuals, go through when transitioning into something new and unfamiliar. What they have in common is the description of transition being a multiphase process that will potentially experience a decrease in performance and well-being. This decrease will usually occur approximately mid-transition, which is similar to the results of this paper.

A common theme reemerging in both the *Before* and *During* phase is information and involving employees. Employee involvement and the application of human-centered design is a prominent topic when discussing the design of Industry 4.0 work systems (Kadir, Broberg, & Conceição, 2019a). Pacaux-Lemoine et al. (2017) argue that a human-centered design approach to intelligent manufacturing systems would have a positive effect on both global system performance and human well-being. Similarly, as highlighted in Sections 3.1, 3.3, 3.7, and 3.9, the results of this paper indicate that employee involvement affects perceived well-being and performance. These findings fall in line with the findings of Tortorella et al. (2018), which uses the empirical results from a survey with 146 Brazilian manufacturers. Tortorella et al. (2018) argue that companies reinforcing employee involvement in their Industry 4.0 journey and implementation of new digital technologies may be able to improve their operational performance. However, successful technology appropriation requires user involvement not only in the design phase but also in the adoption phase (Janneck, 2009).

Informing and involving workers early on can also affect the appropriation of new digital technologies. In Carroll & Fidock's (2011) model of Technology Appropriation shown in Figure 24, the first level of technology appropriation focuses on expectations of the new technology. Thus, before working with new technologies, the users will have some expectations that will affect the choice of adoption or non-adoption. As presented in Section 3.4, Company A had experienced several workers not adopting the newly introduced digital technology and refusing to comply with the new ways of working. Thus, the decision to not use the new digital technologies became a barrier to the appropriation process.

As mentioned in Sections 3.4 and 3.10, in the *During* phase, the perceived well-being and performance tend to worsen before it improves again and move past the baseline of the *Before* phase. Fullan (2001) refers to this phenomenon as the "Implementation Dip" and describes it as

…a dip in performance and confidence as one encounters an innovation that requires new skills and new understandings (Fullan, 2001).

The implementation dip seems to describe the reason behind the decrease in perceived well-being and performance. The workers need to have sufficient information on the changes, understanding of the new digital technologies, their future role in the organization, as well as getting the necessary training and education to perform their jobs adequately. Furthermore, partially developed technologies might also have a significant impact, which explains Company B's decision not to introduce new digital technologies before they are sufficiently developed. The decrease in perceived well-being is a common trait in transition and change processes.

In "Bridge's model of transition" (Bridges, 2003), a transition consists of three overlapping phases, which begins with an ending, then moves into a "neutral" zone and ends with a new beginning. The neutral zone is comparable with what we in this paper described as the *During* phase. Bridges (2003) highlights that in the neutral zone, people's well-being and performance is often negatively affected. This decrease in well-being fit well with the results presented in Section 3.4. This effect on well-being and performance might also affect the technology appropriation process. In Section 3.4, we highlighted that some workers were worried about using the new digital technologies because of the fear of breaking them. Having such fear might limit the users' aspiration to explore the new digital solution (as in level 2 in the model of technology appropriation in Figure 24), thus learning by doing, which is a highly regarded technology appropriation activity (Janneck, 2009).

In the *After* phase, Section 3.10, limited standardized operating procedures and training and lack of decision-makers' involvement and commitment were the main factors affecting the workers' perceived well-being. We argue that decision-makers' involvement and commitment might also contribute to some of the factors negatively affecting perceived performance, e.g., continuous development and dependency on the new solutions. Such factors are highly dependent on the decision-makers prioritizing and allocating the necessary resources to ensure that the new digital technologies are operational and live up to the expectations. Failing to do so can lead to subpar- or, in worst cases, unsuccessful transition. Hindshaw & Gruin (2017) refer to this phenomenon as the "Valley of Death." The valley of death is a phase in organizational transitions where the initial excitement and energy about the transition have vanished, and the people involved have grown tired of the project. We believe that company H, might have gone through this phase and that the management team's lack of commitment and resource allocation after the implementation of the new digital technologies is because of the lack of excitement the digitalization project possessed in the initial phases.

Improved performance (e.g., productivity, competitive advantage, and financial gains) is the essential driver of the move towards Industry 4.0 and the implementation of new digital technologies (J. M. Müller et al., 2018). However, performance and well-being are closely related, and they can influence each other in both the short and long-term (Dul et al., 2012). Thus, understanding how the implementation of new digital technologies affect performance and well-being plays an essential part in realizing the expected benefits of the new digital technologies. The findings of this paper pave the way for a more holistic understating of how new digital technologies affect human well-being and overall system performance before, during, and after implementation. This knowledge and understanding can assist in establishing a foundation for prescriptive tools and methods that can ensure a successful (re)design of new digitalized industrial work systems. Such prescriptions might be essential in aligning humans, technologies, and organization, thus ensuring human well-being and overall system performance in the journey towards Industry 4.0 and a smart interconnected digitalized factory.

Because of the nature of case studies, it is challenging to generalize the findings. However, the richness of the empirical data provides a great insight into some of the different challenges related to well-being and performance that might emerge with the implementation of new digital technologies. Thus, enabling us to provide prescriptive measures to deal with these specific challenges.

People are, in general, reluctant to change and need to be informed and engaged with in order to comply and adapt to new changes. This reluctance is not much different in the case of the journey towards Industry 4.0 and digital transformation scenarios. However, one of the elements that might be different in this aspect is that industrial companies have limited experience with these new digital solutions. Thus, it might be challenging to articulate the benefits and challenges to the employees in the *Before* and *During* phases. Not having this specific knowledge might lead to an increase in organizational friction and stakeholder alignment throughout the different layers of an organization, ultimately leading to negatively affecting human well-being and overall system performance.

4.2. Implications for practitioners

In this section, we will highlight several implications and recommendations for practitioners that might be embarking on an industry 4.0 journey and considering implementing new digital technologies. By practitioners, we refer to internal decision-makers on strategic, tactical, and operational organizational levels that might be in charge of the digital transition as well as internal and external consultants (e.g., ergonomists and HF/E specialists) who might be assisting organizations in their digital transition.

The implementation of new digital technologies is an organizational transition that requires a holistic understanding of the organization in its entirety and acknowledged as a process of overlapping phases that will affect human well-being and overall system performance. While it might be tempting to begin and rush the transition process in expectations of achieving the benefits in the shortest time as possible, it might be wise to slow down and ensure this holistic understanding. Such understanding might lead to crucial insights that could potentially reduce or assist in mitigating uncertainties and risks. Besides, informing and involving employees seems to have an impact on the success and final performance of the implemented new digital technologies.

Practitioners need to be aware of the likelihood of decreasing well-being and performance during the implementation of new digital technologies. However, in successful implementations, it is most probable that both well-being and performance will increase and surpass the baseline level before the implementation.

4.3. Recommendation for practitioners

In the following section, based on the results, we will present several recommendations for practitioners on how to ensure human well-being and system performance throughout the three different phases of *Before*, *During*, and *After*. Decision-makers can use these recommendations as guiding principles when moving through the transition phases, while internal and external consultants can use them to assist their clients in this transition.

4.3.1 Recommendations for the Before phase

- Link digital strategy with the strategic objective to ensure that everyone in the organization understands the reason behind the investment in the new digital technologies.
- Inform and engage all relevant stakeholders on all organizational levels to reduce organizational friction and obstacles as well as aligning expectations.
- Evaluate if the workers have the necessary competences or if there is a need for additional training and education.
- Develop and follow a systematic approach for (re)designing the work systems with the new digital solutions.
- Gain a sufficient understanding of elements and interactions within and between the targeted work system(s). Such an understanding will increase the potential of highlighting technical, as well as organization-related challenges that could have adverse effects on human well-being and overall system performance.
- Apply a human-centered design and involve the affected employees early on in designing the new digital solutions. The benefits of involving the workers are twofold. On the one hand, these employees have much more excellent knowledge about the work systems function in day-to-day operations. On the second hand, involving the workers at this stage might reduce the adverse effects on well-being and performance in the *During* phase.

4.3.2 Recommendations for the During phase

- Apply a systematic, iterative approach for introducing new digital technologies and developing new digital solutions.
- Plan and allocate the necessary resources.
- Continuously inform the organization of the ongoing changes.
- Ensure that the workers know how to use the new digital technologies, but also leave room for exploration and adaptation.
- Establish a system for continuously capturing feedback from the users.
- Get a sufficient understanding of the new digital technologies to generate a basic yet realistic idea on the pertaining limitation.

4.3.3 Recommendations for the After phase

- Standardize the new ways of working after the implementation of new digital solutions.
- Develop standard operating procedures and training materials. Replace and altogether remove non-applicable old materials from sight.

- Establish a program for how to train workers (new workers).
- Develop a life cycle management to ensure maintenance, updates, and continuous improvement of the new digital solutions. This life cycle management plan should include a system for collecting, storing and using continuous feedback from the users to ensure optimal usability and performance.

5. Limitations and future research

Because we have collected the presented empirical data through ten different case studies at ten different companies, it might be challenging to draw broad generalizable conclusions. Thus, the reason we present the data as a sample of various examples that might affect the well-being and performance before, during, and after the implementation of new digital technologies. Also, we might have been able to generate an even greater collection of data with more depth if it had been possible to follow the cases proactively as well as having greater access to the companies and their employees.

Future research could include in-depth prospective case studies that run over an extended period. Because the option of data collection is more extensive and can include a wide variety of both quantitative and qualitative data and measurements, such case studies might generate an even greater understanding of how the transition to Industry 4.0 might affect human well-being and overall system performance. Such an understanding is essential in creating a solid foundation for predictive estimations, preventive measures, and prescriptive guidelines and frameworks, which can ease the transitioning process and increase the success rate of digital transformation initiatives.

6. Conclusion

While the concept of new digital technologies are highly attractive and promising many benefits, most industrial companies have yet to reach a level that can be considered as entirely industry 4.0. The journey towards industry 4.0 involves creating a digital foundation for carrying new digital solutions in the future. However, most companies are not used to using and working with new digital solutions. Thus even small-scale digitalization efforts can create challenges that might affect well-being and performance before, during, and after the implementation of the new digital technologies.

In this paper, we presented empirical data from ten different industrial case studies conducted in ten different industrial companies in Denmark. Using the data from these case studies, we presented a range of factors that have positive and negative effects on perceived human well-being and overall system performance. In summary, the results indicate that during the implementation of new digital solutions, both well-being and system performance are negatively affected, while after a successful implementation, both well-being and performance improve. In addition, we highlight implications for practitioners as well as several recommendations for how practitioners might overcome the challenges presented in the findings.

6. Designing work systems in the transition to Industry 4.0

This Chapter covers the remaining two papers included in this Ph.D. thesis, Papers C and D. The main objective of this chapter is to answer RQ5 and parts of RQ1. In regards to the DRM stages, Paper C falls in under stage 2 (Descriptive Study I), and stage 3 (Prescriptive Study), while Paper D falls across Stage 2, 3, and 4 (Descriptive study II).

RQ5: How should industrial companies approach the (re)design of work systems in connection with the implementation of new digital technologies?

While RQ4 focused on how to ensure human well-being and system performance when introducing new digital technologies in the transition to Industry 4.0, this chapter aims at answering how to approach the (re)design of work systems in this transition. Paper C and D both contribute to answering RQ5; however, each from a different perspective. Paper C focuses on the overall approach for work system (re)design projects in connection to the introduction of new digital technologies. In this paper, I present a conceptual framework that combines elements from HF/E, Lean- and Design Thinking, and highlight that it would be beneficial to use a Human-Centered Design (HCD) approach for (re)designing work systems.

While Paper C highlights the benefit of using an HCD approach, it does not cover and explore this proposal in depth. Thus, as a follow up to this recommendation of using an HCD from Paper C, Paper D proposes a validated framework for using an HCD approach for designing work systems in the transition to Industry 4.0. Thus, providing two frameworks, which combined answer RQ5. It is essential to mention that we developed both of the proposed frameworks using the empirical data from the descriptive studies, similar to going from the DRM stage 2 to 3. However, we only validated the proposed framework from paper D. Thus, only Paper D went through stage 4 of the DRM.

Summary of Paper C

Achieved results

- A framework that combines HF/E and Design- and Lean thinking for how to approach work system (re)design projects on an operational, organizational layer.
- Illustrating the different aspects of the framework with examples from an industrial case study.

Contribution

- A general conceptual approach for how industrial companies might approach the (re)design of work system in connection with the implementation of new digital technologies.
- A prescriptive tool, which practitioners can use in the process of (re)designing work systems in connection with the introduction of new digital technologies.
- A diagnostic tool for academics to apply when analyzing and trying to understand the (re)design process of a work system.

Summary of Paper D

Achieved results

- Understanding of challenges related to the implementation of new digital technologies.
- A framework that combines HF/E, work system modeling, and strategy design for (re)designing industrial work systems in connection to the introduction of new digital technologies.
- Validated the proposed framework through an industrial case study.

Contribution

- Empirical data on implementation challenges of new digital technologies.
- A practical Human-Centered approach industrial companies can apply to (re)design work systems in connections with the introduction of new digital technologies.
- A diagnostic tool, which academics can use to analyze and understand how a newly developed industry 4.0 related concept and solution might affect the overall system performance and well-being of the humans working in the work systems.

Paper C

A framework for designing work systems in industry 4.0

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**Note*
This paper was written and published in British English. However, for the sake of consistency, the version included in this thesis is in American English.

A framework for designing work systems in industry 4.0

Abstract

The introduction of new digital technologies in industrial work systems and increasing implementation of Cyber Physical Systems are evoking new and unknown challenges and opportunities related to aspects of human work and organization. To ensure human wellbeing and overall system productivity, there is a need for interdisciplinary methods and approaches for dealing with the challenges and taking advantage of the opportunities. In this paper, we present a conceptual framework for designing Industry 4.0 enabled work systems, which serves to accommodate this need. The framework combines elements and principles of Design- and Lean thinking methodologies and Human Factors and Ergonomics, thus making it a practical, systematic, and iterative, human centered approach. We use examples from a retrospective industrial case study to illustrate elements of the framework and provide several implications for practitioners.

Keywords

Industry 4.0, Lean design, Collaborative design, Organizational processes, Technology

1. Introduction

The road towards Industry 4.0 leads to an unclear destination, with many uncertainties and unexpected challenges (Qin et al., 2016). While the benefits of new digital technologies are irrefutable, so are the related challenges emerging with the introduction of these novelties into industrial work systems. The term Industry 4.0 originated from Germany's initiative to increase industrial competitiveness through digital technologies (Kagermann et al., 2013) and is similar to the American equivalent, Smart Manufacturing (Davis et al., 2015). These terms refer to the dynamic growth of technological capabilities and the ever-evolving digitalization initiative that has become a permanent bullet point on the agenda of many industrial companies.

One of the key concepts behind Industry 4.0 is Cyber-Physical Systems (CPS). CPS are complex sociotechnical systems where physical and virtual elements overlap and humans and technology co-exist and co-operate in solving complex tasks (L. Wang et al., 2015). Such digitally enhanced work systems are sparking changes and complexities in organization structures, workplace arrangement, and the way people work and perform daily routines (Longo et al., 2017). In addition, the roles and responsibilities of human workers are changing with the increasing automation of work, removing certain job positions and tasks, while paving the way for new ones (Lorenz et al., 2015).

To realize the benefits of Industry 4.0, there is a need to address these emerging changes through the implementation of interdisciplinary approaches for qualifying strategies and suitable human–technology solutions that can create transparency for the human workers (Gorecky et al., 2014). There is a requirement of new human-centric design and engineering philosophies that focus on enhancing the human's sensorial, cognitive and physical capabilities (Romero et al., 2016). To accommodate this requirement, it will be necessary to explore, test and validate new approaches for designing Industry 4.0-enabled work systems founded on the combination of different existing concepts and methods.

Our contribution in this paper is a framework that combines elements from Design- and Lean thinking methodologies with Human Factors and Ergonomics (HF/E) that serves to guide the process of designing Industry 4.0-enabled work systems. We believe that combining these three methods would be beneficial because 1) Design thinking provides a method for dealing with novel and innovative ideas, which could be useful in the case of introducing new and untested digital technologies in industrial work systems that might result in new ways of working and organizing work. 2) HF/E ensures considerations regarding human well-being and human–technology interactions. 3) Lean thinking is a concept many industrial companies are familiar with and it provides a systematic approach for improving work systems. The addition of Lean makes a great vehicle for delivering such a new approach because it includes terminologies and methods most companies are already familiar with, which could potentially increase the usability of the framework. The framework is, on the one hand, a prescriptive tool that practitioners can use in the process of (re)designing Industry 4.0-enabled work systems. On the other hand, it can function as a diagnostic tool that academics can apply to analyze and understand the (re)design process of a work system.

The International Ergonomics Association defines HF/E as 'the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance' (IEA, 2018). Design thinking provides a user-centered approach to innovation that focuses on using sensibility and methods to identify needs, brainstorming and prototyping (Brown, 2009; Carlgren et al., 2014). In addition, as a response to the increasing digitalization in recent years, the concept of design sprints has emerged as a new key method for designing digital products and services (Banfield et al., 2016; Knapp et al., 2016). Because the design of Industry 4.0-enabled work systems includes unfamiliar and untested elements and interactions, using design thinking could be beneficial in overcoming the related challenges.

Combining HF/E and design practices is not new and the concept of Human-Centered Design (HCD) is an example of this combination. HCD combines these two methods with the intent of designing and developing more usable interactive systems (BSI Group, 2010; Giacomin, 2014). While Design thinking and HF/E are not widely adopted approaches in industry, Lean thinking, also referred to as Lean production, is a well-known and common approach used by industrial companies to, for example, improve quality, eliminate waste, create flow, organize work and continuously improve work processes (Womack & Jones, 2003). In addition to Lean production, lean thinking has also branched into digital product development, that is, the Lean start-up concept (Ries, 2011), from which we also include elements in the suggested framework. Thus, our objective with this framework is to provide a practical, human-centered, systematic yet iterative approach for implementing new digital technologies in industrial work systems.

The organization of the rest of this paper is as follows: In Section 2, we explain the methodology used to achieve the results of this paper. In Section 3, we present the results and the proposed framework for designing Industry 4.0-enabled work systems. In Section 4, we discuss the results and findings, implications for practitioners as well as highlighting the limitations of the paper and make suggestions for future research. Lastly, in Section 5, we summarize the paper and provide concluding remarks.

2. Methodology

We combined two different methodological approaches to achieve the results presented in this paper. We used existing theories and models to develop a conceptual framework for designing

Industry 4.0-enabled work systems as well as conducting case studies to highlight a 'best practice' of how industrial companies are currently dealing with the (re)design of industrial work systems in conjunction with the implementation of new digital technologies. We used the results of the best practice case study to present examples that illustrated aspects of the proposed framework. In Sections 2.1 and 2.2, we describe the methodology behind the framework and case studies, respectively.

2.1. Developing a conceptual framework

Our approach for developing the proposed framework focused on using existing methods and theories from different domains dealing with concepts and challenges that bear a resemblance to the topic of this paper, which is the (re)design of industrial work systems to accommodate unfamiliar and untested digital technologies. This approach is similar to what Zahra & Newey (2009) refer to as 'Mode 2: Borrowing and Extending'. This Mode 2 approach is suitable when combining well-known theories to a new phenomenon in a new setting at the intersection of different disciplines. We found this approach highly appropriate because our intent was to combine three different theories, Design-, Lean thinking and HF/E to explore the design of Industry 4.0-enabled work systems.

For the practical process of developing the conceptual framework, we followed the eight-phase approach presented by Jabareen (2009). These eight phases are 1) mapping the selected data sources, 2) extensive reading and categorizing of the selected data, 3) identifying and naming concepts, 4) deconstructing and categorizing the concepts, 5) integrating concepts, 6) synthesis, resynthesis and making it all make sense, 7) validating the conceptual framework, 8) rethinking the conceptual framework.

2.2. Industrial case study

Conducting case studies is an efficient way to collect empirical data and document current standard practices in industrial companies, thus connecting qualitative evidence to deductive research (Eisenhardt & Graebner, 2007). Since October 2017, the authors of this paper have conducted seven different retrospective and explorative case studies, investigating how industrial companies in Denmark approach the (re)design of work systems as the result of the implementation of new digital technologies. These companies were different in size and operated in different industries. To highlight differences and similarities amongst these case studies and identify a best practice approach, we analyzed and compared the cases following the case study research approach by R. K. Yin (2009).

For this paper, we chose to focus on and use the results of one of these seven case studies, which we used to illustrate elements of the framework. The reason behind choosing this specific case study was the case company, which we will refer to as Company A, had what we considered a best practice approach for designing Industry 4.0-enabled work systems. We evaluated Company A's approach as best practice because they had a systematic approach, which included some design considerations in comparison to the other companies. The other companies had paid limited attention to design aspects when (re)designing their work systems and had plunged into implementation straightaway.

2.2.1 Data collection

The case study at company A consisted of qualitative data, which we collected through semi-structured interviews with two production development engineers, whom we will refer to as

Respondent A and Respondent B, who had been in charge of the redesign process and managing the pilot project. We carried out the interviews in face-to-face settings, audio-recorded and transcribed them in Danish. The interview with Respondent A had a duration of approx. 80 minutes while the interview with Respondent B lasted approx. 150 minutes. We were also able to observe the work system in operation using a passive observation type (Denzin, 1978) and took notes in accordance with (Spradley, 1980a). Furthermore, the company granted us access to different materials such as PowerPoint presentations and photos the engineers had taken to document the process of the pilot project. We analyzed the qualitative data with a focus on defining and describing the approach that Company A had applied to redesign their work system. In addition, we analyzed and compared this approach to our proposed framework as well as identified examples from the case study, which we could use to illustrate elements of the framework.

2.2.2 Case setting

Company A is a large (>250) manufacturer of electric motors, generators and transformers. They have been on the path of Industry 4.0 for several years, implementing and incorporating digital solutions in their operational level work systems. Their strategic vision for the next five years also has an intense focus on the utilization of new digital technologies. Company A has many work cells dedicated to the assembly of products with numerous single parts that are too expensive and complicated to automate. This challenge had forced the strategic level decision-makers (executive and senior management) to prioritize digitalization over automation.

With digitalization in mind, the decision-makers had identified certain technologies for implementation as well as choosing a specific work cell for a pilot project. This pilot project focused on digitalizing a work cell by converting all essential information received on paper into a digital format in the form of a touch screen and linking product components and bill of materials through a handheld scanner, thereby going from being highly dependent on the use of paper to becoming completely paperless. In addition, this project relies on seamless information flow between the work system and adjacent departments, that is, planning and quality control, thus the project includes system integration, which Rüßmann et al. (2015) refer to as one of the pillars of Industry 4.0.

The decision-makers had assigned a small team consisting of production development engineers, software developers and the workers attached to the chosen work cell. With the team established, the pilot project had started with a small workshop where the participants had identified the essential elements they could start digitalizing and had created and implemented a working version of the solution after a couple of weeks. Through interactive workshops and continuous feedback and suggestions from the workers, the team had used the initial version as a foundation for the final solution as they had added and tested new features and improved functionalities through iterations.

By a certain date, the team needed to have a viable standardized solution with the potential for a companywide rollout, thus constraining the time the team could spend on developing the solution further. At the time we conducted the case study, the pilot project was ending, and the work cell had experienced a noticeable increase in productivity as well as receiving positive feedback from the workers participating in the pilot project. The project team was still awaiting final formal evaluation from the decision-makers before the solution could roll out to other work cells in the company. Refer to Figure 26 for an overview of the company's process of the pilot project.

Figure 26 – Overview of Company A's process for the work cell digitalization pilot project.

3. Results

In this section, we present and explain the proposed framework for designing Industry 4.0-enabled work systems, and further explain and illustrate elements of the framework with examples from the case study described in Section 2.2.

3.1. Conceptual framework

The framework combines elements from Design- and Lean thinking, with HF/E and has three hierarchy levels, macro, meso and micro levels. The application of the framework is in the following four main phases: Understand, Define, Develop and Deliver. However, the (re)design of a work system is usually sparked and guided by strategic and tactical decisions made by a company's strategic level decision-makers. In the framework, we refer to this initial phase as the Decide/Decision phase, which comes prior to the four main phases. In the Decide phase, strategic decisions refer to a company's vision and overall strategy, such as Company A's five-year digitalization strategy. Tactical decisions serve the purpose of translating the company's strategy into tangible action items. In Company A's example, this is where they decided upon the specific technology, chose a work cell for a pilot project, allocated the necessary resources and assigned a team to the project. Figure 27 is an illustration of the framework in its entirety.

3.1.1 Macro level

The macro level is an overall approach for designing Industry 4.0-enabled work systems, which is similar to the double diamond approach (Design Council, 2007), in that it has a problem- and a solution space, each with one diverge and one converge phase. The 'Understand' and 'Define' phases are in the Problem space, while 'Develop' and 'Deliver' are in the solution space.

The purpose of the Understand phase is to get a holistic understanding of the current state of the work system and to identify wasteful activities as well as challenges related to productivity and HF/E. The purpose of the Define phase is to define what an improved future state of the work system with the novel digital technology might look like. This approach of establishing an understanding of the current state and current challenges, and defining an improved future state is typical of the process of Value Stream Mapping, which is closely linked to the main Lean principles and methodology (Abdulmalek & Rajgopal, 2007). The outcome of the Define phase is the identification of certain focus areas and the definition of criteria for a Minimum Viable Solution (MVS).

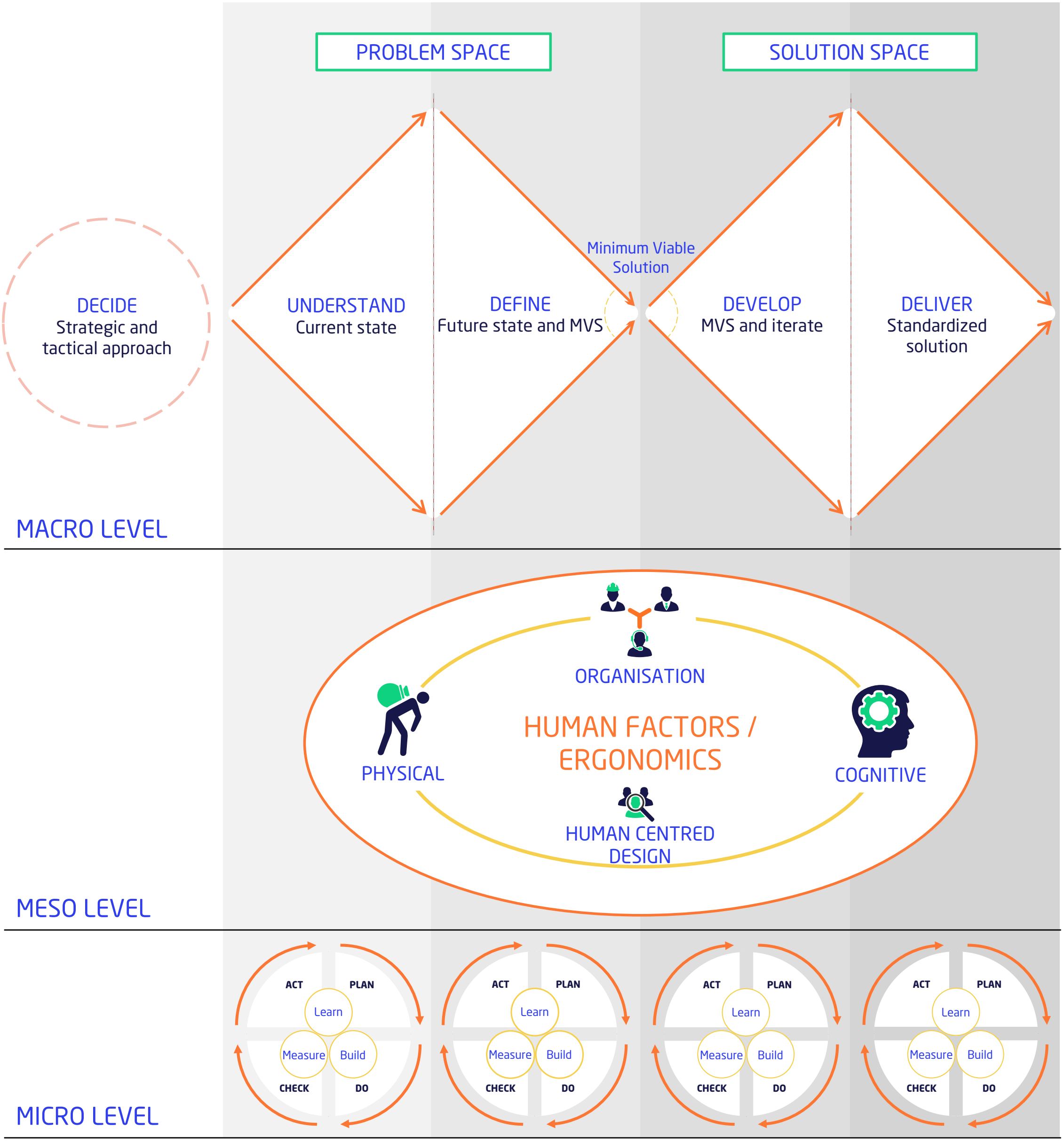

Figure 27 – The proposed framework for (re)designing Industry 4.0-enabled work system.

We define MVS as the smallest solution that provides the most amount of value and possibility to learn. The MVS is similar to—and inspired by—what Ries (2011) refers to as a Minimum Viable Product, which is a minimalistic version of a product that allows the fastest way to learn with the minimum amount of effort in the least amount of time. Thus, the MVS is the first version of a solution that has minimum specifications, is easy to design and develop, and easy to test, evaluate and improve upon. The aim of the MVS is to maximize value and shorten overall project duration while using minimum resources. In the case study, the team had started with an interactive workshop where they had defined criteria for an initial simple version of the solution, which did not include any of the advanced capabilities the chosen technology offered.

The beginning of the Develop phase focuses on developing an MVS based on the criteria established by the end of the Define phase. The objective of the rest of this phase is continuously to develop, test, learn and improve the MVS until reaching a viable final version of the solution. In the last phase, Deliver, the objective is to start standardizing the final viable solution, which was the outcome of the Develop phase and getting the final pieces together before delivery to operations. In the Develop phase in the case study, after the team had established and created the MVS they focused on selecting and adding new features through a constant stream of iterations and making incremental continuous improvements to the initial solution, namely, their MVS. Closing in on the pilot project's deadline, the team had developed what they considered as a viable solution and moved into the Deliver phase. In the Deliver phase, they focused on creating Job Instructions, standardizing the work surrounding the solution, and preparing for final evaluation and potential companywide rollout.

3.1.2 Meso level

The meso level focuses on operationalizing the macro level design processes using HF/E methods and principles. Achieving the macro level objectives requires the inclusion of the different stakeholders, particularly the workers who are working in the current or will be working in the finalized work system. The workers need to be involved in creating an understanding of the current situation, defining the future state, providing continuous feedback as the MVS develops, and take part in the standardization and delivery of the final solution. Stakeholder inclusion is achievable with the adoption of an HCD approach as in BSI Group (2010), thus, making HCD an important element of the framework's operationalization. To account for HF/E and essential elements of the work system while working through the problem space and solution space at the macro level, we suggest using the three main domains of HF/E as defined by IEA (2018) and BSI Group (2016) as guiding principles. These three domains are physical, cognitive and organizational HF/E. In addition, incorporating a model such as the SOFT model (Horgen et al., 1999), could initiate thoughts and assist in identifying interdependent challenges and opportunities in the four dimensions of the workplace, which are spatial, organizational, financial and technological.

Drawing an example from the case study, the project managers had not deliberately made any specific considerations regarding the three main domains of HF/E, however, they had followed an approach similar to BSI Group (2010). Throughout the four phases, the project managers had made a great effort in gathering the different stakeholders through interactive workshops to discuss design decisions, learnings, iterations, improvements as well as planning upcoming tasks and following up on completed ones. In addition, the workers had been in charge of designing the new work processes and contributed with ideas and improvements for the design of the touchscreen's interface. The interviewees attributed the success of their solution in great part to this close collaboration between the stakeholders, and involvement of the shop floor workers. Although, we note that neither Respondent A nor Respondent B referred to this approach using the term 'HCD'. However, both respondents emphasized the importance that including the different stakeholders and granting the workers a feeling of ownership has on the success of a project.

3.1.3 Micro level

On the micro level, the focus is on managing the tasks related to achieving the macro level objectives of each phase and enabling the full benefits of the MVS requires a continuous loop of build, measure and learn (Ries, 2011). To ensure this continuous learning and adaptation, the suggested approach for managing tasks on the operational level is to follow the systematic approach of the Deming wheel, which divides tasks into the four phases of Plan, Do, Check, Act (PDCA) (Deming, 1986). This approach is an essential part of Lean thinking and is commonly used in industry for problem-solving, continuous improvements and quality management (Andersen, 2007). The Plan phase focuses on analyzing and planning activities related to the tasks. In the Do phase, the focus is on carrying out the planned activities. In the Check phase, the aim is to measure and evaluate the effects of the activities. In the Act phase, the objective is to modify and follow up on the evaluations from the check phase. A positive evaluation means an acceptable result that might need standardization, while a negative evaluation will typically result in a new PDCA cycle.

In the case study, the team had used a combination of the PDCA approach and the agile project management method, Scrum, as in Schwaber (2004), to manage the tasks related to the redesign of the work system. Respondent B mentioned that using this approach created a cycle of continuous learning and measurable improvements. To accommodate this approach, they had used a mix of soft and hard solutions, namely, a Microsoft Excel file and a whiteboard next to the work cell to highlight planned, in progress and completed activities. In a similar fashion, they had created a system for keeping track of errors, which the workers had actively used to report errors and shortcomings of the solution that needed attention and action.

4. Discussion

The currently available literature dealing with the design of work systems in Industry 4.0 is limited. This limitation is especially true in regard to the design of work systems with considerations of HF/E. While publications (such as Fellmann et al. (2017), Peruzzini & Pellicciari (2017), Pinzone et al. (2018), Stern & Becker (2017), and Zezulka et al. (2016)) have developed frameworks dealing with different specific topics related to human work in Industry 4.0, there is still a need for holistic and practical frameworks, which practitioners can follow when introducing new digital technologies.

Romero, Stahre, et al. (2016) emphasize the need for new prescriptive human-centered approaches for implementing CPS and Richter et al. (2018) highlight the need for diagnostic tools to study digital environments. Our contribution in this paper is a framework that serves both of these functions. It is a prescriptive tool, which practitioners can use to (re)design industrial work systems in conjunction with the introduction of novel and untested elements, such as new digital technologies, as well as a diagnostic tool, which academics can use to analyze existing work systems. Our framework is different from other frameworks in that it provides a pragmatic, human- and innovation-centred approach developed on the combination of well-established methodologies such as Design- and Lean thinking, and HF/E. To our knowledge, there is no other similar framework that combines these three methodologies with the purpose of designing Industry 4.0-enabled work systems.

In the industrial case studies we conducted, the case companies had paid limited attention to the design aspects of their work systems when introducing new digital technologies, ultimately skipping the design phase and getting into implementation straightaway. This was also the case for Company A, which we had evaluated as best practice. Neglecting design aspects and holistic work system understanding might result in the unsuccessful implementation of new technologies, for example, collaborative robots (Kadir et al., 2018). On the macro level of the proposed framework, the Understand phase in the Problem space aims at minimizing this gap by gaining this holistic understanding and highlighting potential challenges while preparing for the related changes emerging with the implementation of any new digital technology. In addition, achieving such an understanding will align expectations and assist in defining a realistic and achievable future state as well as criteria for an MVS. We attribute Company A's ability to succeed with a limited design phase to the low complexity of the work system. Thus, the success rate of the project might have varied if the case had applied the same approach to a more complex work system.

The continuous development of digital technologies and increasing competition is leading to new ways of developing, testing and launching new products and services. As a response to this increasing demand, the concept of design sprints has emerged as a new key method for digital design (Banfield et al., 2016; Knapp et al., 2016). These new methods and traditional Design thinking methods such as Stanford (2018), which designers typically use for developing new products and services, are highly compatible with the concept of prototyping. However, in fast-paced industrial environments such as Company A, where work systems produce revenue-generating outputs, the concept of prototyping entire solutions is a luxury few companies can afford, thus, making the MVS a next best alternative to prototyping. The MVS allows for a quick start with a minimum amount of resources and grants the ability to build, measure and learn at a fast rate. The MVS also has the potential of limiting the related negative effects on the work system's performance indicators, for example, downtime, speed, quality and cost.

The addition of Lean thinking provides a systematic yet iterative approach for meeting the framework's macro level objectives. Because Lean thinking is common and widely known in industrial companies, it adds an element of familiarity to the framework, which might make it more comprehensible and increase the likelihood of its application. However, it is important to note that not all companies are familiar with Lean thinking and the PDCA approach (Lodgaard & Aasland, 2011). Nevertheless, the elements of Lean thinking presented in the framework such as the PDCA and the ideas of understanding the current state and its challenges as well as defining an improved future state and setting criteria for an MVS are not complex concepts and not too difficult to comprehend. In addition, the application of lean thinking and methods to deal with Industry 4.0 challenges is a highly discussed topic in industry as well as in academic publications. This combination is often referred to as Lean 4.0 (Mayr et al., 2018).

Incorporating HF/E in the design of Industry 4.0-enabled work systems could be highly beneficial in accommodating workers' well-being. This is the reason we have HF/E as one of the three main elements of the proposed framework. With the integration of new digital technologies in industrial work systems, usability, user interfaces and human–machine interactions will need to become an essential element of consideration in regard to job design (Stern & Becker, 2017), and an HCD approach for the (re)design of work systems will be highly beneficial (Pacaux-Lemoine et al., 2017). We suggest that by following an HCD and keeping the three domains of HF/E in mind while working through the phases of the framework, it will be possible to accommodate the workers' needs sufficiently. In addition, it might also increase the workers' well-being throughout the design and implementation phases as well as operations.

4.1. Implications for practitioners

Our findings and the proposed framework are a shift in paradigm in regard to how practitioners are typically approaching the (re)design of industrial work systems. Instead of the common approach of jumping straight into implementation, a practitioner might consider spending some time on an initial design phase and focus on developing a viable solution to reduce the waste of time and resources. This framework is aimed at practitioners on a tactical and/or operational organizational level, who are in charge of introducing and incorporating new digital technologies and solutions into new or existing industrial work systems.

The industrial case study we used in this paper was at a large company that had the required resources for a pilot project as well as assigning a designated team to the project. Because of the number of resources required, this approach might not be fitting or realistic for most small- and medium-sized enterprises (SMEs). However, this does not mean that the framework is only applicable to large companies. On the contrary, we believe that this framework will be as beneficial to apply in SMEs as in large companies. Having a clear understanding of the current state and current challenges, and defining a clear vision for the future of the work system will align expectations and create a holistic understanding, which might be necessary to succeed with new digital technologies and new ways of working. In addition, a well thought out MVS might reduce the initial costs and resources needed to get started, which can be a barrier of entry for many SMEs. Following an approach such as the proposed framework, which divides digitalization initiatives and projects into minor sprints and iterations might reduce this barrier of entry and offset project uncertainties.

4.2. Limitations and future research

The limitation of this paper is that the proposed framework is only conceptual and that it has not been applied and tested in an industrial setting. Future research should address this limitation with prospective industrial case studies designed to test and evaluate the effectiveness of the framework, leading to further development and improvement of the framework. Furthermore, future research should also focus on providing specific methods and tools to apply in the different phases of the framework and provide more clarification and detailed descriptions on what to do, and how to do it.

5. Conclusion

Design is a crucial phase of the implementation of new digital technologies and companies should not neglect and skip this phase by jumping into implementation straightaway. In this paper, we presented a conceptual framework for designing Industry 4.0-enabled work systems and used an industrial case study to illustrate with examples some elements of the framework. The framework has two functionalities, in that it is a prescriptive tool for (re)designing work systems with novel elements such as new digital technologies, and it is a diagnostic tool for analyzing existing work systems. Combined from the three methodologies of Design-, Lean thinking and Human Factors and Ergonomics, the framework provides a familiar, systematic, iterative, innovation- and human-centered approach for designing Industry 4.0-enabled work systems.

Paper D

Human-centered design of work systems in the transition to Industry 4.0

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Human-centered design of work systems in the transition to Industry 4.0

Abstract

The introduction of Industry 4.0-enabling digital technologies in industrial work systems are creating various sociotechnical challenges affecting overall system performance and human well-being. In this paper, we propose a framework for (re)designing industrial work systems in the transition towards Industry 4.0. The framework combines human factors and ergonomics, work system modeling, and strategy design. It accommodates implementation challenges we have identified through ten retrospective case studies. In addition, we present the systematic approach applied to developing and testing the framework. Lastly, the framework was tested in a collaborative workshop in an industrial company, and the results indicated its applicability.

Keywords

Cyber-physical systems; Digital transformation; Digital factory; Digitalization; Operator 4.0

1. Introduction

The concept of Industry 4.0, initially described by Kagermann et al. (2013), started as a collaborative initiative between the German government, academic, and industry representatives aiming at ensuring the future competitiveness of the German manufacturing sector. Kagermann et al. (2013) present a vision for Industry 4.0 characterized by a new level of sociotechnical interactions between networks of manufacturing resources (e.g., machinery, robots, warehouse and conveyor systems, and productions facilities) and actors across the manufacturing supply chain. Industry 4.0 is often associated with new digital technologies and technological concepts such as (but not limited to) Autonomous and Collaborative Robots, the Internet of Things, Augmented and Virtual Reality, Big Data and Analytics, and Additive Manufacturing (Rüßmann et al., 2015).

The transition to Industry 4.0 and the increase of cyber-physical systems are introducing technical, organizational, and human-related changes throughout the different organization layers of industrial companies (Becker & Stern, 2016; Kadir, Broberg, & Conceição, 2019a; Roblek et al., 2016). The introduction of these new digital technologies are enabling new forms of interactions between humans and machines, and are therefore directly affecting operational level workers and the nature of their work. Such challenges include but not limited to

- Stress and burnout caused by reduced autonomy and increase job demands (Cascio & Montealegre, 2016), new skills and competency requirements, as well as information overload (Czerniak et al., 2017).
- Workers' safety when working with tangible automation technologies, e.g., autonomous robots and autonomous vehicles (Fletcher et al., 2019)
- Increasing cognitive load and changing the balance and ratio between physical and cognitive load (Kong, 2019).
- Frustration and loss of motivation caused by the fears of unemployment and limited job opportunities (Adam et al., 2019)

To overcome such challenges and to ensure a successful transition to industry 4.0, several publications (e.g., Pacaux-Lemoine et al. (2017), Richter et al. (2018), Romero et al. (2019), and Sgarbossa et al. (2020)) suggest that it will be necessary to apply new human-centric design and engineering philosophies that account for the workers physical, cognitive and sensorial capabilities.

Sony & Naik (2020) argue that the concept of Industry 4.0 is in itself a sociotechnical system. Thus, to achieve sustainable implementation of Industry 4.0-enabling technologies and to accommodate workers' well-being, it is necessary to apply sociotechnical systems perspectives. However, while the number of research publications dealing with the implementation of Industry 4.0-related concepts is growing, very few address the topic from such a perspective and pay limited attention to Human Factors and Ergonomics (HF/E) (Kadir, Broberg, & Conceição, 2019a; Longo et al., 2017; Sony & Naik, 2020).

In response to this gap, an increasing number of academic publications are calling for research focusing on the development of new frameworks and guidelines. These frameworks and guidelines should aim to assist relevant practitioners in accommodating sociotechnical, and HF/E related aspects in the implementing industry 4.0-enabling technologies (Contador et al., 2020; Gualtieri et al., 2021; Markova et al., 2019; Masood & Egger, 2019; Mühlemeyer, 2020; Olsen & Tomlin, 2020; Rauch et al., 2020; Sgarbossa et al., 2020). Relevant practitioners may include system influencers (competent authorities such as regulators standardization organizations, and governments), system decision-makers (employers, managers, and those who make decisions about system design requirement) and system experts (professional- HF/E specialists, psychologist, and engineers contributing to the design of the system) (Dul et al., 2012).

In addition, we have been able to emphasize this gap by conducting ten explorative case studies at ten industrial companies (located in Denmark) that had started a digital transformation journey. In these case studies, we observed that the majority of the companies also lacked a sociotechnical systems perspective and paid limited attention to HF/E related aspects.

The limited research focus and minimal industrial experience on the transition to Industry 4.0 might result in the neglect of human workers and their well-being (Gualtieri et al., 2021; Markova et al., 2019; Mühlemeyer, 2020), similar to what happened at the beginning of the third industrial revolution. Because of the availability of automation technologies and the means of resources, at the beginning of the third industrial revolution (the 1970s into the 1980s), industrial companies had a strong bias towards automation of work (Kleiner, 2006). Kleiner (2006) highlight that during this period, machine-centered industrial engineers promoted the concept of the factory of the future as computerized, workerless systems, where the disruptive and costly "human factors" were eliminated.

To avoid repeating such a scenario, researchers must focus on developing practical, prescriptive measures to guide practitioners as well as future research in understanding, analyzing, and dealing with the challenges and opportunities emerging in the transition to Industry 4.0. Indeed, a recent jointly prepared publication by the International Ergonomics Association (IEA) and International Labour Organization (ILO) highlight that the increase of new digital technologies and the globalization of economies are creating a growing need for re-evaluating the integration of HF/E principles into the design and management of work systems (IEA & ILO, 2020). To accommodate parts of this growing need, IEA and ILO (2020) present a set of foundational principles and guidelines for HF/E design and management of work systems.

To deal with the gap identified in the literature and emphasized by our empirical data collected through ten industrial case studies, in this paper, we develop and propose a framework for (re)designing industrial work systems in connection with the implementation of new digital technologies. Ostrom (2011) argues that a framework enables the identification and understanding of the general relationship among elements to consider for institutional analysis, as well as organize diagnostic and prescriptive measures.

The proposed framework combines elements from HF/E, work system modeling, and strategy design to incorporate essential design criteria and measurable goals in the early stages of a work system (re)design process. The framework aims at assisting practitioners with the (re)design of work systems in connection to the introduction of new digital technologies. The framework is accompanied by a seven-step approach, which serves to guide the users in using the framework.

The application of the framework serves to create a cohesive understanding of all work system elements and enable the definition of specific and measurable (re)design criteria. These design criteria might ultimately lead to improved human well-being and overall system performance, hence increasing the success rate of a transformation to Industry 4.0. Besides, we have validated the framework's applicability through a prescriptive industrial case study at a large manufacturing company, which is currently in the process of implementing the framework as one of their standard approaches for introducing new digital technologies.

The contribution of this paper and the proposed framework is twofold. On the one hand, the framework presents a practical approach for (re)designing work systems in connections to the introduction of new digital technologies. On the other hand, the framework can function as an analytical tool, which academics can apply to understand and analyze the different elements and interactions of work systems when developing new industry 4.0 related concepts and solutions.

1.1. Human-centric implementation of Industry 4.0

Over the past few years, research in the intersection between industry 4.0 and HF/E has been steadily growing. This growth has led to numerous research publications focusing on testing and exploring new digital technologies and concepts that can accommodate human workers and improve their well-being in highly digitalized work systems. One of the concepts that has gained traction in this regard is the concept of Operator 4.0. Operator 4.0 describes a futuristic vision of smart and skilled workers who perform work, aided by machines and digital technological tools. Thus, Operator 4.0 can fully utilize digital capabilities and capitalize on emerging opportunities in Industry 4.0-enabled factories (Romero, Bernus, et al., 2016; Romero, Stahre, et al., 2016).

Since the development of the Operator 4.0 concept, numerous research publications have focused on further developing the concept and presenting frameworks for incorporating and accommodating Operator 4.0 in factories of the future (Romero et al., 2019). Kaasinen et al. (2019) present a vision for Operator 4.0, which entails that the factories of the future will be ideally suited for workers with different preferences, capabilities, and skills and driven by solutions that empower workers and engage the work community. Taylor et al. (2018) provide another vision, which argues that the operators of the future might transition from operators to makers, thus working alongside digitalized and automated production systems and using creativity to solve unexpected and unforeseen challenges.

Following these futuristic visions, Mattsson et al. (2018) highlight that future operators will need to be able to handle different work situations and complex interactions. Thus, they must receive the right information and knowledge arranged to fit their cognitive processes. To accommodate this need, Mattsson et al. (2018) present a conceptual strategy framework that aims at supporting operators in Industry 4.0 to switch between different tasks. Similarly, Peruzzini et al. (2019) aim at accommodating the needs of Operator 4.0 with a conceptual framework that applies a human-centric approach to integrate aspects human factors in industry 4.0-enabled work systems and test the framework's feasibility with an industrial case study with promising results.

Beyond the Operator 4.0 concept, other academic publications have made efforts contributing to this field by developing prescriptive models and frameworks to deal with sociotechnical aspects of Industry 4.0-enabled work systems. For example, Caputo et al. (2019a), Peruzzini & Pellicciari (2017), Stern & Becker (2017), Waschull et al. (2019), Zavareh et al. (2018), and Zheng et al. (2018) all contribute with conceptual frameworks that deal with aspects of the development and design of Industry 4.0 enabled work and work systems.

However, these frameworks only cover aspects of work system design (e.g., work design, validation of workplace design, and engineering work), and do not provide cohesive prescriptions that focus on ensuring both human well-being and system performance. Also, the majority of these frameworks do not have a specific approach explaining how to use the frameworks in practice. Other publications (e.g., (Golan et al. (2019), Hannola et al. (2018), and Weber et al. (2018) contribute to the intersection between Industry 4.0 and HF/E with conceptual frameworks and methods that focus on topics such as human interactions, knowledge management, and enhanced productivity within industry 4.0-enabled work system.

In addition to contributions from academia, other publications (e.g., gray papers, industry reports, and books) have contributed with frameworks, methods, and guidelines for approaching the digital transformation journeys and the implementation of new digital technologies. Most consultancy service providers and digital technology suppliers (e.g., Küpper et al. (2017), Reinhard et al. (2016), Schlaepfer & Koch (2015), and Schuh et al. (2020)) have shared their take on how industrial companies should approach this transformation, as well as providing survey data on current states and trends in industry. However, similar to the academic publications, these publications also pay limited attention to H/FE and only cover few sociotechnical aspects. Besides, the purpose of industry reports and whitepapers is often to attract the attention of customers and selling products and services. Thus the information and knowledge they provide can be superficial and abstract.

One of the more popular frameworks that has transcended the boundary between industry and research is the RAMI 4.0, which is a reference architecture model for Industry 4.0 with a three-dimensional map demonstrating how organizations can approach the Implementation of Industry 4.0 (ZVEI, 2018). RAMI 4.0 is still highly conceptual and not yet published in its full version (Sharpe et al., 2019). However, several research publications (e.g., (Contreras (2020), Febriani et al. (2020)) have strived to test and validate the framework's usability with small scale industrial case studies. Besides, Sharpe et al. (2019) argue that the RAMI 4.0 framework lacks a human perspective and suggests adding two additional dimensions, one focusing on security and the other on humans within the system.

As we have highlighted in this section, many academic and industrial publications have focused on developing prescriptive methods and frameworks for designing industry 4.0-enabled work systems with considerations for the integration of human workers. However, it is essential to mention that the majority of these methods and frameworks are conceptual, and only a limited few are validated in industrial settings. The limited industrial use cases are especially apparent in scenarios focusing on futuristic visions of highly digitalized and automated work systems, which are only achievable in fully Industry 4.0-capable factories.

However, Industry 4.0 capable factories are still a somewhat far fetches reality for the majority of industrial companies. Thus, as valuable concepts such as Operator 4.0 might be, their practical implementation in industry is still halting (Kaasinen et al., 2019). Indeed, most industrial companies have yet to achieve a successful application of new digital capabilities across their organizational operations (KPMG, 2017). Besides, while the concept of Industry 4.0 was initially developed in Germany, the Germany industrial sector is also still in the very early stages of Industry 4.0 implementation (Wilkesmann & Wilkesmann, 2018). Chien et al. (2017) argue that reaching Industry 4.0 and gaining the ability to utilize new digital competencies and capabilities is a transitional process, which they denote as Industry 3.5. Thus, there is a great incentive and need for frameworks for assisting and guiding academic research and Industrial implementation of Industry 4.0 related technologies and concepts (Zheng et al., 2018).

1.2. Human Factors and Ergonomics and work system design

As mentioned at the beginning of Section 1, to overcome sociotechnical systems challenges and capitalize on the emerging opportunities of new digital technologies, there is a need for new inter-disciplinary design and engineering philosophies and principles. HF/E can accommodate essential parts of this need because of its immense focus on the human component within systems. HF/E is a scientific discipline dealing with the understanding of interactions amongst various system elements and humans. Also, it is a profession that uses theory, methods, principles, and data to design for optimizing human well-being and overall system performance (IEA, 2020). This focus on optimization makes the application of HF/E highly relevant in designing safe and sustainable work systems (IEA, 2020; Zink, 2014), which can ultimately lead to enhanced business results (Hendrick, 2003).

However, HF/E is never applied on its own, but it is usually used in connection with the design and development of new, improved systems and management of existing systems. When these systems include any type of work, they are referred to as work systems (Bridger, 2018). Bridger (2018) highlights that since the end of World War II, the application of a sociotechnical approach and incorporation of HF/E into the design of work systems have become an essential part of work system design. Indeed, ISO 6385 (BSI Group, 2016a) is solely dedicated to the integrations of HF/E connection with the design of work systems.

Depending on the specific frameworks and methods, work systems can have different components and dimensions. However, most popular definitions, methods, and frameworks for work systems and work system design (e.g., Alter (2006), Carayon (2009), Horgen et al. (1999)), put a great emphasis on the role of technological components and human interaction and use of technologies. Alter (2006) defines a work system as

> *a system in which human participants, and/or machines perform work using information, technology, and other resources to produce products and/or services for internal or external customers." This definition encapsulates the role of machines and technological components in work systems very well and is ever more relevant in the context of Industry 4.0.* – Alter (2006)

Industrial companies are increasingly implementing novel and untested digital technologies, which are evoking sociotechnical challenges throughout the different organizational layers and work systems (D. Horváth & Szabó, 2019; Kadir & Broberg, 2020b). Thus, applying a sociotechnical approach with a focus on HF/E principles in the implementation of new digital technologies and solutions might enable a smoother transition to Industry 4.0 and accommodate the pertaining sociotechnical challenges.

The framework we propose in this paper provides a systematic and comprehensive approach for implementing new digital technologies and developing new digital solutions. The aim is to guide the users in gaining a holistic understanding of a target work system, and hereafter use this understanding to define (re)design objectives and criteria before jumping into the implementation phase. Figure 28 shows the proposed framework.

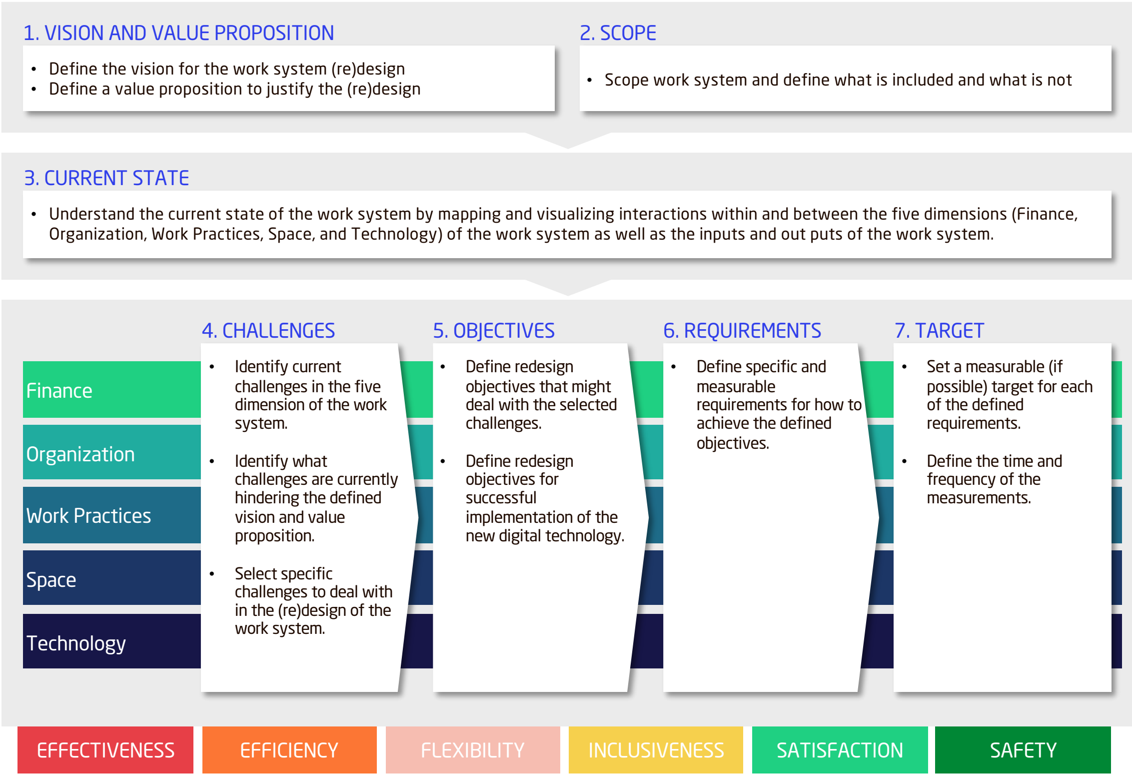

Figure 28 – The proposed framework for designing work systems in the transition to Industry 4.0

The organization of this paper is as follows: In Section 2, we focus on the process of developing the proposed framework. This focus includes the presentation of empirical findings from explorative case studies and the development testing of the proposed framework. In Section 3, we discuss the framework and the results obtained in the process of validating the framework. Also, in Section 3, we highlight the contribution and limitations of this paper as well as present possibilities for further research. Lastly, in Section 4, we conclude the paper and provide final remarks.

2. Developing and testing the proposed framework

As part of a research study on how the introduction of new digital technologies in industrial work systems affect human well-being and overall system performance, we conducted ten different retrospective explorative case studies at ten industrial companies all located in Denmark. One of the focus areas of these case studies was the understanding of the overall approaches to introducing new digital technologies and the development of new digital solutions. The goal of this understanding was to use the findings to develop a framework for (re)designing industrial work systems in connection with the implementation of new digital technologies.

In addition, we tested and confirmed the framework's usability in a workshop setting in an additional case at a company different from the ten retrospective cases. Thus, we used ten descriptive studies to develop the proposed framework, and one prescriptive study to evaluate the framework. This section aims at highlighting the methodology used to collect and analyze the qualitative data from these case studies as well as the development and validation process of the proposed framework. Refer to Figure 29 for an overview of the flow and subsections in this section.

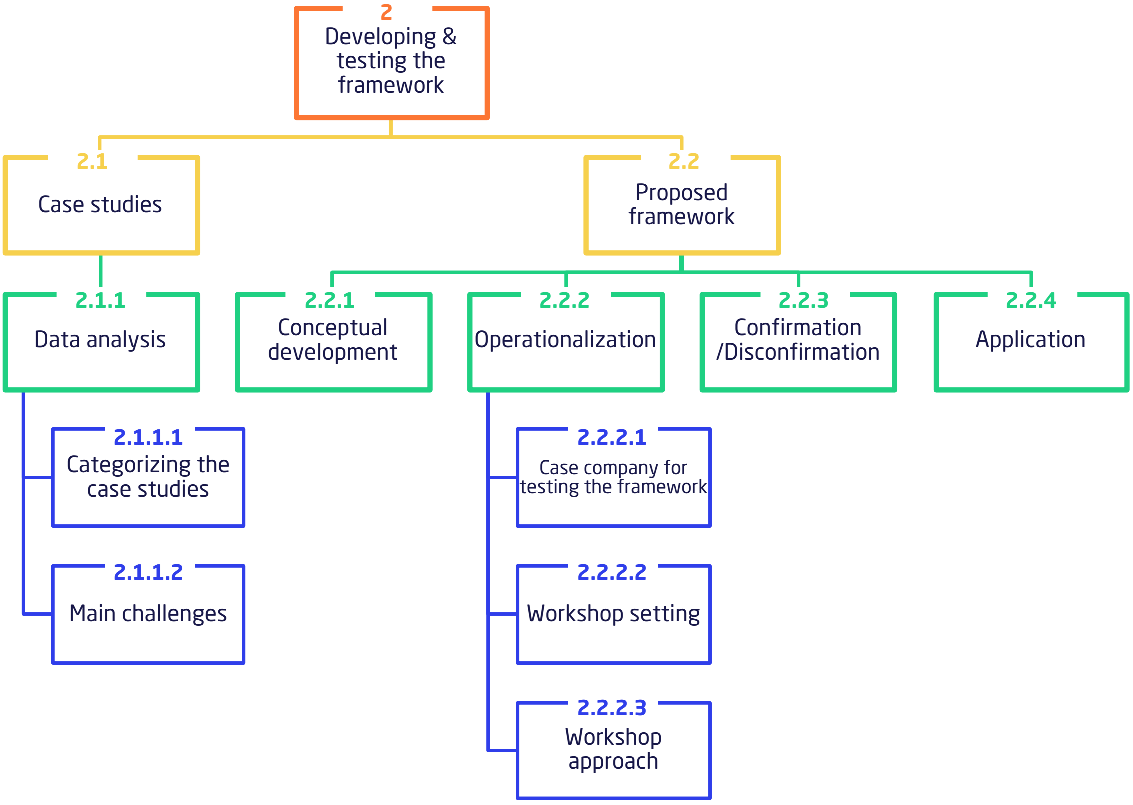

Figure 29 – Overview of the subsections in Section 2 – Developing and testing the proposed framework.

2.1. Case studies

Flyvbjerg (2006) argues that the use of case studies is an adequate and necessary method for some research tasks in the social sciences. One of these research tasks can be qualitative data collected through case studies, which is an efficient method to develop theories inductively and connecting these theories to available deductive research (Eisenhardt & Graebner, 2007). We used the approach of R. K. Yin (2018) to conduct and analyze the case studies, which included qualitative data collected through 35 semi-structured interviews with employees on operational, tactical, and strategic organizational layers. These interviews focused on investigating and understanding how the companies approached the implementation of new digital technologies and how the pertaining changes had affected human well-being and overall system performance.

The majority of the interviews were in Danish and were audio-recorded and transcribed, except for seven interviews, where we collected the data through hand-written notes taken during the interviews. The interviews ranged between durations of 30 – 90 minutes. Refer to Table 13 for an overview of the number of workers and decision-makers interviewed at each case company.

Table 13 – Overview of the number of interviewed workers and decision-makers at each case company.

Company	Decision-makers	Workers	Total
A	4	3	7
B	2	1	3
C	2	-	2
D	3	2	5
E	3	2	5
F	1	1	2
G	2	-	2
H	1	3	4
I	1	1	2
J	1	2	3
Total	**20**	**15**	**35**

We wanted to investigate to what extent these companies paid attention to and included HF/E and work systems principles and considerations when implementing new digital technologies. Having this understanding enabled us to identify the challenges these companies faced when (re)designing their work systems in connection to the transition to Industry 4.0. Hereafter, we used these findings to identify criteria for a framework that could assist industrial companies in overcoming similar challenges and easing their digital transition.

All of the case companies had started their transition to Industry 4.0 and had implemented one or more new digital technologies that they associated with the concept of Industry 4.0. The case companies had no or minimal experience implementing and using these new digital technologies, which included Automated Guided vehicles (AGV), Additive Manufacturing, Data visualization, Industrial and collaborative robots (cobots), advanced computing, and vision systems, digital paper flow, and system integration.

2.1.1 Data analysis

To analyze the data from the case studies, we applied the approach of template analysis, as described by Brooks et al. (2015). This analysis had two purposes. On the one hand, it focused on identifying the extent the case companies followed any standard formal project management approach when implementing new digital technologies and to what extent their approach included HF/E and work systems aspects. On the other hand, the analysis focused on identifying challenges the case companies had faced when (re)designing their work systems in connection to the implementation of new digital technologies.

We defined HF/E aspects as considerations regarding physical, cognitive, and organizational ergonomics with a focus on human well-being and system performance. Work system aspects included considerations regarding work system elements and interactions within and between work systems. We categorized the extent of these aspects and considerations into three levels, where level one is the lowest and level three the highest. Refer to Table 14 for a description of the levels used to categorize the extent the case companies had used and considered project management, HF/E, and work system aspects, as well as an overview of the number of cases categorized into each of the three levels.

Table 14 – Description of the levels used to categorize the extent the case companies had used and considered project management (PM), HF/E, and work system (WS) aspects, as well as an overview of the number of cases categorized into each of the three levels.

Level of considerations	Description	PM	HF/E	WS
Level 3	Formal standardized and documented method with specific focus and considerations.	2	-	-
Level 2	Informal, unstandardized, and undocumented methods with limited focus and considerations.	1	10	10
Level 1	No method, focus, or considerations.	7	-	-

2.1.1.1 *Categorizing the level of considerations regarding project management, HF/E, and work system aspects*

In regards to using a general approach for managing projects related to the implementation of new digital technologies, we categorized seven of the case companies in level 3. These case companies had used generic project management approaches, standard to how their company typically executes internal projects. While each company had its specific approach, none of them had created or used any specific methods for developing new digital solutions and implementing new digital technologies. We categorized two cases in level 2 and none in level 1. The case companies in level 2 had approached the implementation of the new digital technologies following an informal, unstandardized, and undocumented approach.

Regarding the extent to which these companies had included HF/E considerations when implementing new digital technologies, we placed them all on level 2. All of the case companies had, to some extent, considered aspects of HF/E. However, they had only focused on limited aspects of physical or cognitive HF/E. Besides, none of them had a standard and documented guideline for how to incorporate HF/E considerations. In some of the large case companies, the health and safety departments had been involved, but only after the new digital solutions had been fully developed and implemented. Thus, their tasks had only been to evaluate the safety of the final solutions.

In regards to considering work system aspects, we placed all of the case companies on level 2. While none of the companies had applied a comprehensive work systems perspective that took the different elements and their interactions within and between work systems into account, they had all included some considerations regarding the technological aspects while developing their new digital solutions. In cases of tangible technologies such as industrial robots, cobots, and AGVs, the case companies had also included considerations regarding the spatial part and work practices when redesigning their work systems. However, none of the case companies had a standardized and documented approach for including such considerations. Thus, most of the considerations had been made ad-hoc.

2.1.1.2 Main challenges related to the implementation of new digital technologies

The case companies had experienced success with their new digital technology initiatives to different degrees. However, we noted that in all of the cases, the companies had encountered challenges during the implementation process. To identify these challenges, we analyzed the empirical data from the case studies by categorizing statements regarding challenges into a framework similar to the SOFT work system model (Horgen et al., 1999). The SOFT model has four dimensions (Space, Organization, Finance, and Technology), which affect work practices performed within a work system. Thus, we categorized each statement coded as a challenge into these five dimensions. Refer to Figure 30 for an illustration of the SOFT work system model recreated for this paper.

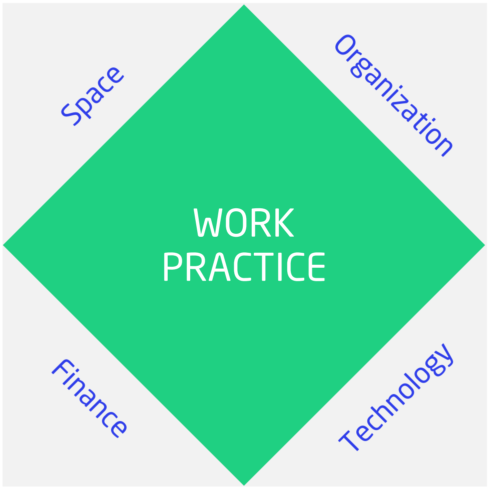

Figure 30 – Horgen et al. (1999) SOFT work system model, recreated for this paper.

Hereafter, we created a two-level affinity diagram (Holtzblatt & Beyer, 2016) for each of these five dimensions, where in the first level, we grouped the challenges and, on the second level, divided them into themes. Table 15 shows the results of this part of the analysis, which is an overview of the main challenges the case companies had experienced, categorized into the five dimensions of the SOFT work system coding-framework.

Table 15 – Challenges identified in the five dimensions of the SOFT work system coding-framework.

Work System dimensions	Challenges
Overall	• Defining a value proposition • Defining (re)design criteria for the work system • Identifying investment opportunities and use-cases • Sustain system performance • Scoping the (re)design of work systems • Defining success criteria • Defining a standard approach for (re)designing work systems
Finance	• Identifying useful financial KPI's • Calculating return on investment • Allocating the necessary financial resources

	• Avoiding a decrease in product quality
Organization	• Allocating the necessary organizational resources • Balance the different aspects of HF/E • Getting organizational buy-in • Division of labor between humans and robots • Identifying necessary skill and training protocols • Defining roles and responsibility changes • Aligning organizational stakeholders • Assessing organizational maturity
Space	• Defining (re)design criteria for the work system • Assessing the safety of the work system • Assessing the physical environment of the work system • Identifying location to place new tangible technologies
Technology	• Identifying what technologies to invest in • Integrating the new digital solutions into the existing work systems • Defining (re)design criteria for the work system • Identifying technical challenges and needs • Assessing the safety of new digital solutions • Avoid partially developed solution
Work practices	• Not over complicating existing work practices • Not sustaining workflow • Standardizing new ways of working. • Avoiding work practice errors

2.1.1.3 Company case example

In this subsection, we will briefly describe the case study of Company A to highlight their experience with some of the mentioned challenges highlighted in Table 15. Company A had implemented several new digital technologies (e.g., cobots, AGV, and digital paper flow), which had changed and affected the work practices in several of their work systems.

At Company A, the decision-makers and engineers in charge had designed and implemented their new digital solutions using an engineering-focused approach with minimal involvement from the operational level workers and limited considerations to the sociotechnical aspects of the work systems. In the design phase, they had mostly focused on developing the technological aspects of their solutions and had paid minimal attention to the other elements of the work systems. Consequently, Company A had experienced challenges in all of the SOFT dimensions of their work systems, as presented in Table 15.

For example, because the decision-makers had not involved the workers, they had experienced extensive organizational friction in the initial phases of their implementation. This friction had resulted in a decrease in the workers' well-being (e.g., stress, lower morale, loss of motivation to work, less autonomy) and performance (e.g., lower output, poor quality, work practice errors). Also, because there was limited attention to the sociotechnical aspects, they had, for example, experienced challenges in work division, needed skills, training, organizational maturity, and limitations of the physical space.

The case of Company A is a typical example of how the case companies had paid minimal attention to the actual (re)design of their work systems and mostly focused on the implementation and development of their new digital technologies and solutions.

2.2. Proposed framework

As highlighted in Section 1, researchers are calling for the development of novel human-centric design and engineering philosophies to ensure a successful transition to Industry 4.0. Thus, the main driver for developing the framework was to propose a standardized method for (re)designing industrial work systems in the transition to industry 4.0. We wanted the method to be able to deal with the challenges highlighted in Section 2.1.1.2 as well as account for human well-being and system performance from the initial stages of new digital technology initiatives.

As mentioned in Section 1.2, the focus of HF/E is to assist in improving human well-being and system performance, and one of the essential aspects of work system design is the consideration of the interaction between humans and technology. Thus, the proposed framework combines elements from both work system theory and HF/E. Besides, to accommodate some of the identified challenges from the case studies, the framework also includes elements from strategy design.

For the overall approach of developing the framework, we followed the General Method of Applied Theory-building Research (Lynham, 2002), which is a highly appropriate approach for developing theories, frameworks, and models that are applicable in practice. The model has the following four phases of where each phase serves a specific purpose.

1. Conceptual development
2. Operationalization
3. Confirmation/Disconfirmation
4. Application

Figure 31 shows a recreated version of the general method of theory-building research in applied disciplines by Lynham (2002).

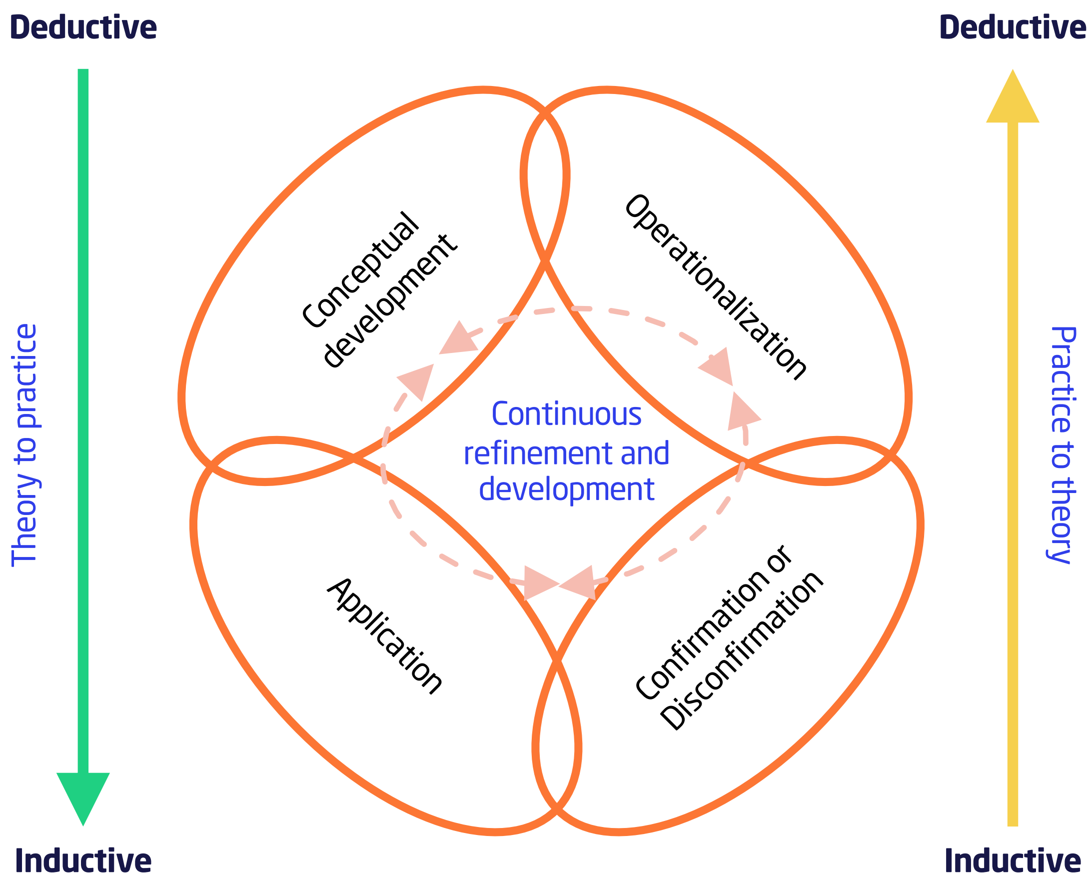

Figure 31 – Lynham (2002) General method of theory-building research in applied disciplines recreated for this paper

2.2.1 Conceptual development

The purpose of the Conceptual development phase is to develop a conceptual framework that enables an understanding and clarifies the nature and underlying forces of the problems or phenomenon in focus. However, Lynham (2002) does not propose any specific method for the actual development of a conceptual framework. Thus, to developed a conceptual framework, we followed an approach similar to the method described by Jabareen (2009). This method has seven phases, which are 1) mapping the selected data sources, 2) extensive reading and categorizing of the selected data, 3) identifying and naming concepts, 4) deconstructing and categorizing the concepts, 5) integrating concepts, 6) Synthesis, re-synthesis, and making it all make sense, 7) Validating the conceptual framework. Table 16 shows a detailed description of the activities and outcomes of these seven phases in the context of this paper.

Table 16 – Description and outcome of each step in the development of the conceptual framework

Phase	Description	Outcome
1	Analyzed the collected data from the case studies, as described in Section 2.1.1.	An overview of the Challenges identified in the five dimensions of the SOFT Work System coding-framework, as shown in Table 15.

	Created a list with different theories, concepts, and methods that could be relevant in regards to the topic.	A list of relevant theories, concepts, and methods such as: • Work system design methods • Service system design methods • Design thinking • Human Factors and Ergonomics • Business process management • Lean manufacturing • Project management • Strategy design • Business model design • Change management
2	Read and categorized the literature from the previous phase to identify relevant and useful concepts, methods, and tools. The main criteria for this selection were practicality, usefulness, and relevancy, in regards to the topic.	A list with the most relevant concepts, methods, and tools, which we could use in the next phase.
3	Grouped the relevant categorized concepts from the outcome of the previous phase into different aspects that were deemed relevant to the (re)design of work systems in the transition to Industry 4.0.	An overview of the different concepts grouped into the three different phases of before, during, and after the design of work systems in the transition to Industry 4.0.
4	Grouped the findings from Table 15 into the three categories of before, during, and after the design of work systems	A new table where the findings from Table 15 are categorized into before, during, and after the design of work systems.
5	Matched and connected the outcome from step no. 3 and 4 in order to identify which concepts, methods, and tools from the literature could be used to deal with the identified challenges from the case studies.	List of the concepts, methods, and tools that are relevant and should be included in the proposed framework for (re)designing work systems in the transition to Industry 4.0, which were: • HF/E with focus on Human-Centered Design (BSI Group, 2010), Human well-being (IEA, 2020) and system performance (Jenkins, 2017; Jenkins & Baker, 2015) • The SOFT Work system model (Horgen et al., 1999) • Balanced scorecard) (Kaplan & Norton, 1992, 1996)
6	Combined the results from step 5 to develop several versions and iterations	The result of this step was the proposed framework shown in Figure 28.

	of the framework until reaching a usable version.	
7	Presented and validated the conceptual framework by presenting it to several subject matter expert scholars and practitioners.	Validation of the conceptual framework and indication that the conceptual framework was ready for testing in practice.

During the process of developing the conceptual framework, we researched and considered many different theories, methodologies, and concepts (e.g., Lean thinking, Designing thinking, Business Process Management), in addition to HF/E and work system methods. The main focus was on usefulness and applicability in practice; thus, the final conceptual framework became a combination of three concepts, the SOFT work system model (Horgen et al., 1999), HF/E with a focus on human well-being and system performance (IEA, 2020; Jenkins, 2017; Jenkins & Baker, 2015), and lastly, Balanced Scorecard (BSC) (Kaplan & Norton, 1992, 1996). These three concepts had overlapping elements and fitted very well together for (re)designing work systems in the transition to Industry 4.0.

As highlighted in Section 1.2, there are several different useful approaches for work system design. However, to ensure simplicity and reduce complexity, we chose only to incorporate the SOFT model. While the model with its five dimensions is simple and easy to comprehend, it is also very comprehensive in covering the essential elements of a work system. Also, because there is an overlap between the SOFT model dimensions, BCS perspectives (e.g., Finance, Organization, and process/work practice) makes the two models highly compatible with each other. Besides, the SOFT dimension also covers the HF/E domains well. For example, the Space dimension can cover Physical HF/E, Work Practice can cover Physical and Cognitive HF/E, and the Organization dimension can cover Organizational HF/E.

BSC is one of the most popular management tools and is considered the number one framework for performance management (2GC, 2019). The primary purpose of the BSC is to assist a company's top management in translating their company's vision and strategy into a set of intelligible and linked financial and non-financial performance measures (Kaplan & Norton, 1996). BSC views performance from the following four different perspectives, Financial, Internal Processes, Organizational Capacity, and Customer.

In regards to the HF/E aspects, the framework incorporates the three main domains of HF/E, physical, cognitive, and organizational, as described by IEA (2020) and system performance measures by (Jenkins, 2017; Jenkins & Baker, 2015). The system performance measures are Effectiveness, Efficiency, Flexibility, Inclusiveness, Satisfaction, and Safety, and are an essential underlying aspect of the proposed framework as well as the red thread throughout the proposed process of using the framework in practice. Refer to Figure 28 to view the proposed framework.

2.2.2 Operationalization

Lynham (2002) explains that the purpose of the Operationalization phase is to link the Conceptualization phase with practice, thus testing the conceptual framework in practice to validate its usability. We tested the framework in a collaborative workshop setting at a large manufacturing company located in Denmark. Using a workshop as a research method usually has two purposes. On the one hand, workshops aim at delivering practical and valuable results that are accommodating the participants' interests. On the other hand, it serves to accomplish research results and produce valid and reliable data on the topic of interest (Ørngreen & Levinsen, 2017). It is essential to highlight that this company was not one of the companies participating in the explorative case studies mentioned in Section 2.1.

2.2.2.1 Case company for testing and validating the framework

The case company is a large Danish manufacturing company with several offices, manufacturing, and packaging facilities both in Denmark and internationally. The company is currently in transition to Industry 4.0 and has established a department that solely focuses on introducing new digital technologies and concepts throughout their facilities. This department and transformation started about two years ago, and the company has spent a large number of resources on identifying and striving to implement new digital solutions such as robotic automation, digital paper flow, system integration, and big data and visualization.

However, our main contact person at the company (who is a decision-maker within digital change management and optimization) explained that their digital transition has only resulted in a few useable solutions. He contributed this limitation to the company's approach to identifying and developing digital solutions. This approach had consisted of engineers (with limited knowledge on the work system operations) developing technical solutions without involving the operational level workers, thus resulting in non-practical and non-valuable solutions. Also, the decision-maker mentioned that in some cases, they had failed to identify the need and justification for creating a new digital solution. Thus, they had only introduced some new digital solutions because digitalization was a part of the company's strategy and not because there was a use for it.

To create better solutions and ease the (re)design and implementation process, the department needed a standard approach or method for introducing and evaluating new digital solutions. They wanted to use such a standard approach to align expectations in terms of proposed value and vision, as well as technological and organizational requirements. Thus, they agreed to take part in testing the proposed framework in connection with the introduction and development of an augmented reality solution for training purposes, which the decision-maker decided upon before the workshop.

2.2.2.2 Workshop setting

In cooperation with the case company, we planned a half-day collaborative workshop with ten participants who had different functions across one of the company's packaging sites. The first author of this paper had the role of facilitating this workshop. The workshop participants included technicians/operators, software developers, engineers, and a decision-maker responsible for the digitalization initiative. Because of the limited time, the workshop followed a strict protocol, starting by explaining the purpose of the workshop and introducing the planned activities. Hereafter, we shortly presented the framework and the approach for using the framework during the workshop and proceeded to start the workshop.

It is important to note that, to ensure that the participants had a sufficient understanding throughout the workshop, each participant received a printed copy of the framework and additional pages with explanations of the different aspects and elements of the framework. These additional pages included Table 17 and another table, which contained examples of aspects of the three main HF/E domains (physical, cognitive, and organizational), as highlighted by Kadir, Broberg, & Conceição (2019a) distributed in the dimensions of the SOFT work system model.

Table 17 – Jenkins & Baker's (2015) System Performance Measures adjusted for work systems

System Performance Measures	Description
Effectiveness	Meeting the primary goal of the work system.
Efficiency	Providing the system, processes, and workers with more time.
Flexibility	Allowing the work system and workers to do more.
Inclusiveness / Usability	Enabling compatibility and easier use and understanding.
Satisfaction	Improving stakeholder satisfaction.
Safety	Reducing the level of risk and uncertainty.

The information and ideas generated during the workshop were stored on post-it notes and converted to digital format after the workshop was completed. Figure 32 shows a photo of the workshop, where the participants are presenting and discussing the objectives they had identified for each dimension of the SOFT work system model. The faces of the participants in Figure 32 are blurred to ensure their and the case company's anonymity.

Figure 32 – Photo from the workshop for testing the proposed framework.

2.2.2.3 Workshop approach

The approach for using the framework during the workshop followed a seven-step process, where each step focused on a specific element of the framework. Refer to Figure 33 for an overview of these seven steps.

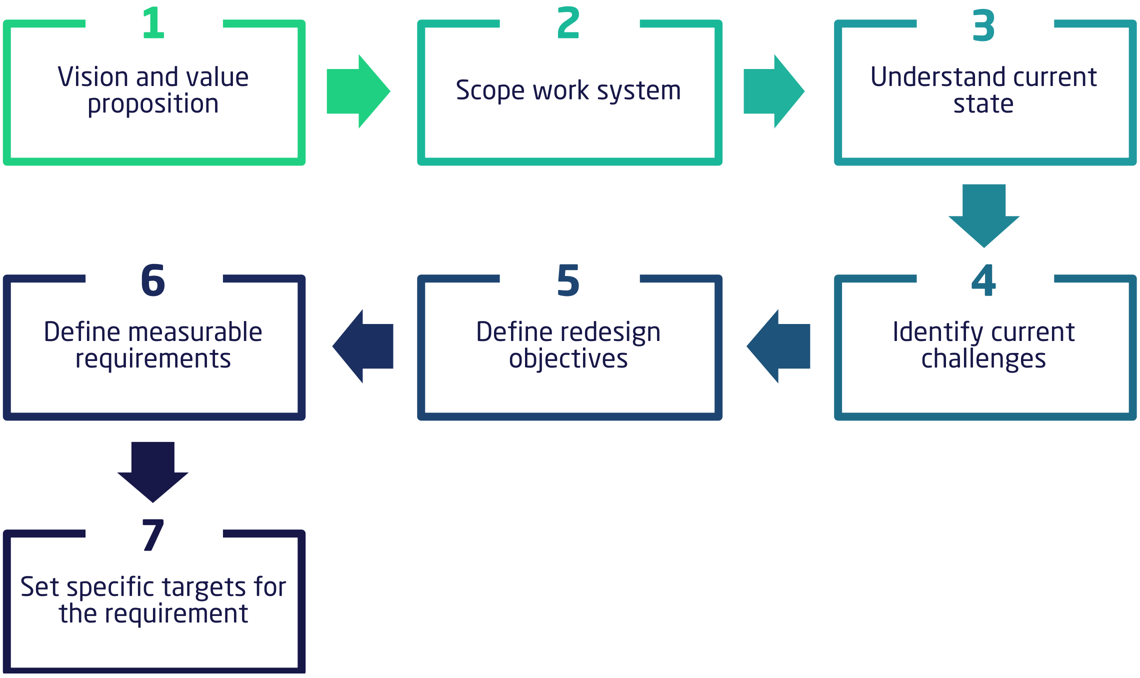

Figure 33 – The applied seven-step approach used to test the framework during the workshop.

The purpose of the first three steps was to create a coherent and mutual understanding of the reasoning behind the (re)design of the specific work system in question, and the work system's current state (processes and work practices). In step 4, the aim was to identify the current challenges in the five dimensions of the work system as well as challenges that might be hindering the vision and value proposition defined in step 1. In step 5, the participants defined (re)design objectives that could deal with the selected challenges and the successful implementation of the new digital technology. It is essential to mention that during both steps 4 & 5, the participants benefited greatly from using the additional complimentary printed materials mentioned in 2.2.2.2.

In the last two steps, the participants defined specific requirements for how they could achieve the defined objectives and set measurable (where it was possible) targets for the defined requirements as well as the timing and frequencies of the measurements. To ensure all participants were aligned and agreed on the achieved outcome, the workshop ended with a quick recap of the results. Table 18 shows a selection of the results obtained during the workshop. It is important to highlight that we are only able to showcase a very minimal selection of the results because of the non-disclosure agreement with the case company.

Table 18 – A selection of some of the results obtained during the workshop

Vision

- Using Microsoft HoloLens instead of paper Standard Operation Procedures (SOP).
- Remove all paper from the work system.

Value proposition

- Less time spent on (re)training of current and training of new workers.
- A standard way of working / uniform way of working.

Scope

Specific work system at one of the sites.

- Creating digital SOPs for how to use the machine and perform tasks in this work system.

Current state

Created several visual maps of the work system, which included a system and process maps. Used the results of these maps to estimate and create a baseline for the time it takes to (re)train new and current employees as well as the time it takes to develop (or update) and implement SOPs.

Current state challenges	**Future challenges**
Finance • Cost of errors • Resources used for training employees	*Finance* • Cost of development and implementation • Cost of downtime
Organization • No available SOP • Limited training in how to work in the work system	*Organization* • Training in using new technology • Getting organization buy-in
Work practices • Unclear job routines • Workers need to rely on their memory	*Work practice* • Learning to use to using the new tech. • Incorporating the new technology into existing work practice
Space • The need to wear face masks in the work system • Accessibility to the work system	*Space* • Storing the unit and getting access to it • Physical maintenance (e.g., cleaning) of the unit
Technology • No explicit instructions on how to use the machine • Machines related errors	*Technology* • Technology usability and stability • Integrating the new system with the existing systems

Objective	**Requirements**	**Target**
Finance • Improve effectiveness	*Finance* • KPI for measuring the effectiveness	*Finance* • No. of issues < x / month
Organization • Faster training and onboarding of new workers	*Organization* • Training workers in using the new technology	*Organization* • 100% of workers trained using the new technology

Work practice • Have a standard guideline and work practice	*Work practice* • Guidelines for when to use the technology	*Work practice* • Relevant employees use the tech. min. 1 time / 3 months
Space • Technology at a close distance to the workers	*Space* • Store in a nearby area that is easily accessible	*Space* • Distance from workspace < 5 m
Technology • Easy to maintain and update	*Technology* • Traceability and transparency of changes	*Technology* • Have a system for logging changes

2.2.3 Confirmation/Disconfirmation

The purpose of this phase is to either confirm or disconfirm the theoretical framework by evaluating the findings from the operationalization phase (Lynham, 2002). To evaluate the usability of the framework and the value and validity of the obtained results, we spend the last 15 minutes of the workshop discussing these notions. While the response of all of the participants was highly positive, several mentioned that one half-day was too short, and they would have been able to obtain more excellent results with additional time.

After the workshop, we also presented the digitalized version of the results to the decision-maker responsible for the digitalization initiative. The purpose of this presentation was to evaluate the value of the obtained results and applicability of the framework. Similar to the evaluation by the participants, the decision-maker believed the results were very satisfactory and evaluated the framework to be highly useful and practical. The decision-maker expressed that he was very impressed with how simple it was to use the framework and the many useful ideas they were able to generate in such a short time. Also, the decision-maker highlighted that it was refreshing to apply a bottom-up approach and involve the operational level workers in a digitalization initiative. Up until that point, the department's senior leadership had started all of the digitalization initiatives in a top-down fashion with minimal involvement of the operational level workers.

The results from the workshop were used to develop a minimum viable product of the digital solution and for redesigning the work system with the new digital technology incorporated. However, it is essential to note that at this stage, we were only able to validate the framework in terms of usability and output generation. Thus, the confirmation does not include whether the output of the workshop and use of the framework had resulted in improved human well-being or system performance.

2.2.4 Application

The purpose of the Application phase is to go beyond testing and apply the developed theory or framework in the working world and practice. This application is to enable further study, inquiry, and understanding (Lynham, 2002).

After we validated and confirmed the framework's usefulness and usability, the decision-maker responsible for the digitalization initiative presented the results to the department's senior decision-makers. At the time of the writing of this paper, the case company is in the process of establishing a standardized approach for using the framework in connection with the future implementation of new digital technologies across the packaging departments at their different national sites. Thus, the proposed framework has not completed the application phase. The targeted users of the framework will be the decision-makers and engineers in charge of designing and implementing new digital solutions, as well as organizational change management professionals in charge of anchoring these new digital solutions.

3. Discussion

3.1. Contribution

As mentioned in Section 1.1, the currently available frameworks and methods concerning the integration of HF/E in the design of Industrial work systems in Industry 4.0 are mostly conceptual and either only focus on aspects of work systems or only provide solutions for the factories of the future. Thus, very few publications cover and provide perspectives on the transition to Industry 4.0. As mentioned in Section 1, several recently published academic publications are highlighting a research gap and calling for research focusing on frameworks and guidelines on the introduction of new digital technologies in this transition.

For example, Sgarbossa et al. (2020) argue that it is essential to re-think the traditional industrial engineering approaches and that researchers need to offer improved knowledge on the links between system performance and human demands. As another example, Masood & Egger (2019), which focuses on the implementation of an AR headset (similar to the case company presented in Section 2.2.2.1), highlight that "organizational fit," including ergonomics, user acceptance, and efficiency improvements are of high importance and high relevance in connection to the implementation of AR headsets. Similarly, Masood & Egger (2019) also calls for further research on the process of adapting and integrating AR in the current work systems with additional focus on operator well-being and safety.

As Chien et al. (2017), KPMG (2017), and Wilkesmann & Wilkesmann (2018) highlight, most industrial companies are still in the transition to Industry 4.0. This notion is aligned with the empirical findings from the industrial case studies presented in Section 2.1. Thus, the application of a framework such as the one we propose in this paper is essential in the journey towards Industry 4.0, as it strives to ensure the successful introduction and implementation of new digital technologies and solutions.

The contribution of this paper is twofold. On the one hand, it caters to a growing gap in practice as the proposed framework provides practitioners with a systematic Human-Centered Design (HCD) approach for (re)designing industrial work systems in the transition to Industry 4.0. Practitioners using this framework will gain a cohesive understanding of their work systems and be able to define specific, measurable (re)design criteria and objectives that will ensure a well-thought-out start for the implementation of new digital technologies. As presented in Section 2.2.1, the combination and structure of the work system elements aim at incorporating considerations regarding all the necessary elements of a work system. These considerations aim at ensuring system performance and human well-being post the implementation of the new digital technologies.

On the other hand, academics and researchers can use the framework when developing new concepts and conceptual tools and solutions related to Industry 4.0. Indeed, because of the framework's comprehensive coverage of the different elements and interactions within a work system, it can function as an analytical tool, which academics can use to analyze and understand how their proposed concepts and solutions might affect the overall system performance and well-being of the humans working in the work systems. Such an analysis could include asking and answering questions related to the seven steps of the framework. Such questions could include

- What is the value proposition of this new solution? How do we imagine the new solution will be used in practice? (Step 1)
- In what kinds of work systems could the new solution be used? (Step 2)
- What is the current situation in practice, without this new solution? (Step 3)
- What are the current challenges related to the six system performance aspects across the five dimensions of the work system, which the new solution is intended for? (Step 4)
- What kinds of challenges could emerge when using the new solution in practice? (Step 4)
- Are there any useful design objectives that might deal with the identified challenges? (Step 5)
- Are there any useful specific requirements and targets for how to achieve these defined objectives? (step 6 and 7)

3.2. Usability of the framework

The application of the proposed framework is highly dependent on a collaborative design approach with active participation and input from the workshop participants. These participants will (for the most part) have to rely on their knowledge and experience of working in or interacting with the work system. As highlighted in Section 2.2.2.2, the participants of the workshop at the case company for validating the framework came from different educational backgrounds and had various roles in the department. Diversity amongst the workshop participants is essential when applying the framework in a collaborative workshop setting. This recommendation is well aligned with the recommendations of BSI Group (2010), which highlights that an HCD team should include participants with multidisciplinary skills and perspectives to collaborate on the design and implementation trade-off decisions, thus creating additional creative and useful ideas.

Teams with diverse participants might not always have a common understanding of the work system elements, processes, and interactions. Thus, the framework has an immense focus on allowing the participants to create and reach a shared understanding throughout its entire seven steps. The purpose of testing the framework in an industrial setting was to validate the usefulness and applicability of the framework. During the workshop, the participants were able to create a shared understanding of the overall vision of the new solution and define the specific value they believed the new digital technology could create once implemented in the work system. This shared understanding through the definition of a vision is an essential element in the BSC.

Kaplan & Norton (1996) highlight that it will not matter how well a company executes a strategy if the defined vision is wrong. We argue that the same applies to the (re)design of work systems in connection to the introduction to new digital technologies and solutions. If the involved stakeholders do not have a shared understanding of the vision for (re)designing the work system, the result might end up as a dispersed solution with minimal or no value. Also, the definition of a value proposition has an essential role in this shared understanding. While the notion of a value proposition is often used in connection to a business model and product and service design (Nylén & Holmström, 2015; Osterwalder et al., 2010, 2014), we observed that it also has merit in the context of work system (re)design. Defining a value proposition at the initial stage of the workshop ensured that the stakeholders could align their expectations regarding the anticipated value of the new digital solution.

Creating a shared understanding of the current state of the work system is equally important as the (re)design vision and value proposition. Without this understanding, it will be very challenging to complete the remaining steps of the framework. Ensuring that all of the participants have a shared cohesive understanding of the current state was an essential part of the workshop for testing the framework. Indeed, the participants co-created several visual representations of the system, each highlighting different aspects and interactions. These visual representations included flowchart, swim lane diagram, and system maps. While these maps were not highly detailed, in-depth representations of the work system, they served the purpose of aligning the participants' understanding. Beyond the systems- and process visualization tools, it might also have been relevant and useful to create a work system snapshot (Alter, 2006) to establish a quick yet, comprehensive overview of the work system and the pertaining elements.

With a shared understanding of the (re)design vision and value proposition as well as the current state of the work system, the participants were able to identify current challenges and define (re)design objectives and measurable requirements for each of the five SOFT work system dimensions. Dividing the work system into these five dimensions allowed the participants to view the system from different perspectives, which might have increased ideas generated. However, because the study did not focus on testing this aspect, it is difficult to confirm this notion with certainty.

Essentially, the framework is not proposing a new way of looking at work systems. However, it provides a systematic approach for considering all of the critical aspects related to ensuring human well-being and overall system performance when (re)designing work systems in the transition to Industry 4.0. Thus, we did not find it necessary to add any additional dimension compared to those of Horgen et al. (1999), which are similar to dimensions and aspects of other work system models, e.g., Alter (2006) and Smith & Sainfort (1989). The SOFT dimensions are simple to explain and understand, and they overlap with some of the dimensions of the BSC (Kaplan & Norton, 1992).

The inclusion of the System Performance Measures (Jenkins, 2017; Jenkins & Baker, 2015) in the framework and redefining them, as shown in Table 17, allows the work system designers (i.e., the participants of the collaborative workshops for using the framework), to consider aspects affecting system performance and human well-being. These performance measures have an underlying role in the identification of challenges and the definition of (re)design objectives. Indeed, throughout the workshop for testing the framework, the participants consistently referred to these performance measures as they presented identified challenges and defined (re)design objectives.

It is essential to highlight that it might be necessary to have one or more participants that are familiar with HF/E to adequately incorporate HF/E aspects and considerations when using the framework in a workshop setting. Participants with HF/E knowledge and experience can provide valuable perspectives on how the current work system challenges might be affecting system performance and human well-being. These participants will also be able to identify how these two aspects might be affected and accounted for when identifying (re)design objectives in the last steps of the framework.

Many new digital technologies will affect human well-being and system performance. We believe that because this framework proposes a general approach for work system design, it complements other relevant and more specific HF/E related frameworks (e.g., Cognitive Work Analysis (CWT) (Vicente, 1999), Cognitive Tasks Analysis (CTA) (Crandall et al., 2006), and Hierarchical Task Analysis (HTA) (Hollnagel, 2003)) very well. Indeed, the application of CTA and HTA could be highly beneficial for analyzing work practices. Similarly, tools from the CWT methods could be useful in understanding the organizational aspects of the work system. Thus, consulting with or having HF/E experts who might know these HF/E methods, as workshop participants, will be highly valuable, and in some cases, a necessity. Lastly, it is essential to have a decision-making participant (e.g., project management or middle manager) that can lead the workshop, follow up on the planned activities, and communicate the outcome to the relevant stakeholders outside of the workshop.

3.3. The frameworks relevance in the transition to Industry 4.0

This framework is especially suited for Industry 4.0 changes and the introduction of new digital technologies for multiple reasons. While the framework accounts for sociotechnical aspects and interactions within a work system, it also has a clear focus on the financial aspect related to the investment of new digital technologies. Dul & Neumann (2009) argue that in order to ensure a company's decision-makers account for HF/E, it is essential to link HF/E with company strategy and business outcomes (e.g., financial goals and performance). Thus, because financial aspects are one of the main drivers of Industry 4.0 (Vuksanović Herceg et al., 2020), it is essential to include this aspect in the design phase.

The link between business outcome and HF/E can also go the other way around, were business outcome is affected by HF/E. Sgarbossa et al. (2020) highlight the importance of this link in the transition to Industry 4.0 and refer to Rose et al.'s. (2013) concept of "phantom profit." Phantom profits refer to the fail achievement of expected performance and business outcomes caused by the poor working environment and lack of attention to HF/E in the (re)design of systems.

In addition to the financial aspects, the seven steps approach (shown in Figure 33) aims at ensuring a systematic approach for aligning humans, organizational, and technological elements of a work system, with specific objectives and measurable targets for dealing with current and upcoming challenges. Applying HCD and encouraging the users to define a vision and value proposition might both limit organizational friction as well as investments in invaluable digital solutions. Revisiting the case example of Company A described in Section 2.1.1.3 can assist in highlighting how using this framework might have helped to resolve some of the company's challenges.

For example, by using the framework and the seven steps approach, Company A might have reduced organizational friction and increased employee buy-in by establishing a coherent vision and value proposition, which could address the potential impact on job security and well-being. Understanding the current state could have assisted the identification of potential challenges and limitations in the different work system dimensions and the interactions within and between them. The following are some examples of what kind of challenges Company A might have avoided or limited by using the proposed framework.

- Spatial limitation preventing their AGVs and industrial robots from functioning optimally.
- Correct placement of new technologies to avoid increased unnecessary movements by the workers.
- Identifying the need for training and competency upgrades to ensure the correct use and interactions with the new digital technologies.
- Establishing reasonable and realistic KPIs for working with the new digital technologies (e.g., lead- and cycle time).
- Correct safety protocols.
- Reasonable work division between workers and new technologies.

- Gaining an understanding of the new digital technologies limitations.
- Realistic definition of return of investments.

These examples highlight some of the challenges which Company A might have avoided if they had followed the proposed framework.

The unique combination of HF/E aspects (i.e., focus on human well-being and system performance), strategy design (i.e., BSC, objectives, and targets), and work systems aspects (SOFT dimensions) and the seven steps approach for application presents a novel method for designing work systems. While we developed the framework, using empirical data collected through case studies on the implementation of new digital technologies, we believe that the framework has the potential of application beyond Industry 4.0 and new digital technologies. For example, the decision-maker from the case company for validating the framework (described in section 2.2.2.1) also highlighted this notion. He mentioned that they also wanted to try and use the framework for redesigning their approach for creating training materials and standard operating procedures.

Finally, it is essential to note that a successful application of this or any other framework to design work systems will only contribute to parts of a successful introduction of new digital technologies. Marnewick & Marnewick (2020) highlight that a successful transition to industry 4.0 depends on several other critical factors (e.g., leadership, change management, organizational agility, and project management). Thus, while the initial design considerations are essential to push a digitalization project in the right direction, the implementation process is equally, if not more important.

3.4. Summary

In summary, testing the framework with the pertaining seven-step approach described in Section 2.2.2.3 and receiving the positive feedback from the case company, as mentioned in Section 2.2.3, indicates the framework's usability in an industrial setting. However, the results might have been even more promising if the workshop duration had been longer than one half-day. A more extended workshop might have resulted in the identification of additional challenges and the definition of additional and more detailed objectives and measurable requirements.

3.5. Limitations and further research

Because we only have tested the framework through one single case study, it might lack the necessary rigor to support the claim of its applications in all industrial settings. Thus, further research could focus on conducting several in-depth prospective case studies to document the application of the framework and identify usability challenges and opportunities for improvements. Similarly, it also might be valuable to have researchers and academics use and test the framework in connection with the development of new Industry 4.0-related concepts. An additional limitation of this paper, which might be valuable to explore in future research, is connecting the empirical findings presented in Section 2.1.1.2 (which are the underlying foundation for developing the proposed framework) with an extensive literature study documenting similar challenges in existing research publications.

Lastly, to ensure the correct application of the framework, further research and development could include a practice-oriented handbook with specific guidelines and tools on how to use the framework in an industrial setting.

4. Conclusion

Redesigning existing or designing entire new work systems in connection with the introduction of new digital technologies possess various sociotechnical challenges that can affect both overall system performance and human well-being. In this paper, we developed and proposed a framework which combines aspects from Human Factors and Ergonomics, work system modeling, and strategy design for designing industrial work systems in the transition to Industry 4.0. Also, we presented the results of ten retrospective, explorative case studies, which highlighted challenges related to the (re)design of industrial work systems in connection to the implementation of new digital technologies. We used the results of these case studies as a foundation for developing the proposed framework.

Lastly, to ensure the applicability and usefulness of the framework, we tested the framework through a collaborative design workshop in an industrial case study. The result of this case study indicated the frameworks' usefulness and applicability.

7. Discussion

As mentioned in Section 2.1, while the concept of Industry 4.0 was proposed in the year 2013 (Kagermann et al., 2013), it seems that most industrial companies are in a transitional phase, having yet to achieve the full vision of the Industry 4.0 concept (KPMG, 2017; PwC, 2018; Wyck et al., 2019). As highlighted in Chapters 5 and 6, our descriptive empirical data suggest a similar notion, adding to the evidence that most industrial companies are indeed only in a transitional phase in their journey towards Industry 4.0. I also highlighted that the majority of the case companies struggled with this digital transformation, as they had limited experience with implementing and working with new digital technologies. Combined with the results from Chapter 4, which highlighted that research at the intersection between Industry 4.0 and HF/E is relatively limited, with more than half of the contribution focusing on theoretical and assumption/estimation based concepts, makes the approach and results of this thesis highly relevant.

Indeed, in the following sections, I will discuss the implications and contributions of the obtained results of this thesis and provide explicit answers to the proposed main and supplementing research questions. In addition, I will discuss the overall limitations of the thesis and provide propositions and suggestions for further research on the topic.

7.1 Contributions

7.1.1 Contribution to research and theory

This thesis contributes to the theoretical landscape of the intersection between HF/E and Industry 4.0 on several fronts. As presented in Chapter 4, one of the main contributions is the identification and establishment of a research gap. Paper A, which included a systematic literature review, aiming at understanding the extent, type, and approach of Industry 4.0 academic publications' integration of HF/E, highlighted several significant findings. The findings indicated that current research in this intersection is minimal compared to research on the two topics outside of the intersections. Paper A also highlights that the majority of these publications are from non-HF/E related outlets, and only half of the total publications rely on empirical evidence.

One of the recommendations for future research presented in Paper A was increasing the focus on empirical data describing how the transition to Industry 4.0 might affect HF/E in industrial companies. As I have highlighted in Paper B, most industrial companies have not entered Industry 4.0. Thus it is essential to emphasize the term "transition," as this is the current state of the Industrial sector. Paper B accommodates the need for additional empirical data and presents some of the findings from the ten industrial case studies conducted in connection with this Ph.D. project. The results of Paper B includes an overview of how the introduction of new digital technologies affect perceived human well-being and overall system performance before, during, and after implementation. These results highlight that, in general, perceived human well-being and system performance are in a somewhat neutral state before implementation. However, both tend to worsen during implementation and improve beyond the neutral state after the implementation is completed.

Regarding empirical data, Paper D also includes such contributions. The empirical data used to develop the framework proposed in paper D highlight additional challenges the companies from the ten case studies had faced when (re)designing their work system and in connection to the implementation of new digital technologies. Such descriptive empirical evidence is essential to the progress of the research field and the development of prescriptive concepts, methods, frameworks, and guidelines.

Lastly, the frameworks presented in Paper C and D contribute to the current theories and body of literature on HF/E and work system design, especially in connection with the transition to Industry 4.0. Both of these papers present frameworks that combine and elaborate on existing concepts and methods for understanding and analyzing interactions within and between work systems and the process of designing work systems. Besides, the framework presented in Paper C enables researchers to analyze and understand the (re)design process of a work system in the transition to industry 4.0, and the framework in Paper D can be applied in connection to the development of new Industry 4.0 related conceptual tools and solutions. Indeed, by applying the framework from Paper D, researchers can get a comprehensive perspective on how their proposal might affect system performance and human well-being.

7.1.2 Contribution to practice

This Ph.D. thesis contributes to practice in several ways. The majority of the research questions (including the main research question) aim to assist industrial companies and other relevant practitioners (e.g., System Influencers (competent authorities such as regulators standardization organizations, and governments), and system experts (professional- HF/E specialists, psychologist, and engineers contributing to the design of the system). From a general perspective, the contribution is twofold.

On the one hand, we have paper B, which included an overview of factors that can potentially affect perceived human well-being and system performance before, during, and after the implementation of new digital technologies. Based on these factors, Paper B provides several recommendations for how industrial companies should approach the introduction and implementation of new digital technologies before, during, and after implementations. These are valuable recommendations with the potential of ensuring both human well-being and system performance in the long run. Guidelines and recommendations aiming at assisting industrial companies with the design and implementation of Industry 4.0 concepts are minimal (Veile et al., 2019), especially regarding the accommodation of human well-being and system performance. While several publications make some recommendations similar to those of Paper B (e.g., using an HCD approach, assessing organizational maturity, and workers' skills), very few provide explicit recommendations based on empirical evidence.

On the other hand, Paper C and D each presents a framework, which aims at guiding practitioners in their approach to work system (re)design projects and the (re)design of work systems in connection with the introduction of new digital technologies. As highlighted in Papers C and D, both the current literature on the topics and the collected empirical data from the case studies highlight the need for such frameworks. It is clear that the introduction of new digital technologies is creating sociotechnical challenges, and the application of the proposed frameworks could be a step in the right direction in dealing with such challenges.

Lastly, an essential part of any academic contribution is its reach to a relevant audience. Because most of the papers included in this thesis are published in ISI indexed journals and conferences, it is safe to assume that academic researchers will be easily able to find and access these papers. However, ensuring that these contributions reach out to practitioners requires a dedicated effort. One of the venues I have used to reach industry-relevant practitioners is by creating an audio podcast. This podcast, titled HTO and Beyond (Kadir, 2020a), focuses on communicating and sharing the industry-relevant results of this Ph.D. project to a non-academic audience.

Summary of contribution to research and theory

- Identification of a research gap in the intersections between Industry 4.0 and HF/E and suggestions for further research through a systematic literature review.
- Empirical data on how the transition to Industry 4.0 affects perceived human well-being and system performance as well as the challenges industrial companies might face when (re)designing work systems in connection with the implementation of new digital technologies.
- Contribution (in the form of frameworks) to the current literature and body of knowledge on HF/E and work system design in connection to the transition to Industry 4.0.

Summary contribution to practice

- Overview of factors that can potentially affect perceived human well-being and system performance before, during, and after the implementation of new digital technologies.
- Recommendations for how industrial companies should approach the introduction of new digital technologies before, during, and after implementations.
- Frameworks, which aim at guiding practitioners' approach to work system (re)design projects and the design of the work systems in connection with the introduction of new digital technologies

7.2 Answering the supplementing research questions (RQ2 - RQ5)

To answer the main research question of this thesis, it was necessary to address and answer four supplementing research questions. These supplementing research questions enabled a sufficient understanding and provided enough data and insight necessary to answer the main research question, RQ1. In the following subsections (Sections 7.2.1 – 7.2.4), I will provide answers to the supplementing research questions.

7.2.1 Research Question 2

RQ2: To what extent, what type of, and how do academic publications on Industry 4.0 integrate HF/E in their research?

Chapter 4 was solely dedicated to answering RQ2, which involved a systematic literature study, including both quantitative and qualitative analysis. The quantitative analysis contributed to answering all three parts of the research question ("to what extent," "what type," and "how"), while the qualitative analysis mostly focused on part three ("how").

To what extent do academic publications on Industry 4.0 integrate HF/E in their research?

The results from the quantitative analysis in Section 3.1 of Chapter 4 indicated that the extent to which publications on Industry 4.0 integrate HF/E in their research is quite limited. Indeed, the final number of publications included in the quantitative part of the systematic literature review was 50 and 40 in the qualitative part. We excluded these ten papers from the qualitative analysis because they either did not include any relevant HF/E-related content or were conference papers published before a journal article by the same authors and with the same content. Also, while the number of academic publications at the intersection has since the year 2013 grown exponentially, it is still minuscule compared to the total amount of publication related to the two respective topics outside of the intersection. The number of publications at the intersection between the two topics published between the years 2013 - 2018 makes up less than 2‰ of the total number of academic papers related to Industry 4.0 and HF/E published in the same period.

What type of academic publications on Industry 4.0 integrate HF/E in their research?

Regarding what type of academic publications on industry 4.0 integrate HF/E in their research, the quantitative analysis showed that the majority (90%) of the 50 papers included were from non-HF/E related outlets. Besides, of these 50 publications, 37 were conference proceedings, while only 13 were journal articles.

How do academic publications on Industry 4.0 integrate HF/E in their research?

Lastly, in regards to how these publications integrate HF/E in their research, we concluded that 26 of the publications contributed with theories and conceptual frameworks and models, while the remaining 24 based their research on empirical data. Also, we analyzed the content of these papers highlighting how the included papers integrate HF/E in their research. We categorized these findings into the three main domains of HF/E, physical, cognitive, and organizational. While all of the three domains were represented, the most populated domain was cognitive HF/E. It is essential to mention because most of these papers were from non-HF/E outlets, the reference and usage of HF/E terminologies were relatively narrow, giving the impression that the authors were not familiar with and did not have a comprehensive understanding of HF/E as a topic and domain. As highlighted in Section 4.2 of Chapter 4, a recurring example was the usage of the term "ergonomics," which many of the papers from non-HF/E publications outlets solely used in connection to physical ergonomics and physical strain.

Summary of the answer to RQ2

- The extent of Industry 4.0 research dealing with HF/E is minimal.
- Industry 4.0 research covers HF/E aspects much more compared to research within the HF/E discipline.
- The current research dealing with HF/E aspects is mostly theoretical/hypothetical, with minimal empirical research as a foundation.
- Most of the current research overlooks the importance of tactical and strategic organizational levels for the success of HF/E and mostly focuses on the operational level.

7.2.2 Research Question 3

RQ3: How is the introduction of new digital technologies affecting human well-being and system performance?

Chapter 5 applied Paper B to provide a comprehensive answer to RQ3. Paper B included the results of ten industrial case studies focusing on investigating how the introduction of new digital technologies affect perceived human well-being and overall system performance before, during, and after implementation.

The results indicated that generally, perceived well-being and system performance are in a neutral state before the new digital technologies are implemented. Then both perceived well-being and system performance worsen and take a dip during the implementation of the new digital technologies and improve beyond the neutral state of the before phase after the new technologies are implemented. Sections 3.1 – 3.12 provide a comprehensive and detailed description of the positive and negative effects on perceived well-being and system performance before, during, and after the implementation of new digital technologies. Besides, Section 3.13 of Chapter 5 includes a list of factors that impact the perceived well-being and system performance before, during, and after the implementation of new digital technologies.

Summary of the answer to RQ3

- During the implementation of new digital solutions both perceived human well-being and overall system performance might be negatively affected.
- After a successful implementation, both perceived well-being and the overall system performance can improve.

7.2.3 Research Question 4

RQ4: How might industrial companies ensure human well-being and system performance in connection to the implementation of new digital technologies?

Similar to RQ3, the results from Paper B in Chapter 5 assisted in answering RQ4. Based on the answer to RQ3, Section 4.3 of Chapter 5 included several recommendations for how industrial companies might ensure human well-being and system performance in connection to the implementation of new digital technologies.

An essential aspect is to recognize that, generally, there are three overlapping phases, which are before, during, and after the implementation of new digital technologies. Each of these phases requires a different set of considerations and actions. Thus, the answer to RQ4 is dissected into several recommendations for each of these phases. These recommendations are:

Before the implementation of new digital technologies.

- Link digital strategy with the company's strategic objectives and ensure everyone in the organization understands the reason behind the investment in the new digital technologies.
- Inform and engage all relevant stakeholders on all organizational levels
- Evaluate the workers' competences and the need for additional training and education.
- Develop and follow a systematic approach for (re)designing the work systems with the new digital solutions.
- Gain a sufficient understanding of elements and interactions within and between the targeted work system(s).
- Apply a human-centered design and involve the affected employees early on in designing the new digital solutions.

During the implementation of new digital technologies.

- Apply a systematic, iterative approach for introducing new digital technologies and developing new digital solutions.
- Plan and allocate the necessary resources.
- Continuously inform the organization of the ongoing changes.
- Ensure that the workers know how to use the new digital technologies, but also leave room for exploration and adaptation.
- Establish a system for continuously capturing feedback from the users.
- Get a sufficient understanding of the new digital technologies to generate a basic yet realistic idea on the pertaining limitation.

After the implementation of new digital technologies.

- Standardize the new ways of working after the implementation of the new digital solutions.
- Develop standard operating procedures and training materials. Replace and altogether remove non-applicable old materials from sight.

- Establish a program for how to train current and new workers.
- Develop a life cycle management to ensure maintenance, updates, and continuous improvement of the new digital solutions. This life cycle management plan should include a system for collecting, storing, and using continuous feedback from the users to ensure optimal usability and performance.

Summary of the answer to RQ4

Recognize that generally, there are three overlapping phases, which are before, during, and after the implementation of new digital technologies.

- **Before** implementing new digital technologies, it is essential to link digital initiative with strategic objectives, inform and engage the organization, evaluate the organization's competencies, understand the work system and apply an HCD approach for (re)designing work systems.
- **During** the implementation of new digital technologies, it is essential to apply a systematic and iterative approach, consider the necessary resources, keep the organization informed, letting the workers explore the new ways of working, have a system for feedback, and understand the technologies' limitations.
- **After** the implementation of new digital technologies, it is essential to standardize the new ways of working, develop/update training materials and programs for training workers, and develop a life cycle management for the new digital solution.

7.2.4 Research Question 5

RQ5: How should industrial companies approach the (re)design of work systems in connection with the implementation of new digital technologies?

Both paper C and D presented in Chapter 5 focused on answering RQ5. The answer to RQ5 is in two parts. In the first part (Paper C), I propose an overall framework (which combines HF/E with Design- and Lean thinking) for how industrial companies can approach a work system (re)design project in connection with the introduction of new digital technologies. In Paper D, I presented a framework for (re)designing such work systems. Aligned with the overall theme of this Ph.D. thesis, the objectives of these frameworks are to ensure human well-being and system performance by incorporating HF/E considerations in the initial stages of a work system (re)design project.

Practitioners should apply a human-centered, iterative design approach for work system (re)design projects in connection with the implementation of new digital technologies. It is necessary to emphasize the importance of including a design phase and making design considerations before jumping into implementation. The inclusion of a design phase will ensure a sufficient understanding of the work system and the interactions within and between the different work system elements, which could ensure a higher success rate of the successful implementation of the new digital solutions.

This understanding will enable the identification of current and likely future challenges and make it possible to define a future state, specific design criteria for the work system, and requirements for a Minimum Viable Solution (MVS). The purpose of the MVS is to maximize value and shorten the overall project duration while using minimum resources.

The methodology I recommend for gaining this understanding as well as defining specific and measurable design criteria is the framework and the seven-step approach proposed in Paper D (Figure 28). This framework is a human-centered design approach that includes elements from work system theory, HF/E, and strategy design. These seven steps are:

1. ***Define vision and value proposition***
   - Define the vision for the work system (re)design.
   - Define a value proposition to justify the (re)design of the work system and implementation of the new digital technologies/solutions.

2. ***Scope the work system***
   - Scope the work system and define what is in and what is out of scope.

3. ***Understand the current state***
   - Understand the current state of the work system by mapping and visualizing interactions within and between the five dimensions (Finance, Organization, Work Practices, Space, and Technology) of the work system as well as the inputs and outputs of the work system.

4. ***Identify current challenges***
   - Identify current challenges in the five dimensions of the work system regarding the six system performance measures (Effectiveness, Efficiency, Flexibility, Inclusiveness, Satisfaction, and safety).
   - Identify what challenges are currently hindering the defined vision and value proposition.
   - Select specific challenges to deal with in the (re)design of the work system.

5. ***Define redesign objectives***
   - Define redesign objectives that might deal with the selected challenges.
   - Define redesign objectives for the successful implementation of the new digital technology.

6. ***Define measurable requirements***
   - Define specific and measurable requirements for how to achieve the defined objectives.

7. ***Set specific targets for the requirement***
   - Set a measurable (if possible) target for each of the defined requirements.
   - Define the time and frequency of the measurements.

Summary of the answer to RQ5

- It is essential to spend time and resources on (re)design consideration before beginning with the implementation of new digital technologies.
- Apply a human-centered, iterative design approach for work system (re)design projects in connection with the implementation of new digital technologies.
- Understand current operations, interactions, and challenges as well as future requirement and specifications of the specific work system using the proposed framework (Figure 28) with the following seven steps: 1) Vision and value proposition, 2) Scope, 3) Current state, 4) Challenges, 5) Objectives, 6) Requirements, 7) Target.
- Define requirements for a Minimum Viable Solution, which is the smallest solution that provides the most amount of value and possibility to learn.

7.3 Answering the main research question (RQ1)

In this section, I will provide an answer to the main research question of this Ph.D. thesis.

7.3.1 Research Question 1

Main Research Question

RQ1: How to align humans, technology, and organization to ensure human well-being and system performance in industrial work systems in the transition to industry 4.0?

By bringing together the answers to the supplementing research questions, it is possible to provide an answer to the main research question. Aligning humans, technology, and organization is not a one-time event but rather a continuous process that requires dedication and involvement from most of the participants and stakeholders on the different organizational levels. As highlighted in answer to RQ2, several different factors might affect human well-being and system performance, especially during the implementation of new digital technologies. Thus, to avoid or limit the adverse effects, it would be beneficial to follow the recommendations presented in Section 7.2.3 and using the seven-step framework from Section 7.2.4 for (re)designing work systems.

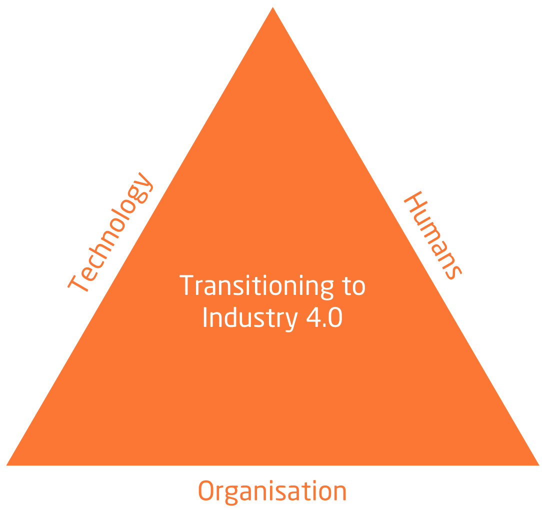

Figure 34 – Humans, Technology, and Organization in the transition to Industry 4.0.

From the results of this thesis, I have defined several principles for the intersection between the three elements of humans, technology, and organization, intending to answer the main research question. Thus, assisting the alignment of humans, technology, and organization in the transition to Industry 4.0 and ensuring the overall system performance of affected work systems and the well-being of the humans working in these systems. The target audience for these principles includes system experts, system decision-makers, and internal system influencers (strategic decision-makers in charge of overall company strategies with limited influence on the actual design of the work system). I have divided these principles into three categories Humans – Technology, Technology – Organization, and Organization – Humans. These principles are

Humans - Technology

The relationship between humans and technology, including how humans use and interact with technologies.

- Evaluate the workers' competences and the need for additional training and education.
- Involve an HF/E or occupational safety and health expert early on in the design.
- Get an understanding of technological limitations.
- Ensure that the workers know how to use the new digital technologies, but also leave room for exploration and adaptation.
- Ensure inclusiveness and physical, cognitive, and sensorial compatibility by designing user-friendly human-technology interfaces and interactions by fitting the new technologies to the workers instead of the other way around.

Technology - Organization

The link between technology to organizational aspects, including the introduction, design, and maintenance of technologies in an organizational context.

- Link digitalization initiatives to overall company strategy and establish a clear value proposition and vision for how the organization might look like when the digitalization initiative is completed.

- Use a sociotechnical systems perspective to get a comprehensive understanding of the company's current systems and the interactions within and between the elements of these systems.
- Understand and evaluate the company's current digital maturity.
- Plan and allocate the necessary time, finance, and organizational resources for before, during, and after the implementation of the new digital technologies.
- Maintain momentum and continuously improve the new digital solutions and the work system in general by establishing a simple feedback loop system.

Organization - Humans

The relationship between humans and organizational aspects, including change management, communications, and protocols.

- Evaluate organizational maturity and readiness for change.
- Involve relevant stakeholders (including the affected employees) and use the seven-step framework (Figure 28) to (re)design work systems in connection with the implementation of new digital technologies.
- Standardize the new ways of working, develop new/updated training materials, and establish training protocols and programs.
- Engage with, and communicate the company strategy, value proposition, and vision to all relevant stakeholders on all organizational levels regularly, before, during, and after the implementation of any new digital solution.

Summary of answer to RQ1

Apply the following principles in the three intersections between humans, technology and organization

- In the intersection between **Humans - Technology**, it is essential to evaluate current competences and training needs, involve HF/E experts, understand the technological limitations, let the workers explore the new ways of working, ensure inclusiveness and compatibility.
- In the intersection between **Technology - Organization**, it is essential to link digitalization initiative with company strategy, get an understanding of company systems, evaluate digital maturity, allocate the necessary resources, maintain momentum.
- In the intersection between **Organization and Humans**, it is essential to evaluate organizational maturity, involve, engage and inform all relevant stakeholders, and apply the seven-step framework (Figure 28), standardize new ways of working, and develop/update training materials.

7.4 Limitations

The scope of this Ph.D. project and methodology applied to collect empirical data creates some limitations regarding the generalizability of the findings of this thesis. The explorative, cross-sectional, and retrospective nature of the case studies limits the depth of the information gained from the collected data. Indeed, I believe that I might have been able to gather greater insight if it had been possible to spend more time at the case companies. I could have used this additional time to collect more data across several work systems, and do more observations and conduct additional interviews with employees and decision-makers on different organizational levels.

Also, it might have been possible to gain greater insight and understanding of the emerging challenges through several prospective cross-sectional or longitudinal case studies. Prospective case studies would have allowed me to follow the implementation of new digital technologies and (re)design of work systems in real-time, for the duration of the projects. Thus, this approach could have resulted in other exciting insights that might not be achievable in retrospective case studies.

Besides, the number of ten case studies makes it challenging to compare the different cases, especially in terms of company size and industry. It would have been interesting to have additional small and medium-sized enterprises as case studies, to compare within and between the different sizes. It is also important to mention the geographical factor in that all of the case studies were at Danish-owned industrial companies located in Denmark. Thus, the results might only apply to industrial companies located in Denmark or other countries with work cultures and economies similar to Denmark. Lastly, yet importantly, as it has not been possible to apply and follow up on the proposed guidelines and recommendations, and document their effectiveness in practice, it is difficult to confirm with certainty that their application will ensure or improve human well-being and system performance. Thus, there is great potential for further research and development in this regard.

7.5 Suggestions for further research

While in this project, I have been able to shed light on many sociotechnical challenges emerging in the transition to Industry 4.0, there is still a great need for additional research. As mentioned earlier in Section 7.4, additional in-depth retrospective and prospective case studies could be highly beneficial to genuinely understand how new digital technologies are affecting human well-being and system performance. Furthermore, further research could also focus on applying and testing the recommendations, guidelines, and frameworks proposed in this thesis. This testing could indeed confirm/disconfirm the proposed prescriptions' usability and if they do assist in improving human well-being and system performance. This testing will also provide the opportunity for further evolving, developing, and improving the prescriptive actions.

I believe that it would be highly relevant, necessary, and interesting to conduct further research on the network of actors involved in the transition to Industry 4.0. Figure 35 shows an overview of the different actors that can influence and affect HF/E aspects of work systems adopted from Dul et al. (2012). However, the model from Figure 35 includes technology suppliers and differentiates between external and internal system influencers. Because of time constraints, this Ph.D. project only included considerations regarding System- actors, experts, decision-makers, and internal system influencers. Thus, further research could include exploring and understanding the roles and responsibilities of all actors, and how they each might influence the HF/E aspects of industrial work system in the transition to Industry 4.0. Such research could highlight additional essential aspects related to designing new ways of working in Industry 4.0 and the alignment of humans, technology, and organization in the transition to and in Industry 4.0 itself.

Lastly, I believe that further research at this intersection could also include a greater emphasis on the technological aspects and elements. It would be relevant to conduct more detailed research and investigate the pertaining challenges and opportunities of specific digital technologies and concepts (e.g., IoT, autonomous robots, 3D printing, Artificial Intelligence) in regards to their specific effects on HF/E and work system design. Such research could also include the investigation of ethical aspects of new digital technologies and the design of autonomous systems, adding to the conversation started by The IEEE Global Initiative (2017) on the topic.

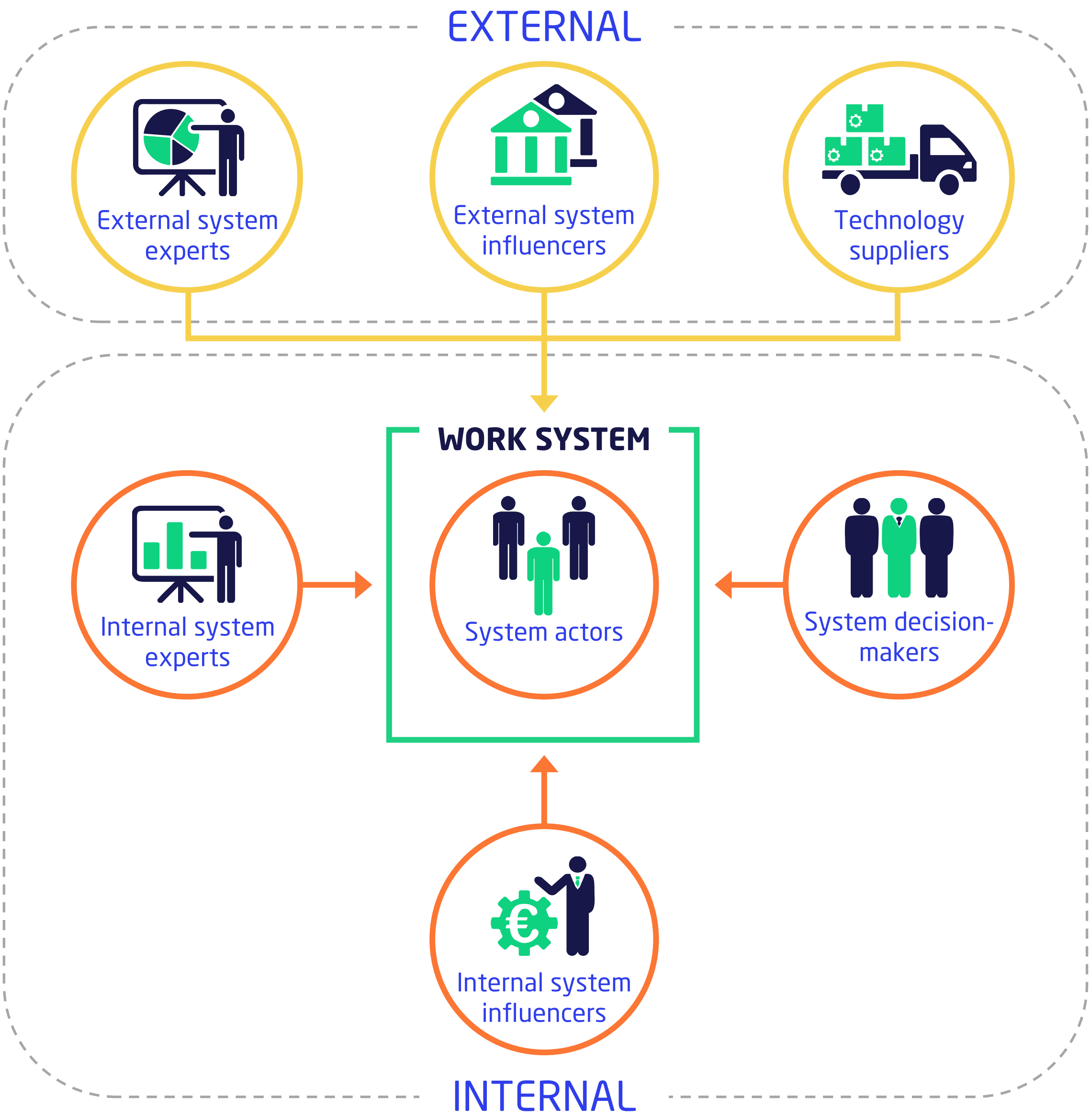

Figure 35 – Actors that can influence and affect HF/E aspects of work systems inspired by the content of (Dul et al., 2012).

7.6 Reflections

The initial thought behind this Ph.D. project was to focus on designing new ways of working in Industry 4.0, hence the title of the Ph.D. thesis. However, I quickly realized that the current state of the industry was far from what anyone would consider as Industry 4.0. This realization set in after I began exploring the current literature on the topic (which was limited), and attending several trade fairs, where I had the opportunity to speak with representatives from many different industrial companies and digital technology suppliers. Many of the industrial company representatives mentioned that their companies were far from industry 4.0, and the majority of the suppliers mentioned that they currently had no or very few customers in Denmark. This notion amplified as I began conducting industrial case studies and gain the first-hand experience. Thus, the focus of the Ph.D. project shifted from industry 4.0 to the transition to Industry 4.0.

Because many companies were in this transitional phase, it was challenging to find prospect companies that were willing to participate in this Ph.D. project. Indeed, I received many rejections from companies that did not want to participate because they did not feel comfortable showcasing half-implemented solutions to externals. Also, I had initially planned to conduct several prospective case studies following and documenting the introduction and implementation of one or more industry 4.0-enabled solutions, which I had to scrap because it was not possible to find appropriate case companies. Besides, it was quite difficult to convince these companies to allocate time and resources to participate in comprehensive and in-depth case studies.

In this project and the pertaining published articles, I mainly focused on HF/E and work system theory. While in Paper C, I included and mentioned the use of an iterative process (a concept from Lean manufacturing and Lean startup) for handling the tasks related to a work system (re)design project, it might have been interesting to explore the application of an Agile approach. While Agile approaches such as Scrum and Kanban, are more common in software development, it would have been interesting to investigate their usability in connection with work system design in the transition to Industry 4.0.

8. Conclusion

The transition towards Industry 4.0 is in motion, and many industrial companies have already started implementing and using new digital technologies. This transition is evoking changes in human work and organization, creating new challenges and opportunities. The objective of this Ph.D. thesis was to explore and investigate Human Factors and Ergonomics (HF/E) related challenges and opportunities in connection with the introduction of new digital technologies in industrial work systems. Hereafter, I used these findings to develop guidelines that can assist in ensuring human well-being and system performance in the (re)design of work systems in connection with the introduction of new digital technologies in this transition to Industry 4.0.

The main research question was, “How to align humans, technology, and organization to ensure human well-being and system performance in industrial work systems in the transition to industry 4.0?” which was supported by four supplementing research questions. The answers to these research questions were covered in four academic publications (three journal articles and one conference paper) and explicitly answered in the discussion section. While one of the papers was a literature study on the intersection between the topic of Industry 4.0 and HF/E, the remaining papers used empirical data collected through ten cross-sectional, explorative, and retrospective case studies conducted at ten different industrial companies located in Denmark. Lastly, in the discussion section, I present the limitations of the Ph.D. thesis and the obtained results, as well as reflections and suggestions for further research.

9. Appendix

Appendix A: Designing human-robot collaborations in Industry 4.0: Explorative studies

Appendix B: A framework for aligning humans, technology and organization in Industry 4.0

Appendix C: Approaches for operationalizing digitalization strategies

Appendix D: Digital transformation: Tilpasning af strategi, forretningsmodel, og organisation

Appendix E: The six aspects of work in Industry 4.0

Appendix A

Designing human-robot collaborations in Industry 4.0: Explorative studies

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**Note*
This paper was written and published in British English. However, for the sake of consistency the version included in this thesis is in American English.

Designing human-robot collaborations in Industry 4.0: Explorative studies

Abstract

We are experiencing an increase human-robot interactions and the use of collaborative robots (cobots) in industrial work systems. To make full use of cobots, it is essential to understand emerging challenges and opportunities. In this paper, we analyze three successful industrial case studies of cobots' implementation. We highlight the top three challenges and opportunities, from the empirical evidence, relate them to current available literature on the topic, and use them to identify key design factor to consider when designing industrial work system with human-robot collaborations.

Keywords

Ergonomics, Industry 4.0, Cobot, Digital Manufacturing, Case Study

1. Introduction

The move towards the fourth generation industrial revolution (Industry 4.0) is promising shorter development times, increased individualized customization, higher flexibility, and resource efficiency. It is creating the notion of a smart factory where everything is interconnected, equipped with sensors, and functions as an autonomous and self-organizing system that requires minimal human intervention with the capability of adapting to human needs (Lasi et al., 2014). Industry 4.0 and the paradigm of a smart factory are bringing a wave of appertaining technological advancements that will enable the creation of smart products and services through smart processes (Preuveneers & Ilie-Zudor, 2017). This paradigm shift and digital transformation is enhancing the transparency of production processes and changing, organizational boundaries and operations of industrial companies throughout the entire supply chain, starting from the identification of the customer's need to the delivery and lifecycle management of the finished product (Stock & Seliger, 2016).

This intense focus on digitalization and implementation of technological advancements is effecting the structure and performance of work in industrial work systems (S. L. Müller et al., 2017). Digital technologies such as Internet of Things (IoT), Cyber-Physical Systems (CPS), cloud technology, and big data are reshaping the concept of manufacturing by increasing the efficiency and effectiveness of daily collaborations, while blurring the boundaries between the physical world and the virtual space (L. Wang et al., 2015).

One of the more tangible technologies effecting the human-technology interactions in manufacturing is collaborative robots, also referred to as cobots. Cobots are a new generation of robots are that born free and unbounded by any type of fencing or enclosure, transcending the boundaries and workspace limitations that prevented their ancestors (standard industrial robots) from cohabitating and working side by side with their human counterparts. Equipped with sensors and being highly responsive to the detection of any unexpected force, grants them the ability to stop immediately when encountering human workers or any misplaced objects in their path. This makes them highly reliable colleagues when it comes to workplace safety, in comparison to standard industrial robots (BSI Group, 2016b). The concept of cobots is not as novel as one would think and dates back to 1996, though it has been through an evolution since this time. First generation cobots were quite different compared to what we categorize as cobots today. While today's cobots are very similar to traditional industrial robots, (with the additional ability to work with human workers without any enclosure) first generation cobots did not have motors, were intrinsically passive in the plane of operation, and had brakes. Figure 36 shows a modern day cobot from Universal Robots.

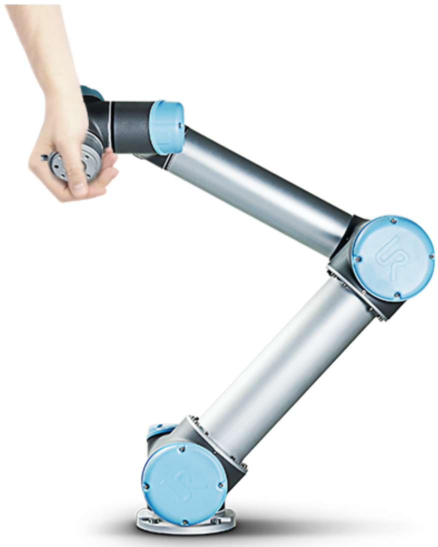

Figure 36 – Universal Robot - Model UR5 model (Universal Robot, 2017)

Current research within the field of human-robot interactions is suggesting the need for further investigation and evaluation of challenges concerning performance, functionality, usability and environment conditions in the design and implementation of industrial work systems with cobots (Djuric et al., 2016). This paper is contributing with empirical evidence to reduce this literature gap by researching this new digital co-worker's ability to work with its human colleagues, and the changes it is evoking with its presence in industrial work system from a human factors and ergonomics perspective. We want to explore and understand the challenges and opportunities related to the implementation of cobots and this new way of working, through the eyes of the people on the shop floor as well as the decision makers that have taken part in the investment decision. Hence, the research question for this paper: What are the work and work organization design challenges and opportunities that emerge when changing from an "old" work system to a new one where humans and collaborative robots cohabitate?

2. Methodology

Exploratory case studies are most appropriate when it is desired to establish an in-depth understanding of a phenomenon with research questions mainly focusing on "what?" and "how?", so as to develop relevant hypothesis and propositions to be further investigated (R. K. Yin, 2009). This coincide very well with the research question proposed in this paper and the chosen approach of conducting exploratory case studies, where the focus is to explore and identify key factors behind the acquisition of cobots, understanding the emerging opportunities and challenges and identifying key design factors in designing human-robot work systems.

2.1. Case settings

We have conducted three exploratory industrial case studies, investigation successful implementation of cobots and design of human-cobot teams. All three participating companies have had their cobot(s) for more than one year, and they are "typical" cases in that the cobots are performing task/tasks in work systems, which previously have consisted exclusively of manual labour performed by workers. The companies are using their cobots in different ways but the element of close human-robot interaction within a work system is the common theme. Table 19 shows an overview of the case companies participating in this study.

Table 19 – Summary of case companies

Company	Size	Industry	Brand and Model	Task
A	Small (< 50)	Machining	Universal Robot - UR5	Pick and place
B	Small (< 50)	Manufacture of metal structures and parts of structures	Universal Robot - UR5	Welding
C	Large (> 250)	Manufacture of plastic	Universal Robot - UR5	Assembly

2.1.1 Company A

Company A is a small machining company and manufacture of fabricated metal parts, established in 2010. It is a family owned business with several family members being a part of its fulltime staff. The company acquired their first cobot in 2011 and currently have two active ones working fulltime in their manufacturing facility, performing pick and place tasks as a part of a Computer Numerical Control (CNC) machining process. This is a repetitive task, taking around 40 seconds, which the workers manually performed prior to the implementation of the cobots. The workers' current tasks consist of feeding the cobot with unprocessed components and preparing processed components for packaging every 20-30 minutes, with each task taking around five minutes to complete. Furthermore, the worker is sporadically passing by the area to check up on the process and the cobot, and perform simple manual tasks like taking samples for quality control, or removing excess metal scrap from the CNC machine, to ensure quality and continuous production.

2.1.2 Company B

Company B, also a small family owned company with less than 50 people on its payroll, was established in the late 1970's, and is specialized in manufacturing metal structures and parts of structures. Over the last 8 years, the company has made an effort to automatize and digitalize several key processes in their manufacturing facility by e.g. implementing industrial robots and digital quality control solutions. Currently, they have two cobots working in conjunction with a human worker on a metal welding process. The cobots pick and place the metal parts and welds them together respectively. The worker prepare the unprocessed parts, starts the process and occasionally control the placement of the metal parts to ensure correct placement before welding. After the completion of a series, the worker will move the finished parts to a temporally stock. Prior to having the cobots, the worker manually performed the entire processes of picking, placing and welding the components.

2.1.3 Company C

Company C is a large manufacture of plastic established in the late 1970's with more than 350 fulltime employees working in its offices and manufacturing facilities combined. Their efforts in process automation and investment in industrial robots dates back to the mid 1980's and they currently have more than 50 industrial robots in their manufacturing facility. While these industrial robots are working in enclosed areas with restricted human contact, the single cobot in the facility is working inches away from its human colleagues, and providing assistance in the assembly of one of the companies many specialized products. The human worker will place the product on the workstation, insert a small part of a long rubber band into the product and signal the cobot by the push of a button to take over and complete the insertion of the rubber band. While the cobot is performing this task, the human worker will prepare another product, and insert rubber bumpers in the products already processed by the cobot. Before the company acquired the cobot, the worker was manually performing all of the tasks.

2.1.4 Data Collection

We collected qualitative data through semi-structured interviews with decision makers (production manager, CEOs) that are responsible are the acquisition and implementation of the cobots, workers that work side-by-side with the cobots, and through observations and demonstrations of the work system and human-robot collaborations in action. Additionally, we interviewed a consultant within the field of cobots, whom has assisted several companies with the implementation of cobots. All interviews were carried out in face-to-face settings with durations between 20-60 minutes and audio-recorded and transcribed in Danish. Using a participant observation type (Denzin, 1978), observations and demonstration of the work systems were video-recorded with consent from the authoritative managers at the companies and relevant field notes were taken according to (Spradley, 1980b). Table 20 shows an overview of the interview participants categorized by their position and role.

Table 20 – Summary of collected qualitative data

Company	Data collection method	Description	Referred as
A	Interview	Worker	A1
		Worker	A2
		CEO	A3
	Observation	Workspace and human-robot collaboration in action	-
B	Interview	Worker	B1
		CEO	B2
	Demonstration	Demonstration of human-robot collaboration	-
C	Interview	worker	C1
		Production manager	C2

	Demonstration	Demonstration of human-robot collaboration	-
Consultancy	Interview	Interview with consultant	Consultant

2.2. Data analysis

We have used a *general inductive approach* (Thomas, 2006) to develop relevant theories and present findings based on summaries of the data collected through interviews and observations and have established relevant links between the findings and the proposed research. The first author has coded and constantly compared the collected data accordingly with the emergence of new categories throughout the process and made use of template analysis (Brooks et al., 2015) to analyse the data according to the themes related to the research question. While the general inductive approach is used as a general approach for the overall analysis, the data generated from the interviews was compared with a purposeful approach to the comparative method (Boeije, 2002), which is an essential part of the grounded theory approach. We have used the data collected from the observations and demonstrations to verify information and statements made in the interviews and to search for and uncover additional information not mentioned or left out in the interviews.

3. Results

The analysis of the qualitative data focused on identifying work and work organisation design challenges and opportunities that emerged when the companies introduced cobots into their work systems. In the following two sub-sections, we highlight and elaborate on the most frequently mentioned challenges and opportunities.

3.1. Challenges

3.1.1 *Cobots are not reflective*

While cobots are sensitive to contact and safe to work with, they still lack the flexibility of their human colleagues and the ability to improvise, adapt and overcome. They can be programmed to perform detailed tasks with precision, but their lack of ability to detect abnormalities such as; variation in raw material or correct placement of components is making them less flexible compared to the human workers. This disadvantage is leaving the workers with the responsibility of ensuring the quality of the work performed by the cobots. All of the interviewed workers, as well as the decision makers from company A and C mentioned this challenge. The production manager at company C explained how this challenge could eventually lead to frustration amongst the workers leaving them to distrust the cobots. He viewed this as the decisive different between workers and cobots, which his company was making an effort to solve.

> *We humans are very flexible… If the rubber band received from the supplier is a bit too long, we will compensate as a human, and push or pull it a little bit. The robot will not do that … people will get frustrated and start doubting the technology thinking that it is not working.* – C2

One of the workers at company A added the following about the cobot's ability to detect abnormalities.

I'll check up on the machine (CNC machine) continuously. If something breaks inside the machine, the product measurements will be completely off. But the machine has no alarms and the robot will not be able to detect if anything is wrong and just continue producing bad products. – A1

3.1.2 *Cobot implementation does not make any sense*

Cobots might be more affordable compared to a standard industrial robot, but they are still coming with a price tag that is considerable for most small and medium-sized enterprises (SMEs). When a company is acquiring a cobot, they usually have a specific task in mind, which they want the cobot to occupy, but since the technology is relatively new and untested, the implementation and achieved results might not always turn out as expected. In the situation where it is not possible to use the cobot as intended, the company has to make a decision that can justify their investment in the technology by utilising the cobot in other human-cobot collaboration tasks in the company. The workers and decision makers at both company B and C mentioned this challenge.

The production manager from company C mentioned that the specific task the cobot was intended for had been put on stand-by, because the customer had decided to delay its order at the last moment. In the meantime, they are using the cobot for a similar task on another product, though with a much lower production volume and frequency leaving the cobot underutilised and often unused. Creating other tasks for the robot seem to be challenging*. Company C is currently collaborating with a university student on his bachelor thesis focusing on finding new tasks for the cobot.*

We want to use the cobot as intended, so it is important to create tasks with the right flow, so it becomes a collaboration and not the cobot doing all of the tasks while the worker is sitting is simply observing on the side. – C2

Company B had experienced similar difficulties. About a year prior to having the current setup of using two collaborative robots for welding metal parts, in their initial attempt, they decided to sell their collaborative robot after having it for only one year, due to inefficient utilisation that could justify the investment and continuation with the technology.

When we have had it (the collaborative robot) for about a year, we realised that it did not make any sense. We took it down and sold it. It did not make any sense. – B2

Apparently, this is a common challenges faced by many companies that have tried their luck with implementing cobots. The consultant mentioned that there are many collaborative robots stored in basements, collecting dust, because the companies did not manage to utilise the technology as intended, leading to impractical and non-functioning human-robot collaboration.

3.1.3 Cobots can hit workers

Sharing a workspace with a non-human entity that is able to roam freely in a fixed pattern without any enclosure is a relatively new type of setup. This might seem a bit freighting and evoke worries for some workers, since they are not familiar with this way of working. It will require an adjustment of movement patterns, behaviour and way of thinking before they can feel comfortable working alongside the cobots. Both workers from company A and the worker from company C mentioned their initial worries about being hit by the cobot, even when they were aware of its safety features and its ability to stop instantly if they came in contact with it.

> *At the beginning, before I was familiar with the cobot and its movement pattern, I was worried about the cobot hitting me.* – A1

Though the workers had initial worries regarding their safety, they all expressed that it quickly passed after having worked with the cobot for a while. The decision makers were also very sure about their workers safety around the cobots. The production manager at company C explained that the work cell they integrated their cobot in, was obligated to have a CE (Conformité Européenne) marking. It should be mentioned that the CE marking is an internal certification and does not require involvement from a third party certification body (European Commission, 2018).

> *When you build a work cell like ours, you are obligated to get a CE marking, and that CE marking contains a risk evaluation where we look at every single part of the work process and assess the risk of getting a finger squeezed or what else might happen along the process. – C2*

The safety features of the cobots seem to be comforting, but the workers still have to overcome their initial worries about being hit. To comfort his workers and to ensure them of the cobots safety features, the production manager at company C had given a demonstration by putting his own hand in an uncompromising position where it easily would have been squeezed and injured if the cobot did not possess its safety features. All of the workers, except for C1 had tried getting hit by the cobot and experienced it stopping automatically and immediately. The experience was in all accounts described as painless and insignificant.

3.2. Opportunities

3.2.1 Cobots enable job enrichment

The cobots are taking the repetitive and trivial manual work away from the workers and leaving them with more time to spend on other and new potentially value creating activities. The decision makers as well as workers all consider this as one of the greatest benefits that derive from the implementation of the cobots. Due to their flexibility and quick learning ability, the worker are able to occupy new functions and take on new roles and responsibilities, which they previously did not have the opportunity and time for. Workers at the case companies had added the following as a part of their job; preparing products for storage, cleaning and servicing machines, programming cobots and other machines, designing new collaborative work with cobots, management of small internal projects, quality control, production planning, making technical drawings, and performing other manual tasks in the production. It should be noted, that none of the workers have officially had their job descriptions updated to encompass these new roles and responsibilities.

> *We are being forced to lower our prices, since everyone was outsourcing to Eastern Europe… in order to retain our business, we had to free up some of our workers time so they could assist with other tasks. So, we let the robots take over the repetitive parts of the job.* – A3

The consultant we interviewed highlighted that the companies he assists usually desire a solution where the cobot might be taking over around 60-80% of a given task, which in most cases are the repetitive and trivial parts of the job, leaving the workers to perform the rest of the remaining and more mentally demanding parts of the job. Seen from the company's perspective, this is a great opportunity to utilise their work force more efficiently and assign new tasks and responsibilities to the workers. Company B and C have used this opportunity to further educate and develop their workers skills and competences by having them participate in relevant courses.

The workers all seemed to be very satisfied with this arrangement, as they get to try their hands on new tasks, gain more responsibilities and develop new skills in the process.

> *…Before when we didn't have the collaborative robot, I was switching the parts manually one by one. That can be very trivial and boring over time. Therefore, it is nice that we now have a robot to take care of that part of the job, so I get the opportunity to try other tasks… I do other value creating tasks in the production.* – A1

3.2.2 Cobots improve workflow

The implementation of cobots have resulted in improved workflow and continuous production. Human-robot teams are much more efficient compared to teams consisting of humans only, due to the fluency of the collaborative effort, where the cobot is performing the repetitive and physically demanding tasks, while the worker is taking care of the more flexible and high variation parts of the tasks. This emerged opportunity was mentioned by the workers and decision makers at company A, as well as the decision makers at company B and C. By implementing the cobot, company C has been able to reduce the assembly time by 50% for that specific work cell, going from two minutes to one.

This continuity has also had its positive effect at company A, which has been able to add evening and night shifts consisting of two workers and two cobots. Previously, this would not have been possible, since the company could not afford having several more employees working these shifts, to produce an output equal to the current setup with the cobots. Company C is also seeing the benefits of this improved workflow. However, they attribute this to their overall effort and investment in cobots as well as other technologies implemented throughout their facility.

> *When considering how we were working in the past, and how we are working now, the working environment is much better¨. The quality is improved and what we are much more punctual when delivering to our customers. The entire flow in the company has improved.* – C2

3.2.3 Cobots take away repetitive tasks

The cobots are taking away the most repetitive tasks from the workers and it is having a considerable effect on the physical work conditions and the workers wellbeing. The workers are getting rid of physically demanding tasks and the decision makers are pleased to have healthy and well-functioning workers that can perform optimally for many years to come. All workers and decision makers except A2 highlighted this opportunity.

> *It is great having it take away this part of the tasks. When I do it manually, I experience wrist pain… The cobot is getting rid of some parts of the tasks that are physically demanding, monotonous and repetitive… We have had a quit many workers getting injured or worn out because they were doing repetitive work.* – C1

> *Previously, I was manually inserting the components one at a time and had to bend over and into the machine 600 times pr. Day… So, seen from a work environment and health perspective, it is removing the parts of the job, which were causing me a lot of back pain.* – A1

Even though the all decision makers made it clear that economics was the driving factor behind the investment, they also expressed great satisfaction with the cobots' ability to improve physical work conditions and their contribution to a better and healthier work environment.

3.3. Summary of results

The results indicates that the case companies had been able to setup and install the cobots relatively quickly and easily. The workers feel safe around them and their arrival has caused a reduction in repetitive and trivial work, which has led to improved physical work conditions and given the workers room to do other potentially value creating tasks. While the installation of these cobots might be easy, finding the right tasks and making efficient use of their capabilities seem to be challenging. The lack of surrounding enclosure restricts them from operating at speeds matching standard industrial robots, and their lack of ability to detect abnormalities makes them less flexible compared to their human colleagues.

4. Discussion

The current literature available on the topic of human-robot interaction and collaborative robots in industrial work systems is indicating several implementation, work, and work organization design challenges and opportunities. However, because the technology is relatively new and in its infant stage, there is still a need for more empirical evidence that can highlight and address the appertaining challenges and opportunities. This paper contributes to reducing this gap with empirical evidence. Empirical evidence based literature dealing with this specific topic is limited, hence the relevancy of this paper and the obtained results. What we have identified as the most frequently mentioned challenges opportunities in this paper are similar to the findings of Djuric et al., (2016) who gives an overview of some of the challenges of cobots, based on a literature review on the topic. However, there is no direct mentioning of the cobots' ability to enable job enrichment by allowing the workers to take on new tasks, develop new skills and professional competences, which we have identified as one of the top three emerging opportunity.

The most frequently mentioned challenge was the cobots inability to reflect and handle component- and process variability, which is a similarly well-known challenge associated with standard industrial robots. However, this can also be viewed as one of the benefits of cobots in comparison to industrial robots, since the cobots can work side by side with a workers that can perform the complex tasks that require sensory inputs and creativity (Matthias et al., 2011). To have standard industrial robots accommodate this challenge will require implementation of advanced sensors and vision systems, which can be very demanding and expensive (Krüger et al., 2009).

If a company is not able to justify their investment, it will no longer make any sense to keep the cobot, as it was the case in company B's first attempt at implementing cobots. In order to utilise the cobots to their full potential and realize the advantages of human-robot collaboration, it is important to have designed well-defined tasks and work organization, which requires a vast understanding of the work system as well as the capabilities of the technology (Grahn & Langbeck, 2005). This correlates with the challenge of the cobots not being able to reflect. When the cobots are efficiently utilized, they will allow the workers to spend time on working on other tasks within their companies. While it was clear that the decision makers and the workers had a pretty god idea of what these new tasks were, none of them had clearly defined or officially documented them.

Work safety and risk management is an essential part of designing human-robot collaborations and must follow regulated safety standards such as (BSI Group, 2016b). Unclear understanding of the technology might result in insufficient planning and considerations for physical work and work safety. It is understandable that the workers from the case companies had initial worries about being hit by the cobots while working in close proximity to the cobots, considering that most injuries in modern manufacturing have historically happened due to unintentional contact between robot and workers (Marvel et al., 2015). Cobots are being promoted as safe to work with, but that does not mean that they can be implemented into a work system without any safety considerations. The Institute for Occupational Safety and Health of German Social Accidents Insurance (BG/BGIA) has developed a guideline and recommendations that can be used for the assessment of risk in the design of workplaces with collaborative robots (Bgia, 2009). Since the challenges and opportunities seem to be highly correlated, it can be argued that the all of the challenges must be addressed in order to achieve the full potential benefits of the technology.

4.1. Implication for practitioners

Designing a successful human-robot collaboration in industrial work systems starts prior to the decision of investment has been finalized. It is important to have realistic expectations of the cobot's ability to perform and manage the tasks you wish to assign upon it and that you are in agreement with the quality the technology is able to deliver (Robotiq, 2018). Successful implementation requires the company to have an in-depth understanding of the existing work system and have created a plan for division of work between workers and cobots. Based on the challenges and opportunities highlighted in this paper, we have identified five key design factors for practitioners to consider when designing work systems with cobots. In any case, it is important to follow and adhere to standards such as (BSI Group, 2016b) and conduct the necessary risk assessments and work evaluations when implementing cobots and designing new or re-designing current work systems, since they provide a good starting point and a solid foundation for implementation.

4.1.1 Understanding existing processes

Before investing in cobots, it is important that the company starts by visualizing the processes of the existing work system in order to gain the necessary understanding of material- and workflow and to identify co-dependencies and co-relations within the work system. Having this understanding will lead to better decisions regarding role assignment, work organization, and work division between cobots and workers.

4.1.2 Clear task division between humans and cobots

When you have a comprehensive understanding of the work system, it should be easier to create a clear task division between cobot and workers. This division of tasks should be based on the capabilities and skills of the cobots and workers, leaving the repetitive and monotonous work to the cobots, and flexible, complex and creative tasks to the workers. In order to create an efficient and effective work system as well as reducing frustration and concerns from the workers, it is essential to clearly define, and document the new tasks, roles and responsibilities of the workers when designing the work system.

4.1.3 Visualize movement paths and workspace

Using visual cues and guides such as colour tape markings to highlight the cobot's movement paths and the division of the workspace between the workers and the cobots could create more awareness and reducing coalitions between the workers and the cobots. This could have an impact on the workers perception of safety and making them more confident and secure while working in close proximity to the cobots. Furthermore, visual guides can increase the efficiency of the manufacturing work environment and create flexibility by providing every worker with the same visual information

4.1.4 Developing standard operating procedures and train workers

Work efficiency, output consistency and the learning rate of the people working within a work system can be enhanced with standard operating procedures (SOP). We do not suggest SMEs to create detailed SOPs consisting of several pages but rather an updatable one-page job instruction that explains the overall process steps. As the workers gain experience of working with the cobots, work- and process improvement opportunities will emerge. However, without standardized procedures it will be difficult to implement any effective and sustainable improvements.

4.1.5 Systematic quality control

The cobots' inability to reflect and detect abnormalities might result in poor work quality. Therefore developing a systematic quality control procedure could have a positive impact on the quality of the work performed by the cobots. Systematic quality control will reduce product scrap and defects, machine stops, lost equipment time and worker frustration. This could be a systematic visual control of the cobots and the process, following a simple check-sheet on a fixed schedule.

4.1.6 Limitations and further research

The limitation of this paper is the number of case companies and interviews conducted, and the limited data on failed implementations of cobots. Further research could include using the data from the paper combined with more qualitative data from new industrial case companies, collected in the same manner to develop a framework for designing industrial work systems with human-robot collaborations.

5. Conclusion

In this paper, we conducted three explorative cases studies to examine the work and work organization design challenges and opportunities. Since the identified challenges and opportunities are highly correlated, we argue that the all of the challenges need to be addressed before it is possible to achieve the full potential benefits of the technology. Additionally we have compared our findings with the literature available on the topic and used the outcome to identify five key design factors that should be considered when designing human-robot collaborations in industrial work systems.

Appendix B

A framework for aligning humans, technology and organization in Industry 4.0

Bzhwen A Kadir, Ole Broberg, Carolina Souza da Conceição

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**Note*
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A framework for aligning humans, technology and organization in Industry 4.0

Abstract

Overcoming human work and organizational related challenges emerging with the concept of Industry 4.0 demands new ways of incorporating Human Factors and Ergonomics throughout the different organizational levels of industrial companies. In this extended abstract, we present a framework for aligning humans, technology and organization with the aim of ensuring human well-being and desired business outcome. The framework provides a guideline for how to incorporate Human Factors and Ergonomics from the design of a strategy concept to operations on factory shop floors. Furthermore, we use empirical data from industrial case studies to illustrate elements of the framework.

Keywords

Industry 4.0, Strategy, Work System

1. Introduction

The changes introduced by Industry 4.0 are creating new opportunities and challenges throughout the different organizational levels, affecting business objectives, performance and human well-being. However, because of the lack of experience and knowledge on the pertaining digital technologies, industrial companies are facing a challenge in aligning humans, technology and organization. While the International Ergonomics Association's defines the aim of Human Factors and Ergonomics (HF/E) as to optimize human well-being and overall system performance (IEA, 2018), many companies often associate HF/E solely with occupational health and safety, thus giving it low priority (Dul & Neumann, 2009). To overcome this misunderstanding and to fully utilize the benefits of HF/E as defined by IEA, Dul and Neumann (2009) suggest linking HF/E to the company's strategy. This is equally important in Industry 4.0 context, where business outcomes is regarded as one of the main drivers (Müller et al. 2018)

These pertaining human work and organizational challenges demand new tools, models and frameworks that integrate business and HF/E, thus the research question of this paper, "how can industrial companies align humans, technology, and organization in Industry 4.0 to ensure human well-being and desired business outcome?"

In this extended abstract, we present a conceptual framework for incorporating HF/E and business throughout the different organizational levels (strategic, tactical, and operational) of a company. We use examples from industrial case studies illustrate aspects of the framework.

2. Methodology

We conducted several case studies at different small, medium and large industrial companies located in Denmark that had started their industry 4.0 journey and implemented new digital technologies in their shop floor work systems. The data collection consisted of semi-structured interviews with workers and decision makers on all three organizational levels, in addition to observations and demonstrations of the new digital technologies in action. We have used the results of case studies to illustrate aspects of the framework with examples.

3. Results

The idea of the framework is to consider HF/E aspects on different organizational levels with the objective of ensuring human well-being and desired business outcome. The framework's intended users are decision makers on the three organizational levels, strategic, tactical, and operational, which we have also have specified in the framework. Refer to Figure 37 for an overview of the framework.

Figure 37 - Framework for aligning humans, technology and organisation in Industry 4.0

3.1. Strategic

At this level, strategic decision makers should incorporate HF/E considerations when designing strategies and developing industry 4.0 related strategic concepts. Decision makers at this level might include senior management e.g. C-level executives or company owner (in SMEs) and/or middle management e.g. regional managers and plant managers as well as consultants and ergonomists. Decision makers should incorporate HF/E in their strategy to evaluate the effect of new digital solutions and compatibility between the new strategy initiatives and the company's current organizational culture, capabilities and procedures. Thus, ensuring the desired business outcomes and human well-being. Decision makers at this level, can incorporate HF/E by achieving a holistic understanding of essential organizational elements and interactions, and evaluating potential challenges. Hereafter, they can address these challenges in the company's strategy and long-term objectives and communicate them to the rest of their organization.

In one of the case studies at a large company (>250), the strategic level decision makers had defined a strategy for the next five years that included digitalization. In this context, they had evaluated that their staff might not have the necessary skills and competences to achieve their strategic objectives. To overcome this challenge, the decision makers had created an organizational pillar in their overall strategy, focusing on staff development and empowerment, which was the second priority (out of 6) in the company's overall strategy.

3.2. Tactical

Tactical decision makers should incorporate HF/E considerations when translating strategic level concepts and decisions into tangible solutions and actions. Tactical level decision makers might include company owner (in SMEs), middle management, and lower-level management e.g. team leaders and assistant managers as well as consultants, and ergonomists. Decision makers at this level should incorporate HF/E in their decisions to ensure successful realization of the company's strategic concepts and HF/E considerations, thus accommodating the workers well-being and overall system performance in operations. Decision makers at this level might incorporate HF/E by defining clear parameters for the operational level decision makers e.g. allocating the right recourses, defining a clear scope, identifying cross-departmental dependencies, and providing needed training. In addition, the decision makers should consider identify and assign operational level decision makers that are familiar with HF/E.

In one of the case studies at a large company, the tactical level decision makers had clearly defined a physical work system for a pilot project, testing a new digital solution to ensure the viability of the solution before companywide rollout. In addition, they had purposely chosen one of their internal Lean consultants to be in charge of designing the new solution because the decision makers viewed him as a young technology enthusiast whom also had an understanding of the “human-side” of the business.

3.3. Operational

Operational decision makers should incorporate HF/E when implementing new digital technologies and designing new digital solutions in operations work systems. Operational decision makers might include lower-level management, production- and production development engineers, operations level workers as well as consultants, and ergonomists. These decision makers should incorporate HF/E to design efficient work systems and accommodate workers’ well-being and ensure overall system performance. Thus, creating well-functioning and human-centered solutions for operations. The decision makers at this level might incorporate HF/E by using human-centered design approaches and other HF/E frameworks and models to (re)design industry 4.0 work systems.

In one of the case studies, the operational decision makers had followed a process similar to Human Centered Design (BSI Group, 2010) to redesign one of their work system in connection with the introduction of a new digital solution. They had actively involved the shop floor workers and created a continuous feedback loop to accommodate the workers and ensuring the action defined by the tactical decision makers.

4. Conclusion

Successful incorporation of HF/E in industry 4.0 work systems in operations require considerations and engagement from all decision making levels within a company. In this extended abstract, we presented a framework for aligning humans, technology and organization in Industry 4.0, with the aim at accommodating human well-being and meeting desired business outcomes. The framework describes who, what, why and how in relations to HF/E considerations for each of the three organizational levels.

Appendix C

Approaches for operationalizing digitalization strategies

Bzhwen A Kadir, Ole Broberg

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Approaches for operationalizing digitalization strategies

The transition into Industry 4.0 and the increasing focus on digitalization and automation of work systems are transforming factories and introducing various organizational, technical and human-related changes, thus creating new challenges and opportunities (Becker & Stern, 2016). To overcome these challenges and fully realize the benefits, there is an increasing demand for new methods, tools and guidelines that can support the alignment of business strategies and operations (Schumacher et al., 2016).

In this abstract, we present two approaches for operationalizing digitalization strategies and (re)designing work systems in connection to the implementation of new digital technologies and solutions. By identifying and applying the right approach at an early stage, it might be possible to mitigate risks and uncertainties related to a digital strategy. The framework was developed on empirical data collected through ten industrial case studies, conducted at different small, medium, and large industrial companies located in Denmark. These companies had all started their digitalization journey and implemented one or more new digital solutions in their factories.

The first approach is an operational excellence approach. In typical context, operational excellence deals with improving performance through existing operational modes focusing on reducing costs, delays, and errors, but without making radical changes (Hammer, 2004). An operational excellence approach to operationalize a digitalization strategy entails introducing using new digital technologies in conjunction with operational excellence methods to identify and implement new improvement opportunities. The introduction of the new digital technologies happens in smaller steps, starting with the definition and development a minimum viable solution (MVS), which is the smallest solution that provides the most amount of value and possibility to learn (Kadir, Broberg, Conceição, et al., 2019). The MVS is iterated until it reaches a scalable viable solution that can be standardized.

The second approach is an operational innovation approach, which requires more efforts and resources compared to the first approach. Hammer (2004) describes operational invocation as developing entirely new ways of how a company do any activities throughout their supply chain and operations. In the context of digitalization, an operational innovation approach focuses on rethinking company work systems in their entirety, and coming up with and designing new improved ways working with the incorporation of new digital technologies. Thus, the changes emerging with this approach might be much greater compared to the first approach. In addition, this approach relies on a holistic understanding of company work systems, an adequate knowledge of new digital technologies and access to potential use cases from other companies and industries.

While both of these approaches might lead to a certain amount of uncertainties, the operational innovation approach involves more risks compared to the operational excellence approach. However, if successful, an operational innovation approach might lead to greater long-term organizational and economic benefits as well as increased competitiveness.

Appendix D

Digital transformation: Tilpasning af strategi, forretningsmodel, og organisation

Bzhwen A Kadir

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Digital transformation: Tilpasning af strategi, forretningsmodel, og organisation

Abstract

Digital transformation kan være en nødvendig rejse for mange virksomheder, i og med den digitale strategi for virksomheden er en fundamental support til dets forretningsstrategi. Men i en verden hvor der hele tiden udvikles nye digitale løsninger, og hvor behov og efterspørgsel ændres i langt højere grad end hidtil, er det nødvendigt at have en struktureret tilgang til at udvikle og implementere virksomhedens digitale transformation.

1. Introduktion

I løbet af de sidste par år er digitalisering og digital transformation blevet en fast bestanddel af den strategiske dagsorden for mange virksomheder og organisationer. de fleste oplever at de er nået til et punkt, hvor de er nødsaget til at have en digital strategi, og indføre et digitalt transformationsinitiativ for at blive mere konkurrencedygtige. I og for sig er denne udvikling på mange måder værdiskabende for både kunder og udbydere. Nye digitale teknologier muliggør udvikling af nye produkter, tjenester og løsninger, der kan være til gavn for både kunder og aktionærer, såvel som virksomhedens ansatte.

Men hvad betyder dette paradigmeskift for små og mellemstore virksomheder (SMV'er)? Det er netop lige så relevant for SMV'er at følge med udviklingen for at kunne efterkomme forbrugernes efterspørgsel, samt at forblive konkurrencedygtige mod større nationale og internationale selskaber, der allerede har implementeret en digital strategi.

I et hav af muligheder, nye digitale teknologier og løsninger at vælge imellem, kan udviklingen og gennemførelsen af en sådan strategi imidlertid være overvældende. Derfor er det vigtigt at definere rationalet for en digital strategi, få den knyttet til et målbart strategisk mål og forstå, hvordan de kaskader gennem organisationens beslutningslag.

2. De 5 aspekter til et digitalt transformationsinitiativ

Generelt er der fem forskellige aspekter, som en organisation skal overveje, når de starter et digitalt transformationsinitiativ nemlig; strategisk mål, forretningsstrategi, forretningsmodel, service- og arbejdssystem design, og daglig drift. Forholdet mellem disse aspekter er illustreret i modellen vist på Figure 38 forneden.

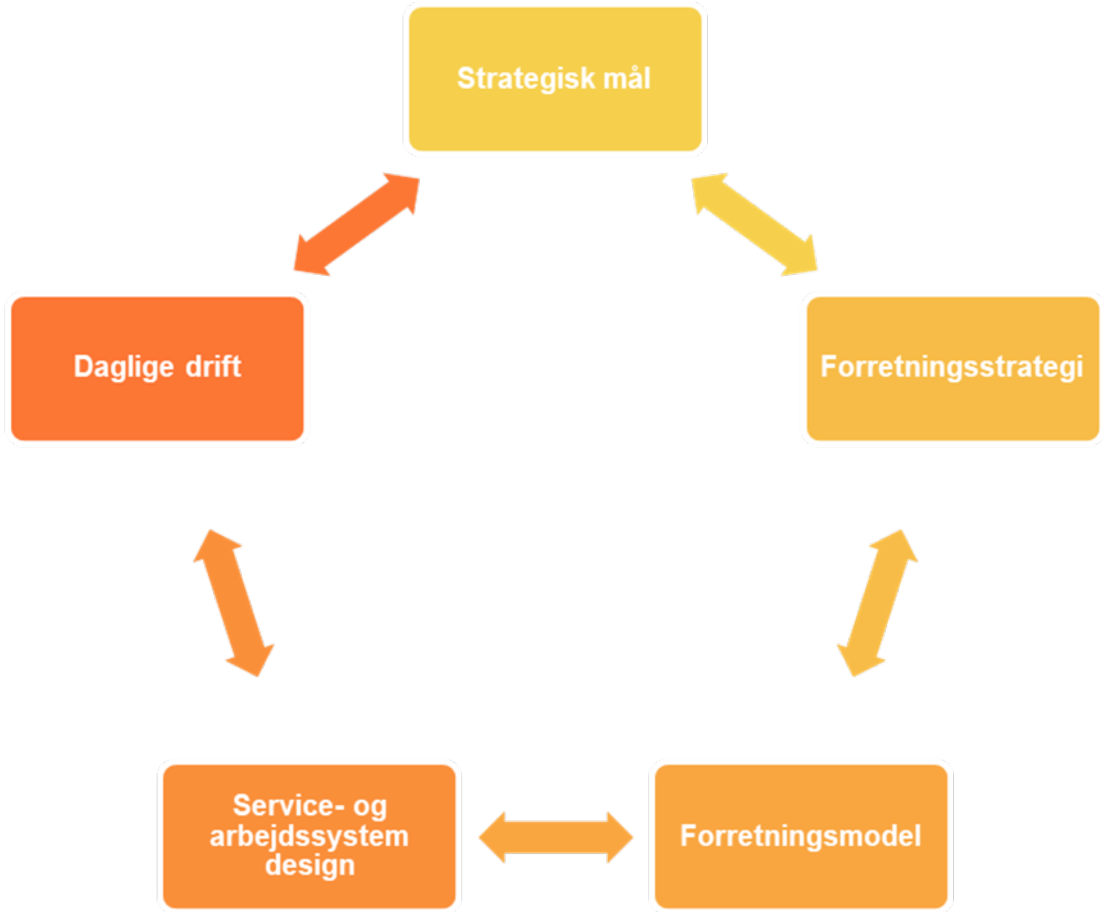

Figure 38 – Organisatoriske aspekter, der bør overvejes i forbindelse med digital transformation

2.4. Strategisk mål

<u>Definition</u>: Hvad ønsker organisationen at nå, og hvilke mål (specifikke og målbar) har man brug for at opfylde for at nå det ønskede mål.

Det valgte mål har en klar indflydelse på de resterende aspekter som skal overvejes i en digital transformation. Et strategisk mål kan eksempelvis være en fremstillingsvirksomhed, der ønsker at øge sin fortjeneste med 10% inden for to år. Som eksemplet indikerer, så behøver et strategisk mål ikke have noget med digitalisering at gøre. Det betydningsbærende i den første fase af modellen er at synliggøre det strategiske mål for virksomheden.

2.5. Forretningsstrategi

<u>Definition:</u> Forretningsstrategien definerer, hvordan en organisation vil nå sine strategiske mål.

Når det strategiske mål for virksomheden er defineret, er næste skridt at kortlægge hvordan virksomheden vil nå disse. Der er kan være forskellige veje for hvordan virksomheden vil nå sine strategiske mål. En måde kan være en digitaliseringsstrategi med fokus på digital transformation. En sådan strategi kan dog omfatte og have mange forskellige elementer. I forlængelse af forrige eksempel kan virksomheden fokusere på at bruge nye digitale teknologier og løsninger til at forbedre sine services til kunder, udvikle en ny forretningsmodel eller forbedre og opdatere sine interne service- og forretningsprocesser.

2.6. Forretningsmodel

Definition: En forretningsmodel sigter mod at fange virksomhedens markedssegment, værditilbud, værdikæde, omkostningsstruktur og profitpotentiale, værdinetværk og konkurrencedygtig strategi.

Hvis virksomheden fra forrige eksempel vælger en digitaliseringsstrategi, der fokuserer på at forbedre servicen og værdien, de leverer til deres kunder, vil det muligvis være nødvendigt at revidere forretningsplanen.

De tre aspekter (strategisk mål, forretningsstrategi og forretningsmodel), er meget afhængige af hinanden. Figur 2 viser et eksempel på hvordan disse aspekter kan hænge sammen. I det første trin vælger virksomheden et eller flere strategiske mål. Hvert mål vil sandsynligvis muliggøre et sæt forskellige strategier, som virksomheden kan følge for at nå deres mål. I det andet trin vælger virksomheden således den strategi, der passer til deres mål. På samme måde kan virksomheden i det tredje trin vælge en eller flere forretningsmodeller, der passer til den valgte strategi.

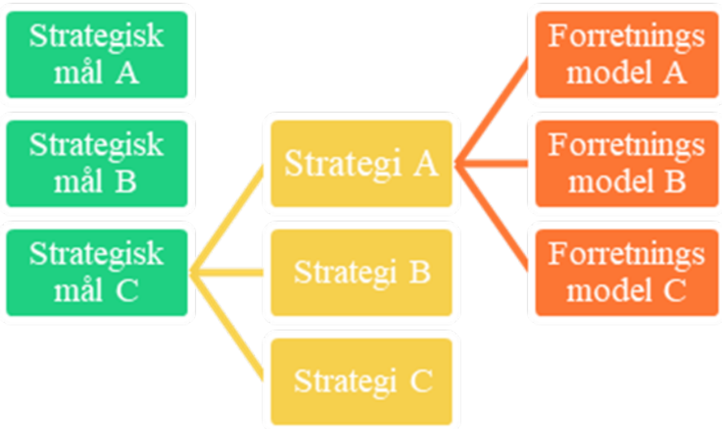

Figure 39 – Eksempel på hvordan man kan gå fra en strategisk mål forretningsstrategi

2.7. Service- og arbejdssystem design

Definition: Et servicesystem består af elementer (f.eks. Mennesker, faciliteter, værktøjer og computerprogrammer), der har en struktur (dvs. en organisation), en opførsel (muligvis beskrevet som en proces) og et formål.

Et arbejdssystem er et system, hvor menneskelige deltagere og / eller maskiner udfører arbejde ved hjælp af information, teknologi og andre ressourcer til at producere produkter og / eller services til interne eller eksterne kunder.

Den valgte forretningsstrategi og forretningsmodel vil have en betydelig indflydelse på virksomhedens service- og arbejdssystemer. Denne indflydelse er især gældende i tilfælde af strategier for digital transformation og digitalisering. Hvis en strategi og / eller forretningsmodel inkluderer nogle aspekter af nye digitale teknologier og løsninger, vil de uden tvivl påvirke virksomhedens service- og arbejdssystemer. For eksempel, hvis en virksomhed ønsker at fokusere på servitization, skal de (re)designe de serviceydelser, den leverer. Eventuelle ændringer i tilbudte serviceydelser vil udløse ændringer i de eksisterende arbejdssystemer og muligvis føre til skabelse af nye arbejdssystemer.

2.8. Daglige drift

Definition: daglige drift er, hvordan en organisation styrer sit daglige arbejde og processer.

Hvordan en organisation opererer, er meget afhængig af, hvordan de har designet deres service- og arbejdssystemer. Designet af disse systemer vil have en betydelig indflydelse på både menneskeligt velvære såvel som den generelle systemperformance. Dette er især relevant ved digitalisering, da det er medarbejderne i det nederste organisationslag i de fleste tilfælde bruger og arbejder med de nye digitale teknologier.

3. Afslutningsvis

Digital transformation er en rejse med mange usikkerheder og risici. Før virksomheder går i gang med en sådan rejse og definerer en digitaliseringsstrategi, bør virksomheder og organisationer etablere målbare strategiske mål for, hvad de ønsker at nå. For at få mest muligt ud af et digitalt transformationsinitiativ er det vigtigt at få en sammenhængende og helhedsorienteret forståelse af, hvordan en valgt strategi vil påvirke organisationens forretningsmodel, service og arbejdssystemer samt daglige drift. En sådan forståelse kan lette overgangen og hjælpe med at nedsætte unødvendige risici og øge succesraten for digitaliseringsinitiativet.

Appendix E

The six aspects of work in Industry 4.0

Bzhwen A Kadir

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The six aspects of work in Industry 4.0

The advancement and availability of new digital technologies introduced with the concept of industry 4.0 are changing the way employees are working and performing daily tasks. This article explores the aspects of work that are changing as we move further into Industry 4.0.

1. Cyber-Physical Systems

The idea of "smart factories" and "Industry 4.0" is founded on the concept of cyber-physical systems (CPS). CPS underlines the notion of vertically integrated and networked autonomous manufacturing systems equipped with sensors and state of the art technologies, merging computational and physical capabilities. The transition from a traditional work system with limited digital capabilities into an efficient CPS requires a holistic understanding of the changes affecting human-technology interactions, processes and performed activities, work organization, as well as the overall work system objectives. Thus, being a human worker in a manufacturing environment is not as simple and straightforward as it may have been in the past. The human worker's role and responsibilities are in a continuously changing state as we strive to find the optimal combination of automation and manual labor.

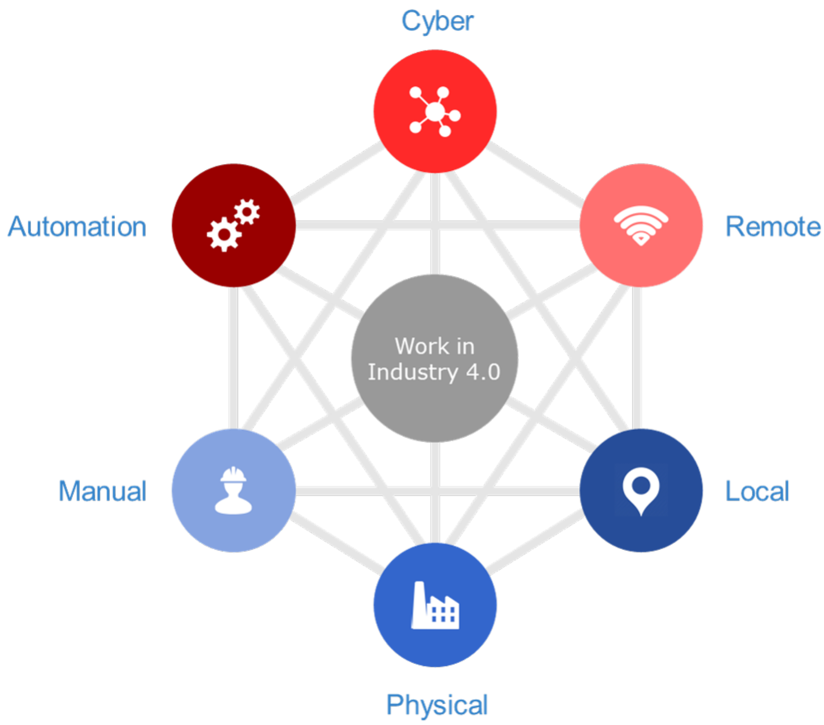

Figure 40 – The six aspects of work in Industry 4.0

2. Working locally and remotely

While the concept of CPS is challenging a (soon to be) outdated paradigm of manufacturing systems, which only consists of physical elements, the increase in digital capabilities is also expanding the workplace and location of work activities. Infographic dashboards shown on large screens on the factory floor, personal computers, and handheld devices such as smartphones and tablets are offering real-time monitoring possibilities. These new digital technologies are increasing connectedness between machines, workers on factory floor level, management, as well as the rest of the organization.

Previously, workers had to be physically present at the factory floor in order to get insights on machines, produced products, and process conditions. These mentioned digital technologies are enabling shop floor workers to overcome this physical barrier and get the necessary information they need to monitor their machines. Being physically attendant will only be a necessity when there is a need for direct interaction with the processes. Real-time monitoring and preventive analytics is only the first step in this track of work system digitalization. Further digital technological developments in this direction will lead to operators having the ability to make changes remotely, and computer algorithms performing predictive analytics and making autonomous changes and corrections.

Besides, combined with hardware such as specialized glasses, helmets, and handheld devices with camera functionalities, Virtual reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are creating unique opportunities in industrial work systems. Several industrial case studies have documented successful applications of these technologies for training and real-time assistance. These technologies are highly relevant in manual labor heavy activities that require a lot of attention and detailed focus. The usage of these technologies is having a positive effect on human errors and process lead-times. The virtual transportation of experts from one location to another is also one of the selling points. In such cases, the expert provides remote real-time assistance to the workers on the site by viewing the physical workplace through a screen captured through VR enabled glasses, helmets, or handheld devices.

3. Manual labor and automation

One of the increasing tendencies in Industry 4.0 is the automation of manual labor. Technical advancement and affordability of new digital capabilities are enabling industrial companies to automate and replace manually performed tasks throughout their operations. Advanced sensor capabilities are sparking new life into existing technologies such as traditional industrial robots and automated guided vehicles, enabling closer interactions with workers. Combined with continuously improving artificial intelligence capabilities, technologies and machines are becoming more autonomous and changing our perception of how industrial work systems function, organized, and designed. Additionally, this transition is forcing industrial companies to reconsider the role and responsibilities of workers and the division of labor between human and machines.

Contrary to the fear of many, the increase in automation is not replacing and completely removing all human workers. Workers are still a necessary component and have an essential role in performing tasks that require flexibility and ad-hoc decision making, while the technologies are handling repetitive tasks with limited variation and changes. This is the case in most complex work systems where full automation is a far-fetched solution due to the amount of financial investment required and the decrease in flexibility coming with it. Implementing fully automated processes and work activities only make sense when the work system consists of repetitive tasks with minimal variation.

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