Ole Madsen · Ulrich Berger ·
Charles Møller · Astrid Heidemann Lassen ·
Brian Vejrum Waehrens · Casper Schou *Editors*

The Future of Smart Production for SMEs

A Methodological and Practical Approach Towards Digitalization in SMEs

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Foreword by Tue Tyge Møller

The Laurits Andersen Foundation was founded in 1929 based on the last will and testament of Laurits Andersen. He was a very successful Danish businessman in Asia and built a thriving business in China. His attitude and performance would today constitute a role model for internationalization, entrepreneurship, and philanthropy, in the same way as it is practiced by SME companies.

Since its start, the Foundation has supported academic institutions and personalities in the memory of Laurits Andersen and his heritage.

In 2016, the Foundation granted Aalborg University funding for a project concerning the development and introduction of Smart Production in Denmark.

The funding allowed significant personnel support and ensured a successful exploration of the targets. The book *The Future of Smart Production for SMEs* reflects the diligent work over the years and enhances excellent visibility for the affiliated researchers, institutions, and networks. Eventually, it provides a sound approach to the future of production in Denmark, the overall intention and target of Laurits Andersen.

Copenhagen, Denmark
June 2022

Tue Tyge Møller
Administrator, Laurits Andersens Fond

Foreword by Dr. Nigel F. Edmondson

As the Managing Director of Denmark's National Cluster for Advanced Manufacturing, I have both had the pleasure of working with hundreds of industrial partners and the SMART-Factory research and innovation team from Aalborg University during the past eight years. A core focus of MADE is to drive the competitiveness of Danish manufacturing SMEs establishing SMART and sustainable manufacturing systems, and the team at Alborg University have play key role in driving this industrial transformation.

When introducing SMART production, there is no one solution, and there is a need to evaluate each manufacturing companies' business needs and competitive drivers, to identify potential solutions, that are tested and iteratively developed in the production environment. The development and implementation of SMART manufacturing in SMEs is particularly challenging as there are fewer resources available, both in terms of manpower, time, and capital to invest in testing, developing, and implementing SMART manufacturing solutions.

This book presents many industrial examples, methods, and collaboration forms which have been developed and tested in the SMART production lab at Aalborg Universities where a strong partnership between industry and the university has driven innovative solutions and the development of new methodologies to the benefit of the manufacturing industry and research institutes involved.

Whether you are from a large manufacturing company, SME, or knowledge institute, this book guides the reader through the process of defining the needs identifying the correct SMART manufacturing solution and then developing and implementing the solution to achieve a competitive advantage using many practical examples from industry and at the same time demonstrates the value of research and innovation partnerships between companies and universities.

June 2022

Dr. Nigel F. Edmondson
Managing Director of MADE
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Advanced Manufacturing
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Foreword by Mogens Rysholt Poulsen

Positioned among Europe's leading production universities, Aalborg University (AAU) has a long tradition in research and teaching in production and is well known for its ability to cooperate and interact with all sizes of enterprises.

Since small and medium enterprises (SMEs) play a large role in the enterprise infrastructure of Denmark, it seems natural for Aalborg University to strategically focus on how the big societal changes such as digitalization and ecological challenges affect SMEs.

These big challenges call for substantial and innovative solutions that contribute to the development of SMEs as the backbone of Denmark's industrial ecosystem.

Therefore, we initiated in 2015 the research initiative: AAU Smart Production with the objective to investigate how Danish manufacturing industries can benefit upcoming digital technologies such as IIoT, big data, advanced robotics, artificial intelligence, virtual reality.

Within AAU Smart Production, a significant amount of interdisciplinary research has been done in the individual technologies as well as in the investigation of the consequences for manufacturing companies in a broader sense (e.g., organizational, human aspects, and new business models). Among the results of the research is this book, which provides important and innovative examples on how SMEs handles the many challenges related to digitalization and simultaneous challenges.

Much of the work has been done in close collaboration with local SMEs, and I am happy to see much of this work are collected in the book *The Future of Smart Production for SMEs*. I am confident that this book will be beneficial for researchers as well practitioners, enabling the transformation of SMEs toward smart production.

June 2022

Mogens Rysholt Poulsen
Dean, The Faculty of Engineering
and Science
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Acknowledgements

This work arose from the collaborative research and innovation work on Smart Production and Industry 4.0 at Aalborg University (AAU) and Brandenburg University of Technology Cottbus-Senftenberg (BTU).

The overall motivation for this book is based on the question, of how SME companies could enact and benefit from the upcoming twin transition toward sustainability and digitalization in a disruptive environment. All aspects such as strategies, methods, technologies, organizational matters, and human factors have been included in our holistic approach. Therefore, we have chosen and invited a broad set of contributions reflecting ideas and standing points from industry, academia, and institutions. All papers were peer reviewed by either the editorial committee or individual domain experts. We thank all the authors and reviewers for their valuable service and endurance.

As this book needed a lot of support on the sideline, we would like to thank everyone involved in conceptualization, planning, and performing this project and give special thanks to the Laurits Andersen Foundation. Especially, we would like to thank all the supporting students, researchers, and engineers of the AAU and BTU community. We owe many thanks to the team at Springer publishers and their helpful recommendations and hints. Finally, we would like to invite you now to enjoy this book and stay in contact with us also in the future.

Contents

About the Editors

Ole Madsen is a professor at the Department of Materials and Production Engineering at Aalborg University, Denmark, where he is the head of the research group on Robotics and Automation. Ole Madsen has worked at Aalborg University as an assistant professor and associate professor. He has also worked for Odense Staalskibsværft A/S as a consultant and robot system developer; at IWA (Intelligent Welding Automation) A/S as co-founder, system developer and manager; and at Grundfos A/S focusing on manufacturing innovation.

He graduated from the Department of Production, Aalborg University in 1983 (Manufacturing Technology), and received his Ph.D. in 1993 on the topic of "Sensor-Based Robotic Multi-Pass Welding."

His research interests include flexible robotics, reconfigurable manufacturing systems, industry 4.0, and smart production.

Ole Madsen is the co-founder of the Smart Production initiative at Aalborg University and has more than 120 international publications. Over the years, he has participated in several national projects as well as international EU-funded research projects.

Prof. Dr.-Ing. Ulrich Berger graduated from the University of Stuttgart (Dipl. -Ing., Mechanical Engineering) and received his doctorate from the University of Bremen (Dr.-Ing, Production Technology).

He worked in production automation for an international automotive supplier corporation and academic management positions at the University of Bremen.

Since 2001, he is a full professor of Automation Technology at the Brandenburg University of Technology Cottbus-Senftenberg (Germany) and since 2016 an honorary professor of Smart Production at Aalborg University (Denmark).

He is the founder and director of the Technology Transfer Center Modern Industry Brandenburg and the German Federal SME Competence Center Industry 4.0 Cottbus. He was appointed in 2010 as a speaker of the Metal Cluster Brandenburg, an industrial association, and in 2018 as a member of the Digital Advisory Council of the Federal State of Brandenburg. Prof. Berger serves as an expert in the R&I programs of Germany and the European Union since 1994. He is the author and co-author of 200+ scientific and technical publications and supervisor and co-supervisor of 30+ doctorates.

His research interests are in the field of robotics and automation, digital twins, advanced learning, and training methods.

Charles Møller is a professor in Enterprise Systems and Business Process Innovation at the Center for Industrial Production (CIP), Department of Materials and Production, Aalborg University (AAU).

Charles Møller is researching the interplay between operations and information systems in industry where the perspectives include both technology and management. Current research interests include ERP/MES systems, IT/OT integration, development of digital supply chains, factories, and smart production.

Charles Møller is currently engaged in the Danish platform: Manufacturing Academy of Denmark (MADE) where he is a primary investigator in: Digital supply chains, smart factories, and value chain execution and optimization.

Charles Møller holds a M.Sc. in Electrical Engineering (EE) from the Technical University of Denmark and a Ph.D. in Industrial Engineering (IE) from Aalborg University.

Dr. Astrid Heidemann Lassen is an associate professor in Operations and Innovation Management at Aalborg University, Denmark, Department of Materials and Production. Astrid is the head of Section in Production and the vice-head of Department.

Since 2015, she has been an honorary visiting professor at the Unit for Innovation and Entrepreneurship at University of Gothenburg, Sweden.

Astrid is the author/co-author of 100+ international journal and conference articles on the topics of digital transformation, innovation management, and knowledge intensive entrepreneurship. She has also published several academic books on such topics.

Her research focus is in particular on the process of developing organizational capabilities for innovation and digital transformation in the context of both established companies and knowledge intensive entrepreneurial ventures.

Brian Vejrum Waehrens is a professor of Sustainable Production and Supply Chain Management at Aalborg University, Denmark, Department of Materials and Production.

He serves as the vice-chair of the standing working group on Production at the Danish Academy of Technical Sciences and serves on the organizing committee of the national future manufacturing platform MADE.

Current research interests are related to digital and sustainable transformation of industry—studied as the effective integration of day-to-day operations across a dispersed operations network, and its link with strategic development initiatives within the company and at the supply chain level, combining theories from the domains of operations/supply chain management, environmental management, and strategy.

Casper Schou is an assistant professor at the Department of Materials and Production, Aalborg University. He received his M.Sc. in Manufacturing Technology in 2012 and his Ph.D. degree in reconfigurable collaborative robots in 2016, both from Aalborg University.

His main research areas and expertise are within smart factories, collaborative robotics, mobile robot assistants, and recently swarm production.

Since 2016, he has been responsible for operation of the AAU Smart Production Lab and lately the AAU 5G Smart Lab. He has been involved in numerous experiments and real-world tests of both robot assistants and smart factory implementations.

He has been involved in four large EU projects and six national research projects, all with high degree of industrial involvement. He has 30+ peer-reviewed publications in international journals and conference proceedings.

Editorial—Introduction to the Book

Ole Madsen, Ulrich Berger, Charles Møller, Astrid Heidemann Lassen, Brian Vejrum Waehrens, and Casper Schou

Abstract With this editorial we aim to shed light on the idea behind the book and to provide an overview of our motivation and founding ideas for the book, an consequently present how we unfold the Smart Production for Small and Medium-sized Enterprises (SMEs).

Keywords Industry 4.0 · Smart production · Manufacturing · Approach

1 Introduction

With this editorial we aim to shed light on the idea behind the book and to provide an overview of our motivation and founding ideas for the book, an consequently present how we unfold the Smart Production for Small and Medium-sized Enterprises (SMEs).

O. Madsen (✉) · C. Møller · A. H. Lassen · B. V. Waehrens · C. Schou
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Smart Production represents a vision towards and an operationalization beyond Industry 4.0 (I4.0). I4.0 as a concept responded to the significantly changing conditions in the industry in the aftermath of the financial crisis, and aimed to introduce new digital technologies in new market-driven applications. From there it has evolved into an all-encompassing vision of the future society driven by technological advances. Baur and Wee (2015) discuss I4.0 as a phenomenon fuelled by four disruptions:

- Rise in data volumes, computational power, and connectivity;
- Emergence of analytics and business-intelligence capabilities;
- New forms of human–machine interaction such as touch interfaces and augmented-reality systems; and
- The increased ability to transfer digital instructions to the physical world, e.g. advanced robotics and 3D printing.

Although some guidance in the form of maturity models and roadmaps from consultants and vendors are available, the I4.0 vision has not yet reached a formative stage where wide spread adoption is assisted by robust and scalable solution, but rather remains a vision of a future manufacturing context and advanced manufacturing technology. This means that after a decade of working with the concept we still need operational approaches and supporting solutions and in particular approaches that address the large base of SMEs. Therefore, in this book we adopted the concept of Smart Production, which has its outset not in the description or development of the foundational technologies alone, but in the operationalization of these in an organizational setting and its systems architecture.

We will address the benefits and challenges for SMEs within the ongoing industrial digital transformation. Value chain configurations in industry are shifting which affects SMEs in terms of their position and scope of the business (Andersen et al., 2019). Smart Production is a key enabler of performance and development in this context, but many SMEs have not been able to cope with these new and changed circumstances. Consequently, many of them have lost track, found themselves in decline, or have went out of business, in other words lessons have been learned the hard way.

2 The Vision of Smart Production

Industrial production is undergoing a paradigm shift. The globalization of value chains is here to stay, but it is reshaped by changing localization demands (Haleem et al., 2018). Likewise, operational efficiency, quality, flexibility and other traditional performance objectives remain key factors of success. However, new challenges emerge in conjunction with upgraded environmental and social standards and requirements, supply crisis and changes to the geopolitical situation. According to UN agreements, environmental social governance (ESG) must be integrated into all industrial operations and upcoming technologies must be evaluated concerning their interaction with human staff members. Encompassing all these movements, the term

Industry 5.0 is rising, and the European Union has already adopted not only the term, but also its interpretation in their framework program (European Commission, 2022).

It should be clear by now that in our perspective Smart Production is not driven by a technology push alone. SME companies experience that the environment in which they operate is becoming more and more unpredictable and dynamic and, therefore, also increasingly difficult to design robust solutions for.

The transformation toward Smart Production is mainly driven by the digitalization of the business. However, digitalization will render new potentials to automate processes across the supply chain (Bejlegaard et al., 2021), which will lead to learning new ways of working and consequently organizing differently (Saabye et al., 2020, 2022). This leads to what might be the single most important critical success factor for an SME in the manufacturing industry: The speed at which a company can absorb new technology into its operations and transform these into practices that benefits their customers and increases the performance of the company. Novel industrial solutions draw on a broad set of technologies that enable the design of new solutions, but they fail to provide means to overcome the organizational barriers towards change. Consequently, we need a new and more comprehensive framework for framing the challenge.

Smart Production provides a technology-driven "autobahn" and to some companies characterized by high levels of absorptive capacity and primarily drawing on generic market solutions, this will be sufficient to guide them towards their goals. To other companies, the road forward will be more experimental and iterative and will as such take many pathways and detours, new competencies and capabilities need to be built along the way, and the journey will be highly path-dependent. Two key determine factors helps us to select the route, the first is the need to develop competitive advantages based on the unique application of technologies, and the other is the level of legacy equipment, competencies and systems. Legacy play a major role in the transformation of SMEs, where the opportunity to wipe the slate clean seldom present itself, but the need to work with, integrate and work around legacy elements remains a key factor for successful transformation processes. Most of the companies we have worked with fall in the category of gaining competitive advantage from their specific application of technology and have significant levels of legacy, which means that they need to approach the transformation with experiments, multiple iterations and high levels of uncertainty. This also means that it is initially difficult to adapt and implement these new ideas. The challenge of adopting is immense since the technologies are new and develop fast. Furthermore, complex interdisciplinary projects are often needed to create good solutions, which often require scarce resources as well as new competencies and a major change in organization, culture, and managerial mindsets.

3 Motivation for the Smart Production Book Project

The book has come out of concerted and collaborative efforts to understand, build solutions for, and implement Smart Production in SMEs and large companies across three primary regional locations namely the Brandenburg and Baden-Württemberg in Germany and Denmark with a particular outset in the northern region. The approach is mainly based on applied research and has unfolded through tight and solution oriented collaboration between industrial partners and knowledge institutions. The book is meant to synthesize heuristic insights with Smart Production developed over the last decade where dedicated labs have been developed, where funding schemes have supported the interaction with several hundred SMEs across the different regions, and where programs to facilitate triple helix collaboration and the effect of this have been nurtured.

This book addresses how to build the capabilities and systems to make an SME smarter. Smart Production motivates and guides the journey, but ultimately any company's journey must be based on its ideas and targets of the future. The future is based on the four generic missions of a manufacturing company: Productivity, Flexibility, Innovation and Sustainability. These are all not new, but the challenge is to support all missions at the same time without suffering major trade-offs. This may be achieved by digitalization as the core of Smart Production. Digitalization enables new ways of automating processes, but the full effects of the digitalization efforts will not be captured, unless the company re-designs work processes and organizes accordingly. This will again lead to new potentials for digitalization and automation, and this is what characterizes the journey towards smarter production. The production system is integrated using new solutions enabled by both technologies and people. This holistic and systemic idea of the production system characterizes a Smart Production system. The book will provide a general overview of the transformation process will highlight market pull and technology push movements and explain the logics behind and interdependencies between elements. The main difference from existing publications will be the holistic approach in combining traditional assets such as technology, process optimization, and digital readiness with new competencies such as ESG compatibility and agility/resilience.

4 Perspectives to Pay Attention to in Industry and Theory

Worldwide, huge investments in technical infrastructure and human potential have been made by production companies, with the promise of sustainable competitive advantages, but the success of these initiatives are questionable and at best not always as expected (Mittal et al., 2018). Consequently, academia and consultants are challenged to build knowledge on how best to support SMEs in analyzing and understanding their current situation, formulating company-specific future visions, setting strategic goals, and finally providing operational guidance towards reaching these goals. We have researched and consulted many manufacturing companies who experience that the environment in which they operate is becoming increasingly unpredictable and dynamic. Four recurring issues arise in our talk to the companies:

- Productivity: There is an ever-increasing pressure on cost and the need for efficiency and productivity. This is in no way a new issue—novelty is, however, found in the fact that this must be combined with the issues below.
- Innovation: There is fierce global competition and customers are increasingly propagating demands to their vendors. This implies new and better products, more features and customers are demanding more for less.
- Flexibility: The world is rapidly changing, and new products must be introduced more often; there are demands for customized/personalized products and the global market is turbulent and uncertain. On top of this, unpredicted events such as a tsunami in Japan or the Corona pandemic have increased the need for resilience to make the production systems more robust. Most likely, the strategy of an SME is neither product leadership, nor operational excellence, but rather a customer intimacy strategy. Successful SMEs in the manufacturing sector survive because they are extremely customer-focused and able to hit the right balance of their market.
- Sustainability: There is an increased focus on the balance between environmentally and economically sustainable production as well as the social responsibility of the companies, and furthermore the supply chain partners need to document this. A specific challenge will be to reach a level of system integration that allow to dynamically generate new life cycle assessment and costing results when material composition of components and products in the value chain shift, either because of design choices or because of changes to the supply chain. Further to this, there are constantly new regulations tightening the grip on the company's ESG (environment, social, and governance) and/or GRC practices (corporate governance, enterprise risk management, and compliance).

All these requirements and constraints place great demands on manufacturing companies' ability to adapt their strategies, business models, processes, machines, competencies and production to new products, market demands, and production technologies. If these adjustments are made too late, it will have dire consequences for competitiveness and ultimately threaten long-term survival. Addressing and balancing these issues at once is difficult. Companies today experience that the solutions that offer flexibility lack efficiency, adding sustainability to the equation increases complexity and cost of the manufacturing and documentation task, which prompt companies towards an incremental maturity based approach to their transformation (Uhrenholt et al., 2022). Existing strategies such as lean production, outsourcing and offshoring do not alone supply the proper response to this challenge, and digital technologies do indeed offer promising new ways of dealing with these issues simultaneously. This poses a particular challenge to the frame for evaluating digital transformation projects applied by SMEs, where a wider value perspective often has to be accepted as a supplement to traditional investment business cases

(Colli et al., 2022). Taking into account the more "intangible" value of their learnings, tackles the fundamental issue of translating explorative innovation efforts into exploitative value—a key challenge when dealing with innovation and one of the main barriers for the digital transformation.

For any company, and in particular, an SME, the journey towards Smart Production will be specific and individual. The right strategy is determined by the competitive situation of the company as well as its specific strength and weaknesses. Yet, SMEs in the manufacturing sector play a pivotal role in global value chains, as they can adapt, change, or transform easier than large companies, thus fostering product and process innovations quite rapidly (Machado & Davim, 2019). They are strong contributors to the fundament of production and foster through their regional embedding significantly to the civil society.

Structure of the Book

As it was mentioned at the start of this chapter we have in this book and in our general approach nurtured and adopted the thinking of Smart Production, which has its outset not in the description or development of the foundational technologies alone, but in the operationalization of these in an organizational setting and its systems architecture. This is also evident in the structure of the book, which start not with the marvels of the technologies, but rather from the idea of building a key strategic intend around the Smart Production agenda. Furthermore, rather than seeing the technologies as solution to any given problem the idea is to understand the application domain as a pretext to selecting technologies and developing solutions from a situated perspective.

The book consists of five parts: Vision, Transformation, Solutions, Technologies, and People. The flow of the book is organized to support understanding from the overall idea of Smart Production down to the details of the operational building blocks. The first chapters are broad and conceptual while the later chapters are more specific. The main structure of the book is illustrated in Fig. 1 above, where the key elements covered in the book are outlined. Some elements are covered in dedicated chapters whereas some chapters also address multiple elements and their interconnection.

Part 1 consist of 4 chapters and aims to set the conceptual background for the Smart Production topic. Initially the vision of Smart Production in SMEs is formulated (Møller et al., 2022a), and the specific challenges in SMEs is investigated and linked to elements of the vision (Gebauer et al., 2022). In this section we define four general missions for Smart Production: Operational Excellence focused on productivity, Customer Value (Innovation), Flexibility (Agility and Resilience), and Sustainability. While specifically the sustainability challenge is expected to be important in the future which is why we have dedicated a whole chapter to this (Waehrens & Kristensen, 2022). Finally, we have devoted a chapter to the research into SMEs and how to develop Smart Production (Møller et al., 2022b).

Part 2, for the elaborate background for Part 2 introducing contribution please see Introduction to Part 2 (Madsen & Berger, 2022). The part focuses on the transformation towards Smart Production. It outlines methods, tools and instruments, which

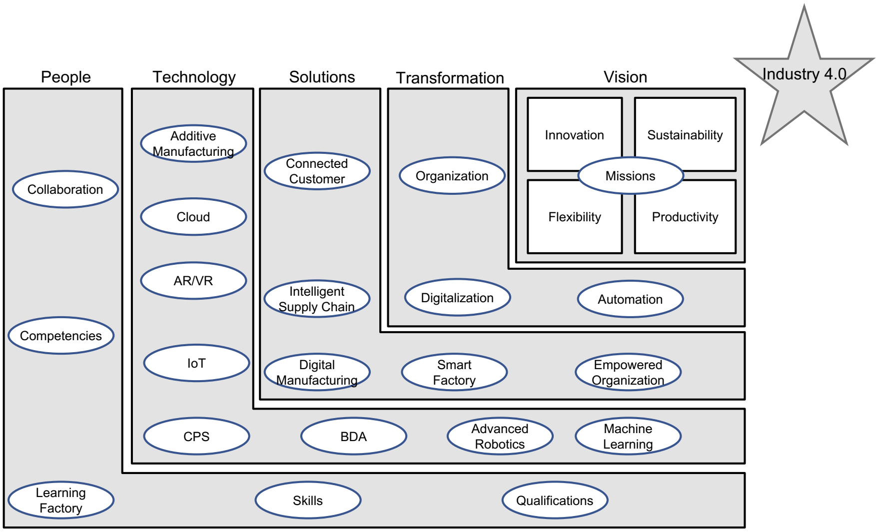

Fig. 1 Overview of the book structure and main content

can assist SMEs in the formulation of a smart production vision and in the identification and prioritization of relevant initiatives, guiding the outline of a project roadmap. Further contributions highlights the concepts and operational impacts of governmental funded SME transfer centres as the IFN (North Jutland, DK), the IMI (Brandenburg, DE) and ARENA2036 (Stuttgart). Finally, it is discussed how subscription-based methods can be used by SMEs to cut upfront investments and reduce requirements for digital competencies.

Part 3 presents an overview of smart solutions relevant to SMEs. This part contains a collection of papers that all describes general solutions for Smart Production (e.g., CPS, collaborative robots, IIoT, reconfigurable manufacturing systems, paperless production, predictive analytics, additive manufacturing etc.) which integrates several enabling technologies to be presented in Part 4 into applications of relevance to SMEs. The general concepts will be presented and illustrated by examples and case studies and the benefits and challenges for SMEs associated with realizing the concepts are discussed. For the elaborate background for Part 3 please see "Introduction to Part 3" (Møller, 2022).

In part 4, an overview of selected technological enablers for Smart Factories is provided. The focus is on the new digital technologies serving as enablers for transforming ordinary factories into smart factories. The part is introduced a general introduction of smart factories, the role of technology in the smart factory and a set of key technologies for realizing smart factories for SMEs. The remaining chapters each introduce a specific technology chosen due to their high relevance to smart production in SMEs. These chapters will provide a short and concise overview of the respective technologies, discuss the implications specifically for SMEs and provide exemplification of the deployment. For the elaborate background for Part 4 please see “Introduction to Part 4” (Schou, 2022).

Part 5 is focusing on the people enabler such as skills, competencies and qualifications, collaboration, and in particular the learning factory, which is a context where we have worked with Smart Production. This part ends with an overall conclusion and future outlook for both industry and research. For the elaborate background for Part 5 please see “Introduction to Part 5” (Lassen, 2022).

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Part 1
Vision

The Smart Production Vision

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Abstract In this chapter, the Smart Production vision is discussed. The Smart Production approach is developed and described, and Smart Production is positioned in relation to Industry 4.0. Smart Production operationalize the journey towards Industry 4.0 and beyond. First, the need for a new approach to manufacturing is discussed, and from the perspectives of Industry 4.0, the Smart Production concept is derived. Then the framework is explored and finally, the approach is outlined. The Smart Production vision is an approach to make an integrated production system smarter by continuous digitizing, automating, and organizing towards supporting the company specific missions.

Keywords Industry 4.0 · Smart production · Manufacturing · Approach

1 Introduction

For decades, outsourcing and offshoring resulting from globalization has built up fundamental tensions around manufacturing and global supply chains. However,

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after the financial crisis, a new industrial paradigm emerged. This was driven by the ubiquitous and extensive digitalization of society.

In most of the Western countries, an increased awareness of the importance of the manufacturing industry, spurred corporate and national initiatives aimed at reversing the flow of jobs and knowledge to low-cost countries (Pisano & Shih, 2012). This has led to appreciating the large base of small and medium-sized manufacturers, the SMEs, and their importance to the economy. It has been realized that digitalization of the industry is key to restore national competitiveness.

So, while the large enterprises were able to implement large scale digital transformation programs, the SMEs have been more challenged. In most of the extant literature (Modrak et al., 2020), the small manufacturers are in fact considered disadvantaged per se. But while the SMEs are disadvantaged by having limited access to investments and knowledge, the SMEs are in fact often highly customer-oriented and quite agile (Chan et al., 2019; Jafari-Sadeghi et al., 2022) But there is an unmet need for qualifying the visions and to operationalize the journey into a systematic approach.

The most prominent manifestation of the vision of future manufacturing is Industry 4.0. Based on these ideas, we have formulated an approach to support the transformation towards Industry 4.0, and we have coined this approach Smart Production.

In the next section we discuss the different perspectives on Industry 4.0. Following this, we present the Smart Production framework and finally we formulate a journey for SMEs to become smarter. This chapter will primarily build on practical experiences gained by Smart Production teams in Denmark and Germany.

2 Industry 4.0

Industry 4.0 is a concept first introduced in 2011 during the Hannover Industry Fair in Germany by the Industry 4.0 Working Group (Kagermann et al., 2013). The working group consisted of a group of industry leaders aiming to change the public opinion on manufacturing and industry in Germany and recommending national and industrial actions.

After its tenth anniversary, it is obvious that Industry 4.0 is more than a passing fad. Although there were many similar concepts and initiatives, like: Factories of the future (Usine du future), Smart Industries, Society 5.0, Smart Manufacturing, etc., Industry 4.0 has established itself as a overarching concept. Today it is used and widely understood in both society, industry, and in academia (Culot et al., 2020). So, what is Industry 4.0?

2.1 Six Perspective on Industry 4.0

What started out as a clever rhetorical trope to frame the next generation industrialization, has now become a complex and multi-facet phenomenon with multiple meanings. While it is not the intent to provide a comprehensive review of Industry 4.0, we will briefly cover six important perspectives on Industry 4.0.

Industry 4.0 as industry politics

The Industry 4.0 concept and the established national platform, is very clearly an instrument for lobbying for a (German) national public–private partnership to promote a major investment in research and development of both the German manufacturing industry, and its key vendors. The German "Industrie 4.0 Plattform" develop concepts, solutions, and recommendations, and they succeeded in advancing some major issues and technologies on the national and European agenda.

However, these are the same conclusions that most countries have arrived at, and in most countries, national research and innovation initiatives and national incentive programs have been put in place. In Denmark the Manufacturing Academy of Denmark (MADE) was launched to advance the manufacturing agenda, but also in countries like China (Made in China 2025) and India (Make in India), large scale programs have been put in place. Industry 4.0 was not the first national initiative, but gradually, the concept has been adopted across Europe, in Asia and in the US.

Industry 4.0 as a globalization agenda

World Economic Forum (WEF) has taken the baton from the Industry 4.0 Working Group and have adapted and promoted I4.0 actively since 2016. WEF has continuously used the "fourth industrial revolution" as a proxy for a new technological driven transformation of society (Bai et al., 2020).

WEF argues that the exponential development of the new technologies has the potential to solve a lot of the grand challenges, such as climate change, inequality, and migration. However, WEF is not blind to the potential downsides of such rapid technological development, such as security, privacy, and lack of democratic control (Schwab, 2016).

However, in the most recent years, the WEF has refocused, triggered by crises such as the pandemic and the Ukraine wars. But still the "fourth industrial revolution" is the underlying force.

Industry 4.0 as technology

It is difficult to discuss Industry 4.0 without considering technology (Oztemel & Gursev, 2018; Zheng et al., 2021). The fourth industrial revolution has been defined as the convergence of physical, digital, and biological technologies. The introduction of Industry 4.0 is triggered by an exponential growth in computer power which forms the basis for a very large suite of new digital technologies such as: Big Data, Internet of Things, Digital Twins, Cloud Computing, Artificial Intelligence, advanced robotics, etc. Through the enabling of data ubiquity and connectivity capabilities, these provide an increasing number of new possibilities for the development of new products, processes, and services. However, a preliminary conclusion may be that there is no one single technology that can be characterized as Industry 4.0. Industry 4.0 technologies are the amalgamation of different technologies into industrial applications, and thus can be characterized as networked technologies. Consequently, interoperability might be a critical success factor, not only to end-users, but also to vendors of Industry 4.0 technologies (Bai et al., 2020).

Industry 4.0 as standards

Industry 4.0 can be seen as a battle of standards, or rather as a battle between vendors. Standardization and reference architectures is one of the key areas of Industry 4.0 (Kagermann et al., 2013). With interoperability as the central feature, vendors are obviously using considerable resources in complying to, and affecting standards.

In Europe, there is a massive momentum to formulate European and International standards which will ensure that vendors can concentrate on developing core technologies. From an end-user perspective, standards and reference architectures help protecting the value of investments in new technologies (Grangel-Gonzalez et al., 2017; Trappey et al., 2017). However, innovation processes can be highly unpredictable, and through-out history we have seen how inferior technologies win market dominance because of higher adoption rates. Consequently, this could mean, that cheaper and inferior technologies, will disrupt incumbent vendors technologies.

Industry 4.0 as affordances

One the main features of Industry 4.0 is that technology development happens exponentially. This not only means technology gets better, but more importantly, it means that advanced technology gets cheaper and ultimately commoditized. While an abundance of technology not necessarily bring any benefits in itself; it is the essence of the Industry 4.0 promise.

This makes it more difficult to compete on technological advances, and therefore companies must compete on solutions rather than technology alone (Culot et al., 2020). The idea is that digitalization will enable a wide range of new solutions to the industrial challenges and that the potentials are awaiting to be actualized. Furthermore, going from technologies to solutions also requires that companies consider adoption and use, and this requires new knowledge, competences, and skills.

Consequently, to realize the potentials, the organization needs to be mobilized, and this require considerable managerial effort in staging the change.

Industry 4.0 as a transformation journey

Even though we are referring to Industry 4.0 as "the fourth industrial revolution", the journey towards the I4.0 vision will be an evolutionary process rather than a radical transformation (Kagermann et al., 2013):

> Current basic technologies and experiences will have to be adapted to the specific requirements of manufacturing engineering, and innovative solutions for new locations and new markets will have to be explored. Achieving the benefits from digital manufacturing is a long-term endeavor and will involve a gradual experimental learning process involving both

technology, systems, and management processes. For the individual manufacturing company, it will be key to ensure that the value of existing manufacturing systems is preserved. This emphasizes the need for a brown-field approach to the transformation. At the same time, it will be necessary to come up with migration strategies that deliver benefits and productivity from an early stage.

These considerations have several implications for the journey ahead. First, it is clear that Industry 4.0 is a company specific journey with no specific end-state, and that no universal solutions are provided. Second, it is clear that the solutions need to be grounded in the specific conditions and constraints. Third, it is clear that experimentation and learning are central to find the best path for each individual organization's journey.

Even the European Commission has positioned Industry 5.0 as its transformative vision for Europe in relation to Industry 4.0 as: "It complements the existing Industry 4.0 approach by specifically putting research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry" (European Commission, 2021).

2.2 *Industry 4.0 as a Vision*

In summary, Industry 4.0 started out as a story framing a manufacturing digitalization initiative and have evolved into an all-compassing vision of a society of the future driven by technological advances.

In academia there have been a huge interest in Industry 4.0. However, diving into the literature, it mainly deals with review of the technologies or digital readiness and maturity models. The detailed industry 4.0 scenarios have been analyzed, generalized, and characterized by the four design principles: (1) Decentralized decisions; (2) Information transparency; (3) Interconnection; and (4) Technical assistance (Hermann et al., 2016) These guidelines operationalize the technical solutions, but fails to address the system level of Industry 4.0, and provide little guidance to the managers in SMEs.

McKinsey (Baur & Wee, 2015) defines Industry 4.0 as: The next phase in the digitization of the manufacturing sector, driven by four disruptions:

- The astonishing rise in data volumes, computational power, and connectivity, especially new low-power wide-area networks;
- The emergence of analytics and business-intelligence capabilities;
- New forms of human–machine interaction such as touch interfaces and augmented-reality systems; and
- Improvements in transferring digital instructions to the physical world, such as advanced robotics and 3-D printing.

This definition points back to the original definition of Industry 4.0 (Kagermann et al., 2013). As a vision, Industry 4.0 is generic and open to new challenges and actual technological opportunities. In the consulting industry, Industry 4.0 have extensively been used for branding digital transformation, and in academia, numerous studies have reviewed Industry 4.0 as a concept (Culot et al., 2020), as technologies (Oztemel & Gursev, 2018), readiness (Hizam-Hanafiah et al., 2020) or as cases (Ortt et al., 2020).

Although some guidance in the form of maturity models and roadmaps from consultants and vendors are available, the Industry 4.0 vision is not absolute, but more a vision of future manufacturing context and the potentials of using advanced manufacturing technology. We need a more operational approaches and in particular approaches that addresses the large base of SMEs.

3 Smart Production

As the analysis of Industry 4.0 indicate, Industry 4.0 is a vision of a future state of the manufacturing industry, mainly driven by technology and automation. However, we find companies are struggling with getting started and embarking on the journey, and one of the reasons are, that the Industry 4.0 concept is an industry perspective, not a company perspective.

To support manufacturing organizations, and in particular SMEs, we have formulated the Smart Production framework as an integrative approach and as a guideline for managing and organizing the journey towards Industry 4.0. The Smart Production framework include the conceptualization of the integrated production system as interacting value streams, and an approach to make the production smarter based on agile practices. The objective is to generalize, simplify and operationalize the journey and to guide the company in the process.

The starting point for conceptualizing Smart Production is to formulate the outcome of the transformation in terms of a strategic gap. This strategic gap is company specific and consist of a concrete Smart Production vision and an assessment of the current maturity. The Smart Production vision is obviously inspired by the visions of Industry 4.0 but need not to be either disruptive or based on any specific technology. Based on the strategic gab, we formulate the desired outcome of the company specific journey. It is these company specific outcomes that is the guideline for continuous improved value delivery.

3.1 Smart Production System

An integrated production system is the conceptualization of a manufacturing business in terms of customer value delivery. Business value is enabled by the products and services, and these are enabled by the business processes. The business processes are enabled by both technology and people. The transformation and alignment of the business towards its vision and future missions, is governed by the strategies and supported by existing infrastructure. This conceptualization is aligned with the work systems theory, socio-technical systems, and other activity-based frameworks (Alter, 2013).

An integrated production system is the socio-technical system that creates the business value from production, and as already indicated, we must view the production system from a perspective much broader than the just transformation of materials.

An integrated production system extends in the entire manufacturing eco-system, and include multiple stakeholders, such as vendors and partners, customers, and end-users, and obviously the focal organization and central value streams.

This understanding of Integrated Production is the foundation of the conceptualization of the Smart Production System as an integrated production system characterized by being instrumented, inter-connected and intelligent (Butner, 2010) which enable employees to collaborate internally and with external partners and customers in a digital ecosystem in order to continuously deliver value to the customers and end-users and optimize performance.

3.1.1 Instrumented

In a Smart Production, all assets and people must be instrumented. In recent years, we have seen the concept of Digital Twins emerge within manufacturing. Gartner defines a Digital Twin as (Gartner, 2021): "A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organization, person, or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant [, or a factory] or a city, and their related processes" (Gartner, 2021). An instrumented production system requires an aggregated Digital Twin of the entire production ecosystem (Fig. 1).

Obviously, the digital twin is not the first step of digitalization. Any digital system, such as an ERP system may be synchronized manually with the physical processes, in which case it is referred to a "digital model", or with automated data collection in which case it is referred to as a "digital shadow".

The primary technological enabler is Cyber-Physical Systems (CPS). CPS is the result of things being equipped with electronics as an interface to the digital world. CPS also include other technologies that bridges the physical and digital worlds such as additive manufacturing (3D printing), robotics, and AR/VR. All these technologies will be elaborated later in this book (Madsen et al., 2022).

3.1.2 Interconnected

In a Smart Production, assets and people need to be interconnected in order to support the main functions of manufacturing. Leveraging the Digital Twin, Smart Production needs to facilitate the "grand" end-to-end processes of operations and supply

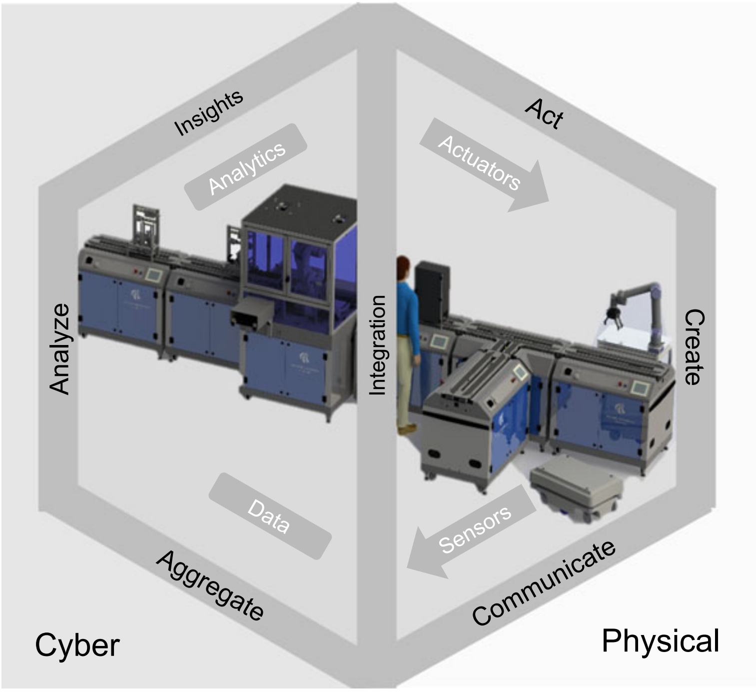

Fig. 1 Digital twin, adopted from (Deloitte, 2017)

chains. In an Industry 4.0 context this refers to horizontal and vertical integration. Operations is the vertical integration of networked manufacturing systems, while supply chain is the horizontal integration through value networks. Furthermore, Smart Production includes the end-to-end engineering across the entire value chain. This is often referred to as a digitalized system lifecycle. The Smart Production system also includes the costumers and end-users and connects organizations in the manufacturing eco-system into "systems of systems".

In a company perspective there are three integrated value streams. The supply chain with generic activities such as Buy, Make, Deliver, Use and Dispose. Operations with the generic activities such as Plan, Make and Enable, and the engineering processes covering generic activities such as: Develop, Make, Redeploy and Use.

The activities are supported by digital tools and enterprise systems such as ERP, PLM, CRM system etc. The primary enabler of inter-connection is Internet of Things (IoT). IoT are technologies that enable the connection of data from CPS leading to transparency. Later in this book IoT and its applications in SME's is elaborated and examples of solutions suitable for SMEs are covered.

We see a pattern of some high-level generic solution or digital capabilities that are needed, as illustrated in the figure below (Fig. 2)

Customer Engagement refer to the capability to create and capture value from connected customers and end-users. Customers and end-users being instrumented

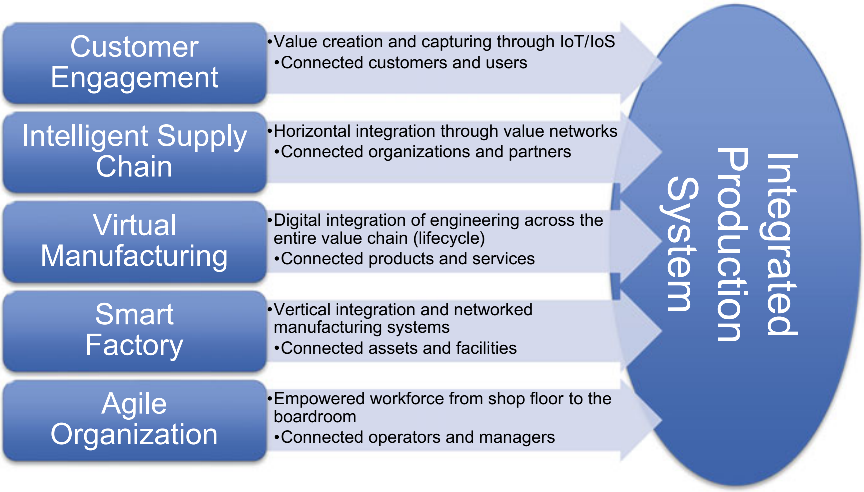

Fig. 2 Smart production system

through smart products and/or services are inter-connected with the organization. Having the insights into customers and end-users enable a business to act not only to predict customer needs but also prescribe and influence customer choices.

An example of a company leveraging prescriptive analytics is Amazon (Nichols, 2018). Through the massive amount of customer insights e.g., collected through Alexa, Amazon can offer anticipatory shipping to their customers.

Intelligent Supply Chains refer to the horizontal integration of demand and supply into value networks by connecting the organization and its partner. This requires an instrumented supply chain where the organizations (and silos) can exchange information in order to build a transparent supply chain.

An example of a company leveraging an Intelligent Supply Chain is Maersk and the IBM joint venture: Tradelens (Moller & Maersk, 2019). Through the Tradelens platform, Maersk have access to almost the entire eco-system of container logistics and may reap the marginal benefits from a balanced demand and supply. In another example, an SME repositioned its role in the supply chain from Engineer-to-order to Assemble-to order, by utilizing digital technologies to integrate the supply chain (Bejlegaard et al., 2021).

Virtual Manufacturing refer to the integration of engineering activities across the entire lifecycle. Having engineering activities digitally connected enables concurrent engineering, and verification and validation of new products or changes in products or manufacturing systems without building physical products or factories.

An example of the potentials of end-to-end digital manufacturing is Vestas (Yidiz et al., 2021) By building a digital twin-based virtual factory, Vestas is able to train the employee (in a VR setting) before the physical factory is build, and before the turbines are final, and thus increasing time to market.

Collaborating Smart Factories across the entire manufacturing eco-system is the foundation for Industry 4.0. According to Schou et al. (2021). A smart factory is:

> … a factory which by interconnecting its assets into a digital ecosystem, uses in-formation to adapt, run and optimize its operations according to actual business conditions, thereby generating and appropriating business value while reflecting societal requirements.

An example of a greenfield Smart Factory is the flexible, digital, efficient and sustainable: Factory 56 of Daimler AG (Daimler, 2020). Factory 56 were opened in 2020 and it embodies the Smart Factory and Smart Production.

An empowered and *agile organization* is a key capability in industry 4.0 and Smart Production. An organization may be empowered by instrumenting employees at all levels, from shop floor to boardroom, and inter-connecting them for optimal decision-making. This requires timely and right level of information needed for informed decision making and presented in an actionable way.

Arla is an example of how a company may empower an organization by decentralizing analytical data in order to support local data exploration and decision making (Asmussen et al., 2021).

3.1.3 Intelligent

In Smart Production, the production system must be intelligent. Intelligence refers to both human intelligence and artificial intelligence, however the appropriation of intelligence opens lots of challenging issues and interesting topics that are not covered here (Møller & Siurdyban, 2012). Intelligence is mainly enabled by Big Data and Analytics (BDA). BDA covers a wide range of tools and technologies such as AI and machine learning (ML). These are elaborated further in part 3 of this book (Møller, 2022). BDA can be defined as the complex process of analyzing large amounts of data in order to support an organization in making informed business decisions. Depending on the level of automation, Smart Production can be completely autonomous (and self-learning/optimizing), or Smart Production can offer decision support to the relevant decision-maker.

Meulen & Rivera, (2014) usually defines four types of analytics capabilities: (1) Descriptive analytics, that enable to understand what have happened; (2) Diagnostic analytics, that explain why it happened; (3) Predictive analytics to foresee what will happened; and (4). Prescriptive analytics that will either provide decision support or autonomous for actions to reach a certain goal (see Fig. 3). While the Descriptive, Diagnostic and Predictive analytics aims to enhance human decision making, Prescriptive analytics may be completely autonomous.

Reaching these levels of analytical maturity is increasingly difficult, and in most cases, SME's will need to work on very basic analytical capabilities, and gradually learn to use data to make decisions. In another chapter (Palade & Møller, 2022) we demonstrate how SMEs can get started with building a simple data-driven demonstrator and use this a basis for starting the journey.

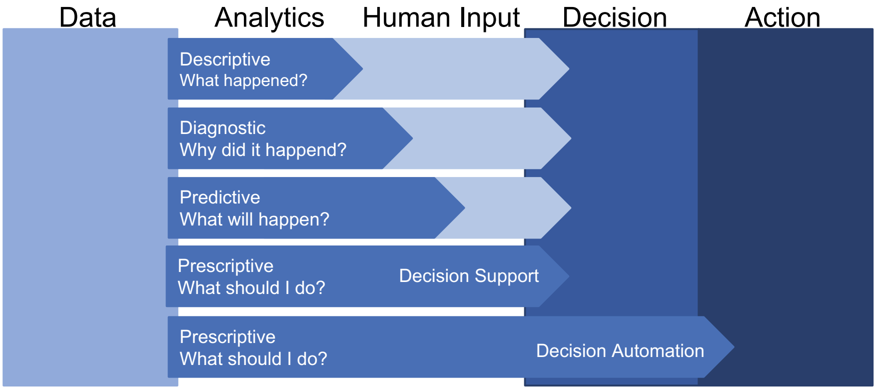

Fig. 3 Analytical capabilities (adopted from (Meulen & Rivera, 2014))

3.2 Transformation Towards Smarter Production

Having framed Smart Production, as an integrated production system characterized as being instrumented, inter-connected and intelligent, we will now build guidelines for how a company can become smarter.

The guiding "North-Star" of the Smart Production vision is obviously Industry 4.0, however, a company specific Smart Production vision will more often be based in the specific competitive situation of the company.

We have identified four generic missions which seems to capture the general tasks for a manufacturing SMEs: Productivity, Flexibility, Innovation, and Sustainability. These generic missions are useful concepts for guiding the transformation.

Development efforts in a company needs to address a performance gap. Peter Checkland (1999) operates with three types of performance: (1) Efficacy, which is getting the desired results; (2) Efficiency, which is using the minimum number of resources to achieve the results; and (3) Effectiveness, which is doing the right things. These goals are obviously inter-related, and Hammer argues that benefits emerge in stages (Hammer, 2004). Most companies will embark on Smart Production due to cost savings and aim for operational gains. This would lead to the second wave of benefits, now aiming for tactical gains from being more effective. The third stage of benefits emerge when the company learn to systematically capture value from innovations and new ways of working. Hammer (2004) argues that it is necessary to spend time to master each stage, and therefore the last stage: "operational innovation" is a strategic capability it is difficult to replicate for competitors. However, the implication is also that manageable small steps and right level of ambitions should be considered. The generic missions of Smart Production represent general goals to ensure sustained competitive advantage, efficiency, effectiveness, robustness, and viability.

Technology is mainly based on the infrastructural assets of a company, but also the digital interconnection with suppliers and customers (Toro et al., 2021). Knowledge is mainly based on human resources, encompassing the digital qualification level of all staff members and the seamless and transparent access to data and information. Digital readiness is a collective term for a company to assess and take risks according to the principle: Aim high, fail fast.

When we refer to Smarter Production, it is the transformation of the integrated production system, capable of supporting the company vision and future missions, mainly by means of digital technologies. The transformation towards Smart Production evolves through a continuous cycle of digitalizing, automatization, and organization of new ways of working, and it requires systematic learning through experimentation along the way.

Smart Production is not an end-goal or a destination. The journey towards Smart Production will be a continuous process of experimenting with new technologies, learning, and building new capabilities and business models, and it requires adapting management approaches, new ways of working and new integrated solutions (Kagermann et al., 2013).

In Smart Production we refer to this continuous process of exploration (operations) and exploitations (innovation) as Digitize, Automate, and Organize (DAO). The DAO process refers to the transformation of business and manufacturing processes. Digitalization allows work processes to be automated end-to-end, which again enables new ways of working, making it relevant to digitalize new processes etc.

For SMEs to embark on this journey, they need a systematic approach and solid guidance, which can be provided in the form of guidelines and transformation roadmaps. In this book we cover several transformation approaches that applies to SMEs.

The transformation guidelines for developing Smart Production, are based on formulating a company specific TO-BE vision based in a company specific assessment of the AS-IS maturity or readiness.

There are numerous Industry 4.0 readiness or maturity models. Hizam-Hanafiah (Hizam-Hanafiah et al., 2020) reviewed 30 models from 2016 to 2018 and identifies six main groups of dimensions: (1) Technology; (2) People; (3) Strategy; (4) Leadership; (5) Process; and (6) Innovation. In our own maturity model (Colli et al., 2019), we operate with five dimensions: (1) Technology; (2) Competences (People); (3) Connectivity (Process); (4) Governance (Strategy, Leadership) and (5) Value Creation (Innovation). In both cases the dimensions represent systemic elements of Smart Production, as an integrated production system (Table 1).

Most methodologies use the term digital maturity and often have a multidimensional approach (Mittal et al., 2018; Schuh et al., 2017). Also, suitable roadmaps for achieving the expected goals are available and will be disclosed in part 2 in this book (Berger & Madsen, 2022).

In Industry 4.0 there is an emphasis on technology as an enabler of value and the organization as the barrier. To approach the transformation from a holistic perspective, we need to look for solutions that are balanced across all dimensions, hence we refer to these as integrated solutions.

In this book we put emphasis on the combination of technological and people (competence) dimensions, since working on these two in tandem is the best approach in SME. However, in many companies, the transformation process starts with

Table 1 Main mechanisms for transforming towards Smart Production

Dimension	Main mechanism (enablers/barriers)
Value	Customer connectivity; business models; innovation
Governance	Vision; strategy; management approach
Process (connectivity)	Smart factories, digital manufacturing, intelligent supply chains
Technology	Cyber-physical system, internet of things, big data analysis
People	Skills, competencies, knowledge

managerial awareness and new mindset, and in Colli et al. (2018) we have presented a "holistic" approach for conceiving context specific transformation roadmaps, and this approach have also been applied in the Innovation Factory North project (Møller et al., 2022).

4 Summary and Conclusion

We have now formulated the Smart Production vision as an approach to make the integrated production system smarter by continuous digitizing, automating, and organizing towards supporting the company specific missions.

In this book (Madsen et al., 2022) we will cover the steps of this approach: Vision, Transformation, Solutions, Technologies, and People. Solutions enabled by both technology and people, are used to transform the company towards the company specific vision.

Huge investments in technical infrastructure and human potential have been made during the last decade from worldwide operating companies, but the success was not always as expected (Mittal et al., 2018). Consequently, we need a framework, which supports SME's in analyzing and understanding its current situation, formulating company specific future visions, setting strategic goals, and finally providing operational guidance towards reaching these goals.

Industry 4.0 and Smart Production are two similar concepts with many similarities, but also with distinct differences. Industry 4.0 is first and foremost an industry perspective, whereas Smart Production is a company perspective. Smart Production is based on the company specific mission as an outset for iteratively reducing the gap. Industry 4.0 is first and foremost a technology driven concept whereas Smart Production is also human-centered. The Industry 4.0 journey is the "autobahn" whereas the Smart Production journey is along the small roads, with plenty of time to learn and to look for new opportunities.

As such, Smart Production is the continuation of an company-specific approach to develop production systems, which we have been working with at Aalborg University for several years (Johansen et al., 2006). At the same time, we incorporate the experiences from working with joint academia and industry projects. Over the last decade we have researched and consulted many manufacturing companies in Germany and Denmark, who experience that the environment in which they operate is becoming more and more unpredictable and dynamic. Industry 4.0 provide the direction; Smart Production shows the way.

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Challenges for SMEs on their Path to Smart Production

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Abstract Small and medium enterprises (SMEs) are said to struggle with several challenges when transforming parts of their value chain to smart production with the means of digitalization. [1] Since SMEs are the backbone of our economy it is important to understand those challenges to cope with them accordingly. [2] This book chapter provides an overview of SME-specific digitalization challenges including possibly challenging SME characteristics and necessary prerequisites from a literature review as well as deeper insights about singular companies from the region of Brandenburg in Germany. Those insights are derived from semi-structured interviews with SME managers. None of the identified obstacles is a showstopper for our interviewees but some of them are more severe than others. This chapter contributes to the existing literature by showing an overview of challenges for SMEs when transforming their value chain to smart production. Additionally, we provide insights with less abstract depictions about the process of SMEs coping with those challenges. This chapter is of interest for SME managers when defining the transformation process of their own SME under consideration of the digitalization challenges. The overview, as well as the insights, help researchers defining their approaches for finding solutions from their perspective on realizing smart factories in SMEs.

Keywords Smart production · SME · Challenges

1 Introduction

Although digitalization and the transition to a smart production holds a lot of potential for SMEs, the utilization of the potential by the SMEs is only at its very beginning.

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Despite SMEs have an extensive impact on the economy, we still do not fully understand the antecedents, challenges, and consequences of the adoption of digitalization in SMEs. (Horváth & Szabó, 2019) Some of the higher-order challenges like the lack of financial resources are obvious. (Rauch et al., 2020) For SMEs to actually go their way to smart production they need to overcome and therefor know and understand more than the obvious challenges they are confronted including different perspectives on them. Thus, we focus this chapter on providing an overview about the challenges SMEs are typically confronted with when pursuing their path to a smart production including the perspectives of five SMEs. Smart production can be achieved by a purposeful inclusion of digital technologies such as Augmented Reality, Additive Manufacturing, Internet of Things, Big Data Analytics and Cyber Physical Systems in an SME´s value creating processes. (European Commission, 2003) Purposes of SMEs can be e.g. scalability, resilience, sustainability, networkability, flexibility and reliability. (Mittal et al., 2019) We find challenges explicitly named in the literature. Additionally, SME characteristics and prerequisites from literature potentially hinder digitalization projects in SMEs and thus, need to be considered for this chapter.

The chapter is structured as follows: In Sect. 2, existing research on the characteristics of SMEs, prerequisites for the integration of smart production elements, and known challenges in SMEs when pursuing smart production are presented. In Sect. 3, we explore these challenges further through five interviews with SMEs from the region of Brandenburg (Germany). Lastly, we provide a conclusion in Sect. 4.

2 Existing Research

The literature published via Elsevier and IEEE during the last five years has identified SME specifics and their interrelation to the integration of smart production in the same companies as relevant. Only since about 2016 the number of publications of the intersecting fields of Industry 4.0 and SMEs has increased exponentially. (Masood & Sonntag, 2020) Our investigation on Web of Science shows a rise of research interest in SME specific challenges. We find lists of challenges as well as related characteristics and necessary prerequisites that need interpretation considering the actual meaning for SMEs (e.g. Horváth & Szabó, 2019). Research on challenges in an SME context is required as the characteristics of SMEs differ from multi-national enterprises (MNEs). Hence, these altering challenges may affect the companies´ paths to smart production. Going further some research has even pointed out, that the smaller the SME the higher the risk, that they may not reap the rewards of smart production. (Rauch et al., 2020).

2.1 Characteristics of SMEs from Literature

Since SMEs do not only differ from MNEs by the three dimensions staff headcount, turnover and balance sheet total, used in the definition of the European Commission (2003), we work with a more complex differentiation of the two types of companies which can be found in Ghobakhloo and Iranmanesh (2021). Starting from financial resources, use of advanced manufacturing technologies, the use of a software umbrella, research and development activities, working with standards and leadership flexibility, alliances with universities, which the authors generally evaluate as low in comparison to multi-national companies, we find SME characteristics that potentially hinder digitalization projects. Going further, the company strategy and the decision making are highly dependent on the company leaders, the organizational structure is less complex and informal and the company's knowledge, human resource development as well as the experience concentrate on very specific areas. Additionally, important activities are outsourced and thus, they strongly depend on a collaborative network. Those attributes potentially hinder the SMEs on their way to smart production.

2.2 Necessary Prerequisites from Literature

Necessary prerequisites for the implementation of smart production in SMEs are a sufficient degree of business partner digital maturity, cybersecurity maturity, digitalization readiness preassessment, external support for digitalization, information and digital technology expertise, information and digital technology readiness, management competency for digital transformation, manufacturing digitalization strategic road mapping, operations technology readiness, change management competency and resource availability. (Ghobakhloo & Iranmanesh, 2021) The state of not fulfilling and the process of creating the necessary conditions can be challenging for SMEs.

2.3 Challenges from Literature

First of all, the general lack of financial resources for new strategic ventures needs to be mentioned. The lack of investment potential is not only part of the SME definition but also ranked as one of the most important barrier for digitalizing in the literature. (Masood & Sonntag, 2020) Thus, SMEs cannot procure new technical equipment as easy as MNEs and furthermore struggle with research and market analysis in advance. (Mittal et al., 2018) Other missing resources that challenge SMEs when digitalizing their processes are missing employees with specialized knowledge for the matter or competencies concerning technologies and methods outside their main business processes. Also, missing skills of owner-managers need to be mentioned. (Arendt, 2008; Faller & Feldmüller, 2015; Larsen et al., 2022; Masood & Sonntag, 2020; Moeuf et al., 2020) Skills needed for digitalization in SMEs are e.g. about media, coding, process understanding, and in general understanding Industry 4.0 and the potentials of its related technologies. Necessary competencies concern "creativity, entrepreneurial thinking, problem solving, decision making and other skills, social competencies such as intercultural skills, leadership skills, language skills and etc., and personal competencies encompass flexibility, sustainable mindset …". (Mohammadian & Rezaie, 2019) Also missing technical standards and technical resources, e.g., production and test facilities in their companies, need to be mentioned as an obstacle to the integration of smart production. (Mittal et al., 2018; Schulz et al., 2020).

More challenges include the adoption of the digital technologies by managers and other employees. Additionally, more subjective problems need to be overcome. SME managers are skeptical when it comes to digitalization projects (Umsetzungsempfehlungen für das Zukunftsprojekt Industrie, 2013) and fear investing in wrong technologies or not adapting the perfect practices for their companies. (Faller & Feldmüller, 2015) Skepticism can be found in SMEs when it comes to digitalization projects going along with the lack of suitable motivation and prioritization. (Vieru et al., 2015) Moreover, managers can be alarmed by the idea of competitors getting access to their knowledge, information and data (Blind & Mangelsdorf, 2013) or "security concerns" (Masood & Sonntag, 2020) in general. Since managers and employees often lack the knowledge about cutting edge technologies (Taurino & Villa, 2019) decisions are not made well informed and based on structured analysis. (Mittal et al., 2018) A struggle with the complexity of digitalization projects needs to be mentioned. (Esmaeilian et al., 2016) SMEs are often astounded with decisions about the what, why, when, where, who and how considering the implementation of smart manufacturing technologies. (Mittal et al., 2019; Rüßmann, 2015).

Focusing on the organization as a whole and its flexibility being part of the corporate culture for experimentation with new technologies (Vrande et al., 2009) and for strategic innovation is usually not adequately focused on in SMEs. (Terziovski, 2010) Other problems concern weaknesses in networking and data management. (Mittal et al., 2018) Lastly, many offers of smart manufacturing suppliers do not meet the needs of SMEs. They are engineered with too advanced applications. (Hawkridge, 2021).

3 Meaning of Challenges for Specific SMEs from Brandenburg (Germany)

After identifying SME characteristics, necessary prerequisites and challenges from SMEs on their path to smart production via digitalization we interviewed five different SMEs from Brandenburg (Germany) to enhance the literature results with

Table 1 Overview interviewed SME

	Vakuplastic Kunststoff gmbH & Co. KG	Lausitzer Klärtechnik gmbH	MBM Lychen gmbH	Mathias Mende e. K	IGEL nobilis gmbH
Founded in	1966	2002	1961	2011	1999
Branch	Production of rubber and plastic products	Production of technical components (sewage treatment) and customer service	Contract manufacturer, machining metal	Production of frames from wood and plastic, insect screens, CNC contract manufacturer	Manufacturing of metal products for commercial kitchens
Employees (SME grouping)	1–9 (7)	50–249	10–49 (35)	10–49 (30)	10–49 (40)
Turnover [€]	close to 1 Mio	close to 10 Mio	nearly 3 Mio	up to 10 Mio	3 Mio

the actual perspectives from company managers. Our interviews consisted of questions concerning the SME characteristics, prerequisites and challenges from literature. The interviewees were asked to evaluate the (resulting) challenges on a Likert scale (none, weak, strong, very strong) and to give explanations about the meaning.

When displaying the results, we focus on the major problems mentioned and evaluated by the companies. Additionally, we include some contrasting answers since the evaluation given by our interview partners varies a lot. The persons we talked to belong to micro as well as medium sized production companies depicted in Table 1 from the network of the Innovation Center of Modern Industry Brandenburg.[1] Considering that those companies do actively and steadily participate in network activities for digital innovation we point out that the interviewed companies belong to the very motivated and driven part of the spectrum concerning the strategic improvements of their processes for their stakeholders. Their way of mastering the challenges of digitization could serve as an example for others, but cannot be generalized to all SMEs.

[1] https://www.imi4bb.de/home.

3.1 SMEs Perspectives on Challenges because of SME Characteristics

From the SME features we identified eight to be connected to severe problems with digitalization projects. Interestingly we heard different positions and perspectives for most of the features.

Financial resources: Starting from the lack of financial resources we found that this is generally a limiting factor and it makes the prioritization of strategic improvement projects necessary. (Heidel, 2022) Thus, not all ideas can be realized at once. (Mende, 2022) Nonetheless, one medium-sized company (Hansen, 2022) states that they allocated a budget for prioritized steps of a digitalization project, realized those steps and are able to reinvest the savings of improved processes in the next digitalization projects. This company did not evaluate low financial resources as a severe problem.

Use of advanced manufacturing technologies: The less advanced manufacturing technologies, on the one hand, go along with difficulties in connecting machines. On the other hand, companies (Hansen, 2022) feel motivated to digitalize their processes because of that older equipment. Although older machines are not easily integrated in a data network they partly are kept until the machine operator will retire. (Köpke, 2022).

Software umbrella: Software solutions, that usually contain tailored solutions are a typical problem of SMEs trying to digitalize their production. (Schwarz, 2022) They need to be exchanged or connected when a broader software umbrella is supposed to be integrated. In one case we were told that broader software solutions usually do not fit the needs of SMEs and are too expansive because of the unnecessary scope of operation. (Mende, 2022).

Research and development (R&D): Most but not all of the companies seek to spend more resources in R&D. The ideas usually grow from the operative business and employees as well as partners from industry or academia come up with new solutions for improvement. (Mende, 2022; Schwarz, 2022) In one case an R&D department is implemented and therefor sufficient. (Hansen, 2022).

Standards: The low consideration of standards can become a problem because standardization is not only an enabler but also a necessity for digitalization. (Mende, 2022).

Organizational structure: The less complex and informal organizational structure is usually seen as a benefit because of quick and easy communication as well as decision making. (Hansen, 2022) Since specialists are needed for more advanced digitalization projects, a more complex organization chart has its advantages, too. (Mende, 2022) With regard to complex digitization projects, it would sometimes be desirable to have more specialists going along with a special department than generalists in a typical organization chart of an SME with fewer and more general departments.

Human resource (HR) development: Our interview partners generally agree that the HR development focusses on the core activities of the companies and do not see severe problems for digitalization as a result. Some managers desire a higher interest for digitalization possibilities as a basis for new employee driven ideas (Heidel, 2022) or management capabilities for a higher degree of decentralization. (Mende, 2022).

Alliances with research institutions: The companies from our interviews cooperate with universities and see this kind of cooperation as a necessity. (Hansen, 2022; Heidel, 2022) Sometimes a higher degree of collaboration is wanted. The limiting factor is time. (Schwarz, 2022) Additionally, the flexibility from the university´s side to react to SME specific needs can become a problem. With an SME and a university two very different partners need to work together to pursue a suitable goal for the company as well as creating beneficial output for the university. (Mende, 2022).

3.2 SMEs Perspectives on Challenges connected to SME Prerequisites

Considering the necessary prerequisites from literature all are seen as a barrier on the pursuit of smart production if they are not given in the company. As the most serious ones to meet we find:

- the digitalization readiness preassessment with external partners,
- expertise in digital and information technologies as well as management capabilities specially for digitalization, which can be built with external partners and can be considered as learning by doing, (Köpke, 2022),
- the manufacturing digitalization strategic road mapping because digitalization does not work without a plan (Heidel, 2022),
- the cooperation with universities since external partners are absolutely necessary (Hansen, 2022),
- the resource availability considering HR, finances and time.

Being short of resources results in minor steps to smart manufacturing for SMEs. (Schwarz, 2022) One interviewed company has been limited by customers ordering via telephone or fax and potential partners who promise more than they can deliver for an SME. (Mende, 2022) Another one would appreciate external support when choosing partners according to their abilities. (Schwarz, 2022).

3.3 SMEs Perspectives on Challenges from Literature

We found different perspectives on the challenges from literature in the interviews. The ones being rated as most severe are mentioned below. The lack of financial resources is a major problem for most companies we talked to, especially for members from the group of micro-companies. Strategic projects need to be prioritized carefully. Finding employees with digitalization skills is necessary and difficult. (Köpke,

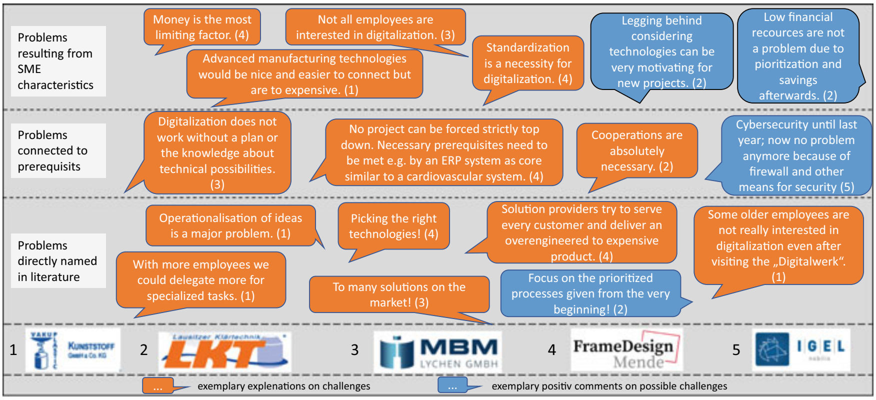

Fig. 1 Explanations and comments from SME managers about challenges

2022) They are needed since the lathe operators will not adjust implement the new technologies. (Heidel, 2022) Managers have difficulties in awaking the interest in digitalization especially of older workers. In case the decision for a digitalization project is already made, finding a fitting solution for the needs of a specific SME is tough since solutions are often too complex and too expensive. (Schwarz, 2022) Managers should prioritize carefully, pick manageable steps and chose the data that is needed thoroughly. The number of possible solutions on the market can also be overwhelming for an SME. (Heidel, 2022) Choosing the What, Why, When, Where, Who and How represents very difficult decisions for a small company. (Schwarz, 2022) Fig. 1 displays a set of summarizing and also contrasting statements from our interviews.

4 Conclusion

We do find a number of challenges for SMEs on their paths to smart production. Some of them, such as the lack of financial resources, finding employees with the right capabilities or unsuitable digitalization solutions on the market, are directly listed in the literature. But also, the SME characteristics, i.e., less advanced manufacturing technologies or isolated software solutions, as well as the necessary prerequisites for digitalization, e.g., digitalization preassessment to define priorities or the interest of staff for new strategic journeys hint at possible challenges.

None of the challenges turns out to be a showstopper, especially since our interview partners are very motivated considering digitalization. In our interviews SME managers have different opinions about the most severe problems when implementing digital solutions to gain transparency or approach other strategic goals. For the smallest ones it turns out to be tougher to handle the challenges mentioned in the literature. Although they are SMEs according to the numbers, they differ in detail considering the soft characteristics, such as organizational culture, company strategy and decision making from the characteristics we find in the literature. The managers do have a strong, but also very positive impact on the innovation processes. Considering the prerequisites our interviewees see them as very relevant and are longing to meet them successfully. The challenges are also confirmed, but in addition we do hear about individual strategies to cope with them. The companies have ties with research and technology transfer institutions and they have prioritized the ideas for innovation projects with self-assessments and road mapping. Thus, knowledge about SME characteristics, necessary prerequisites and the challenges from literature are helpful for SMEs and their partners to define strategies to handle those obstacles on the way to smart production.

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The Vision and Development Trajectory for the Twin Transformation—Cross-Pollination Between SMART and Circular Production

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Abstract In this chapter, we present a vision and a development trajectory for twinning the digital and the sustainable transformation, to both ensure a stronger push, but also to enable synergies within the two agendas. Research related to Circular Economy is presented, together with examples of how digitalization has enabled the push towards sustainability. In addition, three concepts for the vision are presented, alongside discussions related to enabling a systemic change towards sustainability, namely through creating operational value systems, enabling substitution and eco-system lock-ins. These concepts should enable a push towards resource efficiency and effectiveness, on a company, supply chain and eco-system level, as well as linking this to a digital transformation agenda.

Keywords Twin transformation · Circular economy · Digital production · Development trajectory

1 Introduction

The industry has for decades been affected by sustainable goals, with the science-based target initiative (SBTi) aiming at the reduction of greenhouse gasses (Andersen et al., 2021) and Sustainable Development Goals (SDGs) affecting most areas of industry. Even before the strong regulatory push for sustainability, many companies have applied various approaches to sustainability, such as Triple Bottom Line reporting (Norman & MacDonald, 2004), seeking to balance the economic, social and environmental aspects of an organization.

In the context of Small- and Medium-sized Enterprises (SMEs), we see large progress in terms of resource productivity over the last ten years, leading to a significantly lower environmental impact (Climate Partnership of Denmark, 2020). However, as with industry in general, SMEs are at a point in their sustainability

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journey, where the low hanging fruits have been exploited and where more challenging steps will follow affecting operational processes, strategic decisions and ecosystem relationships.

This calls for approaches that are more radical or new technologies to further enhance the sustainability potential. These approaches have been in development for some time, such as the Cradle-to-Cradle approach for product design (Braungard and McDonough, 2009), the Industrial Ecology and Symbiosis approach (Ramsheva et al., 2019) or the Circular Economy (CE) approach (Bockholt et al., 2020) amongst other. While these approaches in themselves can help industry and SMEs towards achieving higher sustainability goals, then an alternative vision is found by twinning the agenda with Industry 4.0. The synergies between Industry 4.0 and sustainability are well established (Pagoropoulos et al., 2017). In a Danish context, the Danish Business Authority and the Ellen MacArthur Foundation (Bjerre & Parbo, 2021) report on the best practices for looping data to create a better foundation for the CE, which is further supported by empirical studies on how Internet-of-Things (IoT) can enable the circular flow of products and material (E.g. Colli et al., 2020).

This chapter presents the vision for *twinning* the agenda for Industry 4.0 and sustainability. The purpose of the twinning is two-fold, first to ensure that sustainability is included in the organizations' visions for Industry 4.0, to ensure sustainable future production, as well as ensure that sustainability becomes part of the push for a fourth industrial revolution. Second, the introduction of Industry 4.0 has proven to have a synergetic relationship with sustainable approaches, such as enhanced options for product take-back (Colli et al., 2020). In the paper, we will explore how the twinning of Industry 4.0 and sustainability builds up capabilities cumulatively (Flynn & Flynn, 2004), allowing the two agendas to progress in unison and reach greater potentials than could be achieved without their combination.

The next part of the chapter will present an overview of CE approach followed by the vision for twinning CE and Industry 4.0.

2 Circular Economy (CE)

This approach seeks to be regenerative and restorative by intention and design, by avoiding waste and pollution, while keeping products and materials in use, mimicking biological systems (Bockholt et al., 2019). The goal of CE is to fully utilize the value of the functionality and materials in the products, even once the products reach End-of-Life (EoL). This solution supports the sustainability agenda in the sense that it reduces environmental pollution while also addressing the area of resource scarcity (Heshmati et al., 2016). In addition, companies that adopt CE may also achieve; material savings, reduced supply risks, improved customer loyalty and new revenue streams (De los Rios & Charnley, 2017).

The benefits are achieved by either *narrowing flows*, *slowing resource flows* and/or *closing resource flows* (Bocken et al., 2016). The notion of narrowing flows relates to using fewer resources per product, slowing relates to extending the product life, while closing relates to designing systems that can reuse materials and functions from End-of-Use (EoU) products.

This notion is further expanded in the principles around the R-Framework (Lieder & Rashid, 2016; MacArthur Foundation, 2013), which seek to create a guideline for handling EoU products, from reusing products to recycling, with various options in-between. However, for an organization, the recovery of material is not limited to the recovery of EoU products, but looks at all waste generated within the supply chain.

In practice, one of the major barriers has been the financial sustainability of such initiatives (Bockholt et al., 2020), where recycling traditionally only unlocks the material value of product takeback (Kumar et al., 2007), which in itself is sustainable for valuable materials, but in general, cannot financially support a take-back program. The most CE value is found when recovering the functional value embedded in the product (Thierry et al., 1995).

As a foundation for the circular system the need to qualify the technical, organizational and processual integration of two types of data flows in the circular supply chain arises, namely: 1. Product configuration, performance, flow and use data: including after use destiny data, assembly data, sales price, take-back price, use conditions and frequency, consumer-specific configuration, product usage, product maintenance, and product damage. 2. Material and traceability data: including Bill-of-material (BOM), the origin of materials, recycled content, product design, resources used in the process, content and the production of the product and packaging, product origin and companies involved in the supply chain.

The drivers of CE can be found in three areas; business model innovation, sustainable product design and operating system design. Together, they constitute a systemic change. The following will present these, and how they could benefit from the Industry 4.0 agenda.

First is the business model innovation, as one of the most powerful enablers of a CE (Pigosso & McAloone, 2015). The business model draws on the integration of strategies such as reduced consumption, eco-design, reuse, sharing, leasing, repair, refurbishment and recycling. Integrating the most suitable of these approaches to business- and product development will play a significant role in maintaining the utility of products, components and in realizing circular business models. By focusing on the value system rather than merely the product, one has the opportunity to decouple the creation of wealth from resource and energy use.

Second, is the sustainable design, as CE is often realized by the development of products, services and product-service systems that can be easily disassembled, remanufactured, recycled and reused (Bakker et al., 2014; Tukker, 2015). Less focus has been given to the manufacturing systems that are to respond to these strategies and which need to be apt for integrating material streams and reused components that do not necessarily meet existing specifications or the planning and control systems (material requirement planning and product life-cycle management) that are to ensure high efficiency in the utilization of manufacturing flows and compliance of these in the manufacturing flow and supply chain (Andersen et al., 2022). Common approaches for the design of circular products include the application of Design for Recycling, Design for Remanufacturing and Design for Disassembly methods. Nevertheless, to ensure a superior sustainability performance of products, the entire life cycle of products needs to be considered.

Third, the operating system has to be considered, especially related to resource conservation and consumption. The consumption of critical materials is expected to more double by 2050 (Bobba et al., 2020), which means that there is huge pressure on reducing the consumption and equally importantly recovering end-of-use materials to ensure that critical functionality will still be available with the existing/reduced level of virgin materials consumption (Kjaer et al., 2019). Another critical element is the unintentional consequences of current supply chain footprints and manufacturing network design. Logistical optimization avoids component tourism and waste from overly complex supply systems—i.e. the environmentally inefficient logistical configuration, representing the lead-time, handling and extent of logistical transportation needed for delivering a product (Chen et al., 2014).

These are both examples of how Industry 4.0 and CE go hand-in-hand (Colli et al, 2020), which introduces the idea of cumulative capabilities where the mutual supporting interdependencies are in focus (Flynn & Flynn, 2004). The next part seeks to propose a vision for twinning the sustainability and industry 4.0 agenda.

3 Twinning—Building the Vision Towards Sustainability

Technology has unleashed new potentials for business performance, and thereby, also environmental impact. As a result, resource productivity has increased in the Danish industry overall (Grenaa et al., 2021), and across all resource categories (water, raw materials, CO_2, energy). This means that the Danish industry has been capable of gaining higher/more appropriate outputs with fewer resources consumed pr. unit produced. The problem herein is that Danish industry is also experiencing an increased demand, which means that the overall draw on most resource categories has increased except for CO_2 and as such the industry has only managed the relative decoupling and not the absolute decoupling, which will be necessary for reaching ambitious environmental targets at the national level.

Technological and digital solutions have so far played a significant role in this transformation by providing access to optimization and waste reduction and will continue to play a significant role, but so has offshoring, which often hides national impact by pushing the burden to the sourcing destination (The Climate Partnership of Denmark, 2020). While many uncertainties related to the emerging climate technologies remain (e.g. Power2X, Carbon capture, storage and utilization). Actions directly available to industry can be found in sustainability technologies readily available to industry, such as tracking, reducing material consumption through product and process optimization driven by intelligent tools (simulation, emulation), and automation with the potential to backshore production. However, their adoption in SMEs remain limited, as they are often designed for large companies and the efforts/competencies/cost required to integrate them into business processes remain extensive.

To unlock potentials, this section seeks to promote a vision for combining industry 4.0 technologies and sustainability, which will be described through three core concepts.

Concept 1 (Company level): Value Chain to Value System

The first concept presents the value systems view. Within CE, it is well argued that there is a need for a system perspective, to assess the potential for improved sustainability (Uhrenholdt et al., 2022), whether in terms of business models or implementation (Niero & Rivera, 2018). Similarly, while the supply chain is the main motor of value creation, it is a large contributor to value loss and resource waste, through scrap and byproducts. Therefore, this concept proposes that we adopt a *value systems* view on supply networks, rather than the dominant value chain competing against value chains.

With regards to the use of waste and byproducts, there is a long tradition for industrial symbiotic relationships that builds on the notion of biological symbiotic relationships, inspired by nature (Bockholt et al., 2019), in which at least two otherwise unrelated species exchange materials, energy, or information in a mutually beneficial manner. These relationships are, however, centered on local exchanges between companies in close physical proximity, which holds natural advantages related to infrastructure, knowledge, trust etc. (Ramsheva et al., 2019), but have more lately been leveraged by the establishing of digital platforms and intelligent sorting (Prosman & Waehrens, 2019).

At the business system level, intelligent assets could allow us to remove barriers that prevent sharing, leasing and performance models from advancing. But, also by opening up sourcing markets that can help to avoid suboptimal use of waste streams. The emergence of secured information exchange through blockchain and real time in operational data through IoT technologies is enabling this (Bjerre & Parbo, 2021). These technologies are currently being brought together through the introduction of digital product passports (Adisorn et al., 2021). With this passport, the materials used, as well as the owners and usage of the products can be tracked, which enables value recovery from multiple parties.

Concept 2 (Supply Chain level): Substitution for sustainable source

The second concept adds to the previous, as it challenges the feasibility of reusing the waste material. It seeks to ask the question: How well does the alternative (recycled, reused or otherwise sustainable) material/fuel substitute the virgin/fossil material/fuel? This remains an open question both in terms of functional and environmental performance. The challenge is that inferior properties and higher costs are often associated with alternative fuel/material, and often more resources are needed to generate the same amount of energy or functional properties of the material. This leads to more transport and handling, by having to deal with multiple sourcing streams and calls for increased demand for testing capacity to secure the quality of the sourced materials. As a consequence, companies can expect loss of production capacity due to lower processing speed, more changeovers, more maintenance due to lower homogeneity of materials and fuels. Understanding the performance of alternative materials and fuels is an experimental process supported by continuous tests, data collection, and analytics (Prosman and Waehrens, 2019). It is, however, also a process that can be advanced through dynamic PLM/commissioning tools, which continuously can update the variables in its optimization model. Ultimately the vision is that information about materials and products are tracked throughout their production and use phases to allow accurate real-time data in support of sustainable decisions. In support of this journey EU is passing regulation on eco-design for sustainable products (ESPR). All regulated products will be required to have *Digital Product Passports*. This will make it easier to repair, reuse or recycle products and facilitate tracking along the supply chain.

To summarize the two first concepts, then Fig. 1 has been made to illustrate how the physical and digital flow can be synergized. At the physical flow, the resource loops are illustrated, as well as the common sources of product takeback, simultaneously, it is also acknowledged that parts of the reverse flow cannot be used internally and is then channeled through the waste system. The proposed concepts will add digital flow to support the internal value system, as well as open up for external reuse and value capturing. In the forward flow, it will enable traceability of data, for material content, as well as information on construction and repairs to prolong the lifetime of the product and make it easier for waste handlers and third parties to extract value from the products. On the reverse flow, is IoT supported product performance data, such as the usage, performance and maintenance of the products during their use phase. This information can be used by the OEM to assess the remaining value of the product, as well as condition of components and materials, which then can be reused to have a second life.

Concept 3 (Eco-system level): Using technology to break suboptimal lock-ins

The third concept is found at the eco-system level. It addresses how systems can be set-up to maintain value through material and energy in an industrial system. It is given, that when using waste in one way, it prevents us from using waste/energy in another and potentially more valuable way. This is often illustrated by waste hierarchies (Pires & Martinho, 2019). To exemplify Denmark has since the 1970-ties established a highly efficient waste incineration system, as a result, landfill represents less than 1% of the overall waste flow, and waste supplies a major share of fuel for the energy consumed in the district heating system. This infrastructure has, however, also meant that higher value utilization of waste fractions to a lesser extend has been sought out, which means that Denmark has a low capacity for recycling of e.g. plastics (Andersen et al., 2019). In other words it is important to avoid these structurally determined lock-ins—i.e. having strong solutions to address the outcome of an ill designed process should not deter us from addressing the issue itself. Today most Danish plastics waste is incinerated—57% is burned for heating and energy (18% points above the EU average). Only 13% is recycled in Denmark, 28% is exported for recycling, while 2% is landfilled. This is not likely to change unless value is

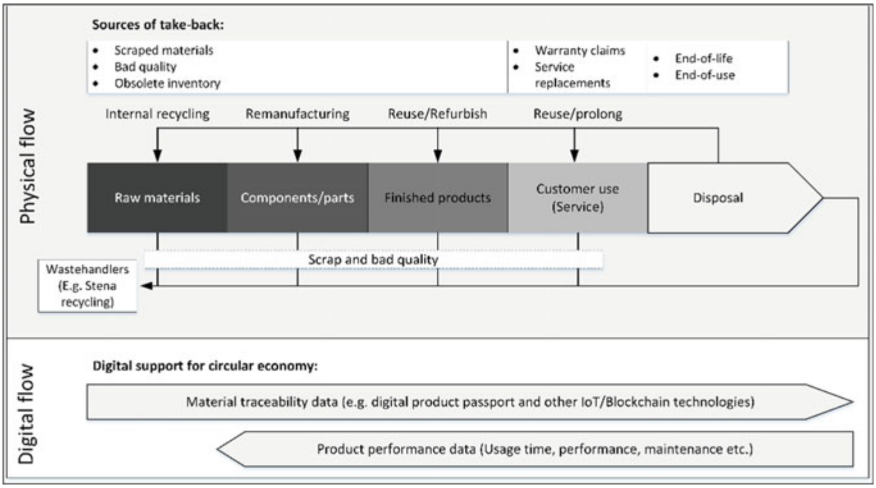

Fig. 1 Representation of the physical flow of products, and the needed digital data for support

allocated to the upgrading of these material streams building strong intensives for sorting, upgrading and reintegrating a cumbersome waste stream. PET is a likely candidate to demonstrate this, as the market value of rPET exceeds that of virgin PET, providing a strong incentive for salvaging the PET fractions that today is mixed with the residual waste. This, however, also requires the further development of intelligent sorting, data processing/analytics, and balancing of mechanical/chemical/enzymatic processing.

Building the capability to utilize the potential in this waste stream represents a potential savings from not importing new raw material amounting to as much as half a billion euros per year (McKinsey & Innovation Fund of Denmark, 2019). Most of these savings would come from recycling domestic plastic waste rather than importing more expensive new raw materials. At to moment, we face two potential new lock-ins at each end of the waste handling system namely: sorting at the source and pyrolysis, each demanding high infrastructural investments and each not currently tapping into Smart technologies, which could enable re-engagement of potentials at a higher level.

4 Discussion—Achieving the Vision

While the twinning agenda seeks to combine Industry 4.0 and CE, the actual transformation process relies on capabilities. Here, it is found that different capabilities calls for different levels of capability maturity (see eg. Uhrenholt et al., 2022b). This thinking is also illustrated in the figure (3), which have been used in a recent practical twinning workshop, illustrating the placement and concerns/visions across the three levels of analysis outlined above.

In terms of the vision for the digital twining, then the ultimate goal is to reach a *regenerative* stage, a net-zero stage where resources are recirculated and reached from sustainable sources. However, to reach this, we need to pass through the stages; *Compliance, Transparent, Integrated* and *Restorative*. The *Compliance* stage is the initial stepping-stone, by becoming ready for future standards, such as the Corporate Sustainability Reporting Directive (European Union, 2021), but also to be compliant with legislation such as the 'The Right to Repair' and 'Digital Product Passport'. As a result, and through further data analytics, the next step involves *Transparency*¸ in this phase, the digital technology is used to create transparency towards products materials, design and usage, this transparency is essential to boost CE in terms of enabling product take-back (e.g. Saebye et al., 2020), or just to avoid inefficient recycling of materials. Reaching the *Integrated* phase the critical inflection point of 40% absorption of low impact resources will be met, thus achieving a relative decoupling of growth and resource consumption. The following phases *Restorative* and *Regenerative* illustrate idealistic phases, where the transformation has reached a level where consumption is focusing on repairing the environment, instead of the current focus of conducting the least amount of harm.

The capabilities needed to achieve this transformation fall within the following interdependent system elements (Fig. 2):

- *Technology capability pertains to supporting technologies:* at initial capability levels manufacturers have adopted IoT technology to gain insights into the use

Fig. 2 Capabilities for adopting CE with key inflection points clarified through Delphi interviews and workshop

of products before the recovery operation (E.g. Colli et al., 2020; Saabye et al., 2020), furthermore it enables efficient reverse logistics, product evaluation and disassembly (GreenBiz and UPS, 2016). At later stages predictive capabilities supported by live performance analysis enable that devices can be replaced or repaired before irreversible damage occurs (Morlet et al., 2016).

- *Governance and Regulation pertains to internal and external framework conditions enabling and driving transformations.* At initial stages strategies are formed and funded, at later stages regulation and standards operationalize the scaling of initiatives and finally sustainability is a natural part of business.
- *Competences and Social Adoption pertains to the behavioral changes and skills necessary for advancing the transformation:* At initial stages competences are scattered and social adoption marginal, at later stages they are driving forces.
- *Transparency and Interoperability pertains to the ability to track, identify, characterize and for seamless communication between supporting systems:* Initially transparency is built into pockets of the value system and systems beyond this suffer from media-breaks. At later stages real time and comprehensive data and analytics drive decisions throughout the value system.
- The *Value Creation and Market Pull pertains to the need for strong incentives to drive the transformation forward:* Capturing functional value calls for data from the use phase to evaluate condition and to analyze the failure mode and to obtain data about how the product has been used (e.g. in which medium it was used, how many starts–stops etc.). This should be supplemented with product and production data to evaluate fit for purpose (Bjerre & Parbo, 2021), ideally implemented in digital product passports (Adisorn et al., 2021).

Each element has strong interdependencies with the other dimensions and these interdependencies change with time as the configuration of and role of the elements change. Different configurations apply to different levels of maturity. Following from this twin transformation would be the transition from one to the next configuration and the facilitation by the application of various boundary objects (Waehrens & Riis, 2010), which in this context could be IoT, analytics, detection technologies etc. Understanding the specific configuration and evolvement of the system elements and their effect on outcomes should be a key concern for further research.

5 Conclusions

The link between the smart and the sustainable transformations cannot be reduced to a single trajectory, it is a multifaceted journey presenting us with several development problems: 1. multiple potential pathways (reduce, reuse, recycle, regenerate), 2. multiple stages of development (compliance to regenerative), and 3. multiple levels of engagement (eco-system, supply chain, operations process). The availability and use of data in the interconnected supply chain have a significant impact on the financial and environmental performance of CE initiatives across these three problems with effects related to: (i) efficiency improvements in the supply chain minimizing value loss and waste generation and (ii) resource effectiveness build on the capability to close resource loops by designing out waste and designing for highest possible value application. The function of data as a key enabler of resource effectiveness can be demonstrated through the recovery of product data from IoT devices and extensive product testing restores the ability to close resource loops or increases the recoverable product value. The loss of data during the course of a product life cycle is a systemic problem. Traditional discrete manufacturing products are only designed for one product life cycle and so is the data flow and its supporting IT infrastructure, these problems are solvable and can be greatly assisted by SMART production and digital solutions, which if designed properly can supply this missing link.

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An Action Design Research Approach to Study Digital Transformation in SME

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Abstract In this chapter, we develop an action design research approach to study digital transformation in the small and medium-sized companies engaged in Innovation Factory North. The Innovation Factory North is a research and innovation project aimed at making Small and Medium-sized Enterprises (SME) smarter by engaging in joint industry/academic activities. The collaborative activities are framed as participatory design (PD) and the research activities are framed as action design research (ADR). This leads to formulating an approach to study the mechanisms for making small and medium-sized manufacturing companies smarter, by conducting a series of interactive research engagements with SME's centered around the AAU learning factory, the AAU Smart Lab.

Keywords Digital transformation · SME · Design science research · Action design research

1 Introduction

When researching real-world applications, e.g. Industry 4.0 (I4.0), researchers face many challenges, including the balance between industrial relevance and academic rigor. In operations management as in many other fields, the discussion of rigor versus relevance has been an ongoing debate (Aken, 2004, Holmström et al., 2009) One of the predominant recommendations is a much closer engagement between industry and academia (Van De Ven et al., 2006) which enable co-creating new knowledge. However, the fulfillment of this promise may be difficult to realize since industrial challenges are complex and "messy", where academia prefer to work with well-defined problems (Checkland & Scholes 1990). Digitalization is one of the new challenges where academia and industry can meet, on the basis that neither academia nor practitioners are working from a mature knowledge base, and therefore jointly can create new knowledge.

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Industry 4.0 (I4.0) has been proposed as a vision of a technological driven transformation of the industry towards a highly competitive digitized ecosystem, and obviously this attracts the attention of most managers within manufacturing.

The German I4.0 report concludes that the journey towards the I4.0 vision will be an evolutionary process rather than a radical transformation (Kagermann et al., 2013) The report further states: "that current basic technologies and experiences will have to be adapted to the specific requirements of manufacturing engineering, and innovative solutions for new locations and new markets will have to be explored. Achieving the benefits from digital manufacturing is a long-term endeavor and will involve a gradual experimental learning process involving both technology, systems, and management processes. For the individual manufacturing company, it will be key to ensure that the value of existing manufacturing systems is preserved. This emphasizes the need for a brown-field approach to the transformation. At the same time, it will be necessary to come up with migration strategies that deliver benefits and productivity from an early stage" (Kagermann et al., 2013). This emphasizes the practical focus on the road to achieving I4.0, rather than the end-results, which is also elaborated in (Møller, Madsen et al., 2022a, 2022b).

For an average small manufacturer, the big ideas of digital transformation and Industry 4.0 may appear daunting and will often require fundamental change in mindset, new ways of working and collaborating with external partners. On the other hand, the SME's who manage to crack the code are often much faster and agile than larger companies.

Therefore, we need to identify and develop mechanisms to trigger and accelerate the transformation. From a research perspective we are interested in understanding and generalizing such mechanisms, and to study the mechanisms from a variety of perspectives, in order to bridge practice and academia. Consequently, the Innovation Factory North (IFN) project were formulated.

IFN is as a platform for a collaborative industry/academia approach to trigger and accelerate industry 4.0 based innovations in small and medium sized manufacturing enterprises (Møller, Hansen et al., 2022a, 2022b). The IFN approach is described comprehensively later in this book (Møller et al., 2022a, 2022b), and what distinguishes the approach is that we are both creating the interactions and also studying the impact. From a research point of view, this very practical and holistically approach is challenging in terms of: (1) what is researched? (2) from which perspective? And (3) how can we systematically create high quality research data that will allow for rigorous contributions to several fields?

These are the questions we set out to address in this paper. In the next section we will analyze IFN project from a research design perspective and formulate the gaps related to the research design. In the third section, we will present the actual research conceptualizations of the IFN project, after which we will discuss the implications and potential for researching SME's. Finally, we summarize and conclude.

2 The IFN Approach

Innovation Factory North (IFN) is an approach for making small and medium sized manufacturing companies smarter by implementing industry 4.0 technologies in an iterative collaborative process. The main activities are conducted by a group of researchers together with a small group of company participants. The activities are organized in three stages: (1) Awareness; (2) Demonstrator; and (3) Anchoring. In the Awareness stage, companies are developing a roadmap for the transformation, and in the Demonstrator stage, the companies are developing a prototype of a solution, and finally in the Anchoring stage, the companies are developing a plan for scaling and implementing the solution. Between the stages, there are "Pivo" seminars, where the direction and scope are defined (see Fig. 1). The IFN approach is being applied in a research and innovation project called Innovation Factory North (IFN) and the IFN approach has been empirically tested over several years with more than 50 industrial companies involved. The IFN project is a set of longitudinal structured interventions building on the assumption that digital transformation can be triggered by helping the SME to successfully complete small experimental digitalization projects, creating direction, building momentum, and making sense of the transformation (Fig. 1).

When the IFN were initiated, we have formulated three theoretical grounded hypotheses regarding the approach: The first hypothesis is regarding the *innovation* process, and why the companies need to innovate. The assumption is here that the technology is out there, and that it is just a matter of identifying the right knowledge/competencies and adopting it to the specific needs and apply the solutions to the right problem. The second hypothesis is on the *development* process. New solutions need to be built through co-locations of the stakeholder and in close collaboration with the solution providers in the lab, thus co-creation. The third hypothesis is on how to create new knowledge and competencies through an iterative and experimental

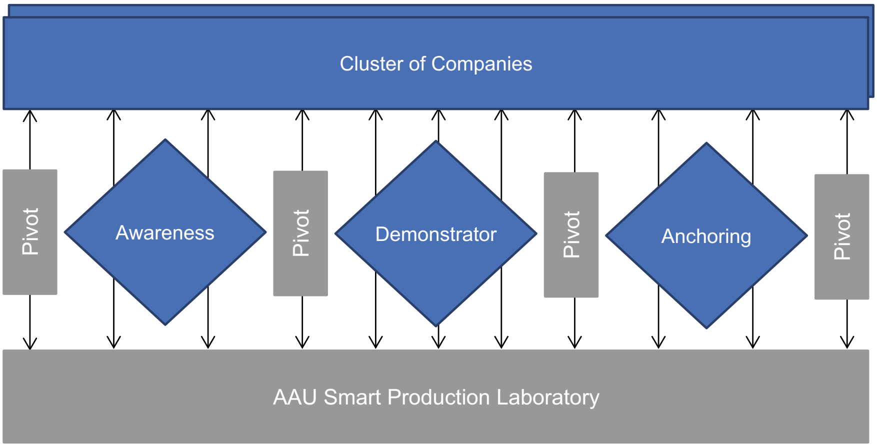

Fig. 1 The IFN approach

learning process. The learning process is facilitated partly by a structured process and partly facilitated by the researchers involved in the process. Those hypotheses and assumptions are continuously being refined based on the empirical findings from the engagements, and they form the mechanisms we want to study.

Making sense of this research project is challenging because of the complexity of the project configuration and the collaboration and the interplay between many different stakeholders. There are at least three challenges: First we need to get industry to sign-up to this project, get them to be inscribed in the ecosystem, and understand their needs and motivation to participate in this research. Second, we must ensure that we have access to the knowledge and resources needed to address the concerns. Third, we need an operating model to guide the research engagements.

The framework for the IFN research engagements is illustrated in the figure. There are four interconnected domains in the framework.

First (1) there is the academic domain where the researchers are coordinating the activities through an operating model prescribing how the interactions are conducted. Second (2) there is the industrial domain where the participating companies engage in IFN with 2–3 managers. Third (3) there is the joint domain where researchers, the participating SMEs, and technology vendors are engaged in a structured development process guided by the IFN approach. Fourth (4) there is the learning factory, the physical space, which provide the platform for the IFN approach.

The learning factory, the AAU Smart Lab (Madsen & Møller, 2017), is a controlled context in which in-vitro demonstrations and experiments can be build. Those activities are being conducted collaborative between researchers and the participating companies. The engagements are facilitated using a set of orchestrated schemas consisting of models and tools that are standardized and harmonized across multiple engagements, providing us with the opportunity to compare and to contrast the impact of our design choices with respect to improving and generalizing the approach (Fig. 2).

Outside of the Operations Management field, this kind of collaborative research is often considered as participatory design (PD) and innovation research (Clausen et al., 2020). In science and technology studies (STS), staging is used as a concept and a tool for planning and facilitating the design and innovation activities (Pedersen, 2020).

Staging is a theatrical metaphor aimed at making sense of the activities, events, and workshops in participatory design. In this perspective, the IFN approach can be considered as three negotiation spaces, where the spaces refer to a specific stage (Awareness, Demonstrator, and Anchoring) in the IFN approach. In the Table, the theatrical metaphor is applied to the IFN approach. The letters in the table refer to the link to the research approach to be elaborated in the next sections.

Due to the explorative nature of the IFN project, we decided to track all the possible data collected in a structured logbook to be used in systematic reflections and in the refinement of the engagements and how to manage the engagements as researchers. This logbook is also connected to the administrative tasks of documenting the progress and results as part of the project management. The conceptual

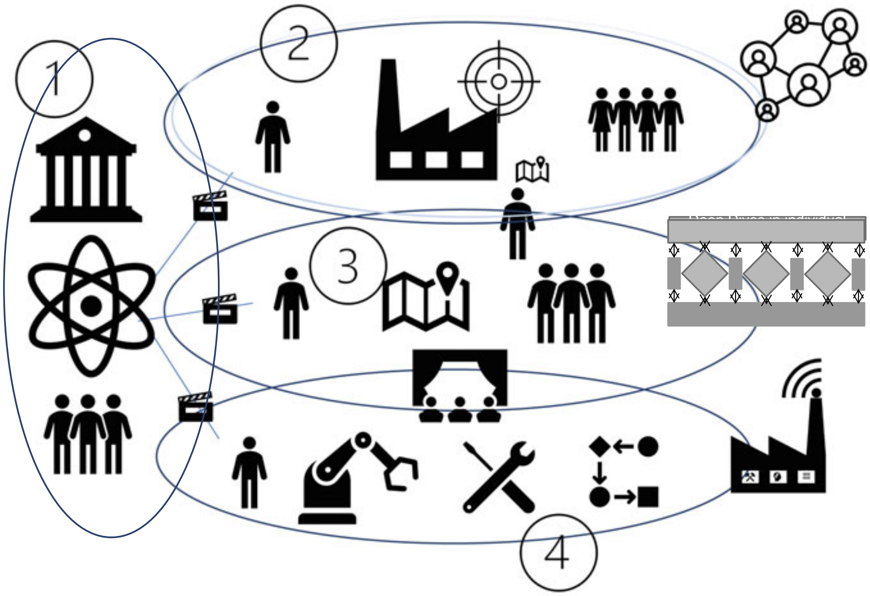

Fig. 2 The IFN research framework

framework is further instantiated in an app developed in Airtable (www.airtable.com). This app tracks all stakeholders, events, participants, activities, and observations. To supplement this, we have collected agendas, notes and minutes, interviews, and recorded sessions in a SharePoint site shared between the researchers. Thus, this platform ensures that all activities are visible to all researchers and throughout the project period, there have been a weekly check-in meetings and larger project meetings where reflections have taken place.

In the beginning of the project, the approach was almost identical from the approach applied in previous engagements with only one participating company. Therefore, the assumption was that the overall approach was working and consequently the focus was on refining the approach. The first cluster of companies was handpicked (screening) from companies with already existing relations with the researchers. The first cluster was aware that their engagement was a prototype and they willingly provided lots of constructive feedback. The research team met weekly to plan the activities and to reflect on the feedback. Besides planning activities aimed at the building and sustaining the ecosystem in order to be able to continuously recruit companies, the focus was on making the joint workshops and the company specific activities work and create the intended outcomes for both practitioners and researchers. The research team has continued these meetings for the duration of the project.

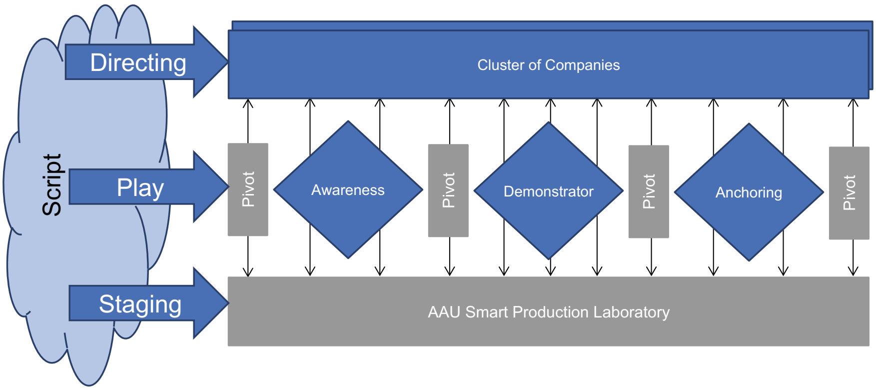

Fig. 3 The IFN approach in a staging perspective

The aim of the IFN project is ultimately to formalize the engagements into a scripted playbook (an operating model) that will make the engagements repeatable and the outcomes predictable. In the staging vocabulary, we started the IFN project with some structure and lots of improvisations. Beside the playbook, we also need guidance on the screening of companies, casting and directing the participants. Finally, we need a systematic approach to shape the socio-technical "negotiation space" by providing the proper materiality support (physical equipment) for the storyline of the play. In practice this means how we can build demonstrators in the Smart Lab, and which demonstrators to build to achieve the desired effect (Fig. 3).

Having framed the IFN research engagement and activities in this section, the next section will frame the research approach.

3 Designing the Research

In this section the research problem is analyzed, and several research approaches are considered. This is leading to framing the IFN research from a particular Design Science Approach (DSR), the Action Design Research (ADR) approach, and we formulate and build a research design that can be used to study the mechanisms of the IFN project in a longitudinal perspective.

The research is aimed at studying the impact of the engagements in the context of IFN with the purpose of increasing the impact of both the ecosystem as well as providing benefits for the individual stakeholders. However, due to the nature of the assumed impact, and the timeframe in the project, we are restricted from making proper evaluation studies, and in this work, we are evaluating impact based on preliminary indicators and the perception by the participants.

There are several examples on how to approach a collaboration between academia and industry, which focus on innovation and novel technologies such as Learning

Factories (Abele et al., 2019), Learning Laboratories (Leonard-Barton, 1992), Change Laboratories (Helle, 2000) and research projects and centres among others e.g., 5GEMII and the HELIX research center (Galvao et al., 2019).

3.1 Engagement as Action Research

The IFN project can be studied through the lens of a classical action research (AR) approach where the interactions are leading to organizational change (Davison et al., 2004). The overarching problem for all participating companies is the I4.0 driven digital transformation towards smarter production, and the theoretical lens is mainly business transformation.

However, the purpose of the IFN project is not primarily to create the desired impact in the individual company, but mainly to produce shared knowledge (co-creation) and to institutionalize this knowledge in the IFN ecosystem by using the Smart Lab as a generic knowledge container. This leads us to consider the IFN project from the perspective of designing and materializing the interactions.

3.2 Engagement as Design Science Research

The IFN project can be studied as a case of designing the artifacts and the interaction processes (Hevner et al., 2004). Although Design Science Research bears resemblance to AR (Jarvinen, 2007), it is generally considered to be a distinct approach. This means designing the Smart Lab, methods, and approaches as instances of a generalized idea of a learning factory to be elaborated later. Considering the IFN project from this perspective would have the advantages of being able to develop prescriptive design knowledge through building and evaluating the artifacts intended to solve this particular type of problems. However, the utility of the artifact would be difficult (and irrelevant) to assess without the context and without unfolding the specific organizational interaction.

3.3 Engagement as Action Design Research

This led us to consider a combined approach. In recent years, a new research approach has emerged, that acknowledge the duality of the artifacts and the actions taken: Are we interested in the technology or the application of the technology in a specific context? Action Design Research (ADR) was first coined in Sein et al. (2011) and the duality has been widely debated (Goldkuhl, 2012) whether it should be seen as separate, complementary or combined perspectives and is an ongoing debate (Iivari & Venable, 2010). ADR has been applied to a wide variety of problems. In this paper

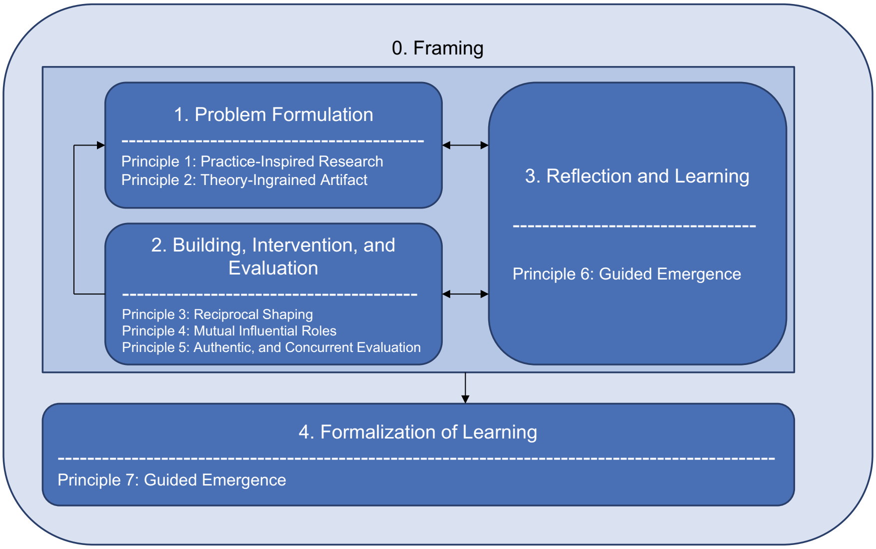

Fig. 4 ADR method stages and principles (after Sein et al., 2011)

we apply a slightly enhanced version of ADR inspired by (Mullarkey & Hevner, 2019) (Fig. 4).

ADR is a research method for generating prescriptive design knowledge through building and evaluating ensemble IT artifacts in an organizational setting (Mullarkey & Hevner, 2019). The ADR method is by large a four-step iterative approach guided by seven principles (see Fig. 4), related to, but different from the seven principles of DSR (Hevner et al., 2004).

The steps in the original four-step ADR approach (see Fig. 1) are: (1) Problem Formulation; (2) Building, Intervention and Evaluation (BIE); (3) Reflection and Learning; Formulation of Learning. Sein et al. (2011) distinguish BIE using a scale from IT-Dominant BIE (innovative IT artifact is main concern) and Organization-Dominant BIE (innovative solution is main concern). In this case we are interested in both, but our point of departure is the new IT artifact (the I4.0 technologies).

The ADR principles (see Fig. 4) in the context of the IFN project are:

1. Practice-Inspired Research. IFN is researching both technological and organizational issues (integrated systems) related to embarking on an industry 4.0 journey.
2. Theory-Ingrained Artifact. The demonstrators created are generalized solutions adapted to the context of the smart lab.
3. Reciprocal Shaping. The demonstrators are adapted to reflect both the technological opportunities and constraints as well as the situation of the stakeholders.
4. Mutually Influential Roles. All participants contribute to the solution, which is a central assumption in the IFN project.

5. Authentic and Concurrent Evaluation. Throughout the initial stages and the prototype development, the evaluation has mainly been reflection in action, but to some extent also reflection on action.
6. Guided Emergence. This principle is the core topic of this paper and is elaborated below. The IFN approach can be seen as a model to guide emergence.
7. Generalized Outcomes. For this paper we only have preliminary outcomes formulated as refined hypothesis, but the aim will be a small set of schemas for distinct demonstrators (level 1), the demonstrations (level 2) and the refined hypothesis (level 3). This would be equivalent to design principles according to (Chandra et al., 2015).

The principles of 1 and 2 support problem formulation, principle 3–5 support BIE, principle 6 support reflection and learning, and finally principle 7 supports formalization of learning. Mullarkey and Hevner (2019) generalize the approach towards an iterative four stage process spanning: (1) Diagnosis; (2) Design; (3) Implementation; and (4) Evolutions. In the IFN context, this matches the three stages and the follow-up studies.

Each of the engagement cycles include the following distinct activities: Problem Formulation and Action Planning (P); Artefact Creation (A); Evaluation (E); Reflection (R); and Learning (L). Mullarkey and Hevner present an additional principle 8: Abstraction that supports the creation of different levels of artefact abstraction for the current state of research goals in the problem environment (Gregor & Hevner 2013). They further describe how this will lead to four possible entry points for the research: (1) Problem-centered (Awareness); (2) Objective-centered (Demonstrator); 3) Development-centered (Anchoring); and (4) Observation-centered (not part of the IFN approach). We will argue, that over a larger number of engagements, all four will be needed for the IFN research, leading to the introduction of a proposed stage 0: Framing (see Fig. 2) where the generalized outcomes are hypothesized guiding the application of the approach, iterative and recursively. This means that we start with formulating hypotheses covering the expected generalized outcomes (Fig. 5).

Action Design Research (ADR) can be considered to be a methodological guidance for the researchers who study the design of ensemble artifacts (Goldkuhl, 2012) ADR is a methodology that emphasizes both the organizational intervention and the design of the artifact. The artifact is then both hardware and software as well as the methods and tools guiding the intervention. In the IFN context the awareness phase starts with the problem, the demonstrator phase starts with the technology (the artifact), and the anchoring phase starts with development. As we hope to continue follow the companies, we will eventually also be able to generate observation centered research.

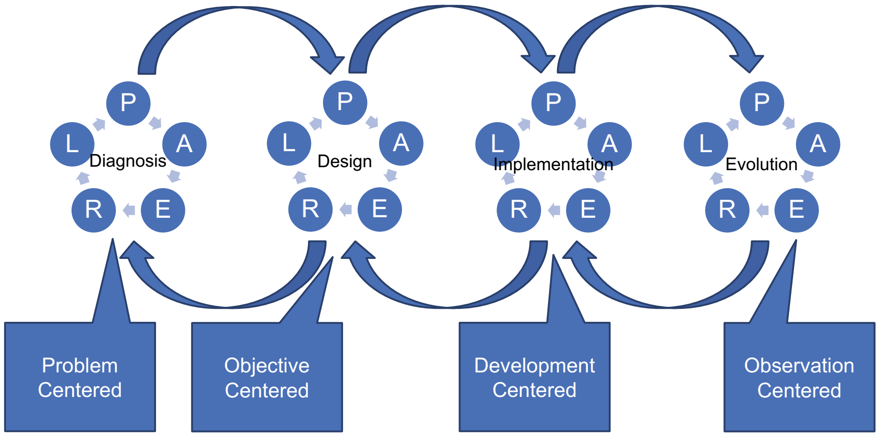

Fig. 5 Conceptualizing IFN research as ADR stages

3.4 The Role of the Ensemble IT Artifact

The significance of physical and material appearance of technology has been studied in information systems (IS) for several years (Orlikowski & Scott, 2008, Leonardi & Barley, 2010, Barley et al., 2012) The ensemble IT artifact (Orlikowski & Iacono, 2001) can be understood as a mediating mechanism between the technology and the organizational context. The debate is still ongoing regarding the use of ensemble artifact and views in ADR, but here we align on (Purao et al., 2013) that emphasize the materialization of a solution and its use in the organization. However, we could also consider the ensemble IT artifact as a communication tool (cf. sociomateriality), and in the IFN case, the "props" for storytelling during the workshops.

In the IFN approach the Smart Lab is being used as a platform to deliver the engagements. The Smart Lab and the physical environment, the tools, and techniques, are considered a learning factory for I4.0. A learning factory is described by (Abele et al., 2015, Madsen & Møller, 2017) as representing a realistic manufacturing environment for education, training, and research. In this case we focus on the ability to create awareness, to demonstrate solutions and to engage and motivate the participants and anchoring the knowledge in the organizations. Consequently, we need to reconsider aspects such as operating model, didactics etc. Another option is to extend learning factory concept from mere learning factory, over solution development platform to innovation factory.

The ADR approach is still young, however there is a larger number of studies reporting on ADR in practice (Haj-Bolouri et al., 2018). Though, the critique towards ADR touches upon the fact that many of the studies seem to be lacking the empirical grounding or are lacking systematic evaluations (Cronholm & Göbel, 2019). This led us to also consider improving the methodological base of ADR as a future endeavor.

Conceptualizing the IFN project from an ADR perspective is not straightforward and a number of considerations leading to several caveats are needed. These are similar to those that are reported in (Haj-Bolouri et al., 2018).

The IFN ecosystem is the organizational context of the overall engagement. However, in each of the stages: awareness, demonstrator and anchoring, a particular subset of companies called a cluster are engaged. Furthermore, since the companies participate with a smaller number of managers and key employees, we consider the participants as proxies for the entire organization including the end-users such as operators. Consequently, the in-vivo impact is only considered indirectly.

The IFN engagement is not continuous but is carried out through a number of discrete events over time. And each of the interactions has a particular group of stakeholders with very different aims and motivations. Consequently, a recursive perspective is needed, and again, considerations to the various analytical levels must be taken.

The pace of the IFN project is forcing decisions to be made that are not necessarily grounded in finalized theoretical considerations. Decisions are then determined by practicalities and the contingencies which must be factored into the research design.

The empirical setting can therefore be considered an ensemble artifact, and the research problem formulated as the design of an ensemble artifact consisting of a learning factory and two interacting processes of in-vivo and in-vitro analysis and design of a solution.

The ADR Principle on guided emergence has two parts. The ex-ante design guided by the initial hypothesis and the ex-post reshaping of the hypothesis. Using Mullarkey and Hevner, 2019 as a reference (take design from method) the research process evolves around each engagement: (P) Problem Formulation and Action Planning; (A) Artifact Creations; (E) Evaluation; (R) Reflection; (L) Learning. Since the IFN activities are carefully planned and staged it makes sense to use the structure of a scene play as a metaphor for the activities. See the connection to the research engagement concepts in Table 1.

4 Discussion

Following the framing of the IFN project as ADR and framing the engagements as staging, we can conceptualize the IFN research project as illustrated in Fig. 3.

The project's initial challenge is to formulate a sustainable operating model for IFN that is able to deliver value to all its stakeholders, is feasible from a resource perspective, and is motivating and engaging for all actors. The initial operating model has evolved iteratively over each engagement and the aim here is to create a systematic approach that can be formulated into a playbook with a scripted approach with packaged knowledge modules or commercially available in order to be able to replicate and industrialize the engagements once the public funding of the project expires.

In the rich picture in Fig. 1, the domain 1 illustrate the research process and the three levels of research engagement: Domain 2 illustrate the screening and the

Table 1 IFN Research Engagement using staging and the theatrical metaphor as a vocabulary, Legend: (P) Problem Formulation and Action Planning; (A) Artifact Creations; (E) Evaluation; (R) Reflection; (L) Learning

Concept	Meaning in IFN context
Script	The plot or storyline of the engagements. To be formalized as a playbook
Parts	The three parts of engagement: Awareness, Demonstrator, and Anchoring workshops
Scenes	The scenes are the individual seminars making up the workshops
Bridge	Pivot seminar intended to connect two parts (workshops)
Cast and roles	Participants and their roles in the engagement
Screening	The process of recruiting the cast
Staging (A)	Back-staging is the setup of the smart lab and environment to facilitate the workshops and front-staging is the workshop setup
Directing (P; E)	The guidance and coaching of the participants before, during and after the engagement
Play (E)	The actual execution of the engagements
Critique (R; L)	Observations (R) and redesign (L) of the engagement
Playbook (P)	Guidelines to standardize and support activities

casting of the participants in the project from the ecosystem. Domain 3 illustrates playing the play, guided by the playbook, and domain 4 illustrate the staging. Later in this book, an example of a particular demonstrator on "paperless production" is presented in depth (Palade & Møller, 2022). In this case, a group of SMEs, together with a technology provider set out to automate manual indirect processes using a low-code tool and explore the implications.

In the project application, the assumption was that learning to quickly build new solutions would lead to innovation and will initiate a digital transformation in the company. This initial assumption of the mechanism driving the digital transformation is leading to formulating three hypotheses regarding the activities in the IFN approach: (1) the engagement as an innovation process; (2) the engagement as a solution development process; and (3) the engagement as a learning process.

The value propositions presented to the industrial partners have included the immediate operational benefits from digitalization, but also the more long-term intangible benefits from achieving operational excellence and innovation, and in general, to learn about industry 4.0 and Smart Production.

So, the next step of the research is to improve impact of the IFN activities by refining the approach by explaining, challenging, and refining the hypotheses and the assumed mechanisms of digital transformation. This will lead to reformulating the hypotheses and to redesigning both the Smart Lab setup and the IFN approach for better guidance of the engagements during the reminder of the project period. This will further contribute to enhancing the learning factory concept and potentially providing a new class of didactics in the learning factory morphology (Abele et al., 2019).

5 Conclusions

In this chapter, we have developed an action design research approach to study digital transformation in the small and medium-sized companies engaged in Innovation Factory North. The Innovation Factory North is a research and innovations project with both collaborative and individual activities. The collaborative activities are framed as participatory design and the research is framed as action design research. We set out to answer: (1) what is researched? (2) from which perspective? And (3) how can we systematically create high quality research data that will allow for rigorous contributions to several fields?

We found that the staging concept is a useful sense-making tool for shaping the research engagement, and that this concept may enhance the learning factory concept by introducing the ensemble artifact and in particular identifying the significance of the back-staging activities using the Smart Lab as an enhanced learning factory (see later chapters). Another perspective is the problem-based approach to I4.0 which is made operational by the IFN approach. Finally, the approach is particulary suited SME's because of the low-cost, low-risk nature of this approach.

The further research is the refinement of the approach to make companies smarter and to guide the design of the interventions building on the learning factory as a mediator between industry 4.0 and its use in manufacturing.

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Part 2
Transformation

Introduction to Part 2

Transformation of SMEs Towards Smart Production

Ulrich Berger and Ole Madsen

Abstract This chapter will introduce the second part of the book. This part contains a collection of chapters aimed at supporting the SMEs in the transformation toward the Smart Production vision. In this part, different approaches are presented, which can assist SMEs in the formulation of a smart production vision and in the identification and prioritization of relevant initiatives, guiding the outline of a project roadmap. Furthermore, the part will introduce different regional innovation platforms in Denmark and Germany which support the SME transformations. Finally, it will be discussed how subscription-based methods could be used by SMEs to cut upfront investments and reduce requirements for digital competencies.

1 Introduction

Smart Production and Industry 4.0 offer manufacturing companies a vast number of new digital technologies with the potential to significantly improve their effectiveness and efficiency.

However, it is not a simple case for SMEs to take up the new digital technologies. The technologies come in different price ranges, require new digital competencies, and the benefit is often difficult to assess. Furthermore, reaching the potentials of smart production and Industry 4.0 is not just a question of investing in new technologies. Instead, the technologies must be adapted and integrated into the operation of the companies. Hence, reaching the Smart Production vision is a transformation process rather than an investment project. This transformation requires

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that the company evolve not only in the domain of technology, but also in digital competencies, governance, and business models (see Colli et al., 2019).

Transforming in a structured way is a difficult task, and forming a roadmap of digital implementation projects is one of the fundamental challenges for manufacturing companies (De Carolis et al., 2017).

Hence, in the following chapters different experts will present and discuss several methods, platforms and concepts that can be used by SMEs. They can serve as a support to the design of a structured approach enabling the transformation of the SME towards Smart Production.

2 General Approach

The approaches taken in these chapters are to a very large extent following the steps found in many traditional transformation processes (vision - > diagnostics - > Roadmap - > Pilot - > scale up). See Fig. 1.

Important for the transformation is an understanding of the business opportunities/potential provided by Smart Production. In the following chapters, it will be explained, how different methods (e.g. lectures, seminars, workshops and training) can be used to obtain the needed awareness.

The awareness builds the basis for elaborating a vision for the company answering the question: where would we like to be in X years? Different time horizons and details are used in approaches presented in the chapters.

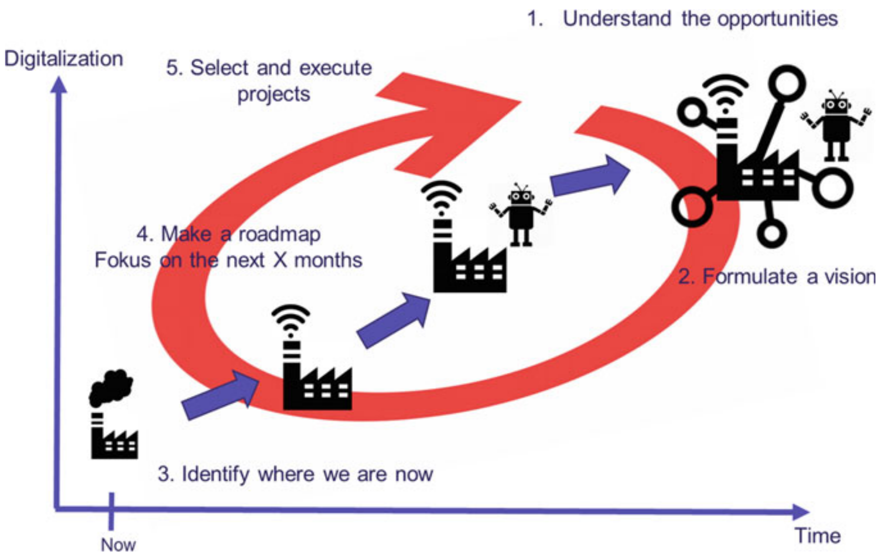

Fig. 1 A generalized approach for digital transformation in SMEs

The third step consists of the identification and definition of the starting point of the individual company by answering the question: where are we now? This procedure is performed by the thorough assessment of the individual SME portfolio, which tackles the necessary topics of smartness, e.g. the status of the digitalization and automation but also the ability to adopt new technologies. The operational work plan is supported often by a digital maturity assessment or synonymous terminologies. Several maturity assessment models and theories are available (see Colli et al., 2019 for an overview).

The fourth step involves an analysis and identification of how the gap between the present state and the vision can be closed. Here the focus is on the immediate future—e.g. the next six months. Projects can then be selected and executed.

The process runs iteratively, so that the vision, the present state and the roadmap are updated regularly, e.g. after the finalization of the identified projects.

This general approach corresponds to the overall strategy outlined by the European Commission for the twin transition towards digitalization and sustainability of SME companies (EU, 2020). The EU strategy puts forward actions based on the following three pillars: (i) capacity-building and support for the transition to sustainability and digitalization, (ii) reducing regulatory burden and improving market access, and (iii) improving access to financing. The main goal is to support the power of Europe's SMEs of all kinds to lead the twin transitions. It aims to considerably increase the number of SMEs engaging in sustainable business practices as well as the number of SMEs employing digital technologies. Ultimately, the goal is that Europe becomes the most attractive place to start a small business, make it grow and scale up in the single market.

3 Content of the Following Chapters

In the first chapter in this part of the book, Blobner and Lay, (2022) presents the the *Industrie 4.0 CheckUp,* developed by the Fraunhofer Institute for Factory Operation and Automation Magdeburg (IFF). This paper reflects the initial objectives, provides an overview of previous and existing solutions and reveals valuable results from industrial case studies. The results would benefit SMEs in evaluating the level of their actual standing point and draw a line of transformation with several milestones, targets and goals.

In a logical sequence, the following chapter Colli, (2022) supports the transformation by applying the method of digital factory mapping. This method enables production companies to identify relevant digital innovation projects to capture performance improvement opportunities and also quantify their impact. The author describes a workshop based operational methodology, where implicit and explicit knowledge of the SME staff members are collected and a sound impact is obtained. This contribution is step-by-step described, meaning an SME gets a guiding principle toward transformation.

The continued four chapters introduce and discuss distinct existing regional innovation platforms in Denmark and Germany, which convey the transformation of SMEs towards Smart Production. They follow mainly the triple helix innovation approach of Ranga & Etzkowitz, (2013), where research, business and government are interlinked transparently and seamlessly. According to Cai & Amaral, (2021) the triple helix process is a well-established practice and should be carefully planned and implemented in an individual region and/or an individual branch. Common approaches have often failed, as they are not covering regional aspects e.g. availability of qualified staff, digital infrastructures and social bonding requirements between companies. The innovation platforms can be used as role models for other attempts but will also provide valuable information for SMEs to engage with such initiatives.

Within this context, Hansen & Hansen, (2022) deal with the non-availability of distinct solutions for smaller companies, which are sometimes important technology drivers and innovators. The contribution explains and summarizes experiences of how smaller companies can be supported. The empirical background is a municipal business support program Northwest Smart Production Program in Denmark (NVSP), which supports SMEs in exploiting development opportunities for Smart Production. An action research approach is described, where the development of the individual company has been the aim of the NVSP program. The research results are documented with qualitative observations and supplemented with case studies.

Møller et al., (2022) present the Innovation Factory North in Denmark (IFN) as a platform for a collaborative approach to trigger and accelerate industry 4.0 based innovations in small and medium-sized manufacturing enterprises. The potential for SMEs to become ‘smarter’ is visible and well-recognized. However, ‘how’ to approach this is difficult. In IFN, manufacturing companies, technology vendors, and academia join forces to trigger digital transformation. The IFN approach is accompanied by a regional research and innovation project in a collaboration between industry, academia, and the government in Denmark. The obtained results cover the empirical approach of a triple helix innovation process, which is covered by literature and case study descriptions.

In comparison, Kilimis et al., (2022) are dealing with SMEs in the industrial area of Brandenburg (Germany), which is characterized by a heterogeneous and dispersed industrial basis. Aspects of digitalization and automation represent both a major challenge and a long-term opportunity for SMEs to secure their business success. They often lack specialist knowledge and a sufficient financial scope and therefore need external support in meeting these challenges. Knowledge and technology transfer between scientific institutions and companies is felt like a mandatory setting. However, different goals, approaches and expectations of researchers and companies inhibit or complicate successful cooperation. The Innovation Centre Modern Industry Brandenburg (IMI) presents a way, how knowledge and technology transfer can be implemented by pragmatic, customer oriented tools and methods. Furthermore, possible success factors for the digitalization of Brandenburg’s SMEs and implementation of knowledge and technology transfer are discussed.

Ferran et al. presents the platform ARENA2036 at the University of Stuttgart which is an example of a living innovation ecosystem of mobility technologies. The disruptive impact of digital technologies opens the opportunity to redefine the innovation ecosystems across (and between) several industries. This initiative links to research and business so that large enterprises in the automotive sector generate start-up initiatives and open co-working and co-innovation spaces to foster collaboration within all supplier tiers in a flat hierarchical setting. The contribution describes the creation of ARENA2036, its organizing mechanisms, and its function as a catalyst for collaborative innovation. The description summarizes the lessons learned in its first years of operation and provides an outlook on the future.

Finally, in the chapter by Krüger et al. (2022), a new transformation method is introduced, namely the implementation of Industry 4.0 subscription-based business models, which are entering the market nowadays. The authors discovered a moderating effect of the dimensions of subscription business models on the challenges and benefits when using these models. SMEs can generate the greatest benefits in a comprehensive model, where the provider takes responsibility for the output and all downstream processes by offering digital dashboards, consulting services and providing consumables. However, such a model requires the following items: (i) The subscriber must be able to meet the technical conditions. Often the provider can support, but a low Industry 4.0 maturity level of the subscriber increases the implementation time. (ii) The subscriber increases its dependency on the provider. Data releases should be clarified in advance, own employees comprehensively taken along. Management-driven change management is just as relevant as a proper weighing of the objective of handing over as much risk as possible to the provider and the resulting higher dependency on the provider (locked-in effect).

4 Summary

For companies to reach the Smart production vision requires that they engage in a transformation process, where they not only focus on new technologies but also on building new digital competences, new governance structures and new business models. This is a difficult task, in particular for SMEs.

Hence, the following chapters provides a number of methods, platforms and concepts that can be adopted by SMEs for enabling the transformation of the SME towards Smart Production.

The approaches can assist SMEs in.

- Getting awareness of the content and potential of Smart production
- Formulating a smart production vision matching their needs
- Identifying their present digitalization level
- Identifying and prioritizing relevant digitalization projects,
- Guiding the creation of a project roadmap leading toward Smart Production.

The different methods can form a basis for inspiration for SMEs to carry out a structured and efficient transformation process. The methods can be used directly or combined to fit the particular needs of the company.

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Maturity Assessments to Support SME Overcoming Structural Changes in Their Business Environment

Christian Blobner and Lina Katrin Lau

Abstract With the increasing drive towards digitalization and automation, Small and Medium-sized enterprises (SME) face significant challenges in continuously adapting to their ever-changing business environment. Navigating those changes, including its technical, organizational and individual requirements, is hard for SME because they often do not have the necessary resources for a sufficient analysis and derivation of parameters for change. To support especially SME in positioning them to adapt to the ongoing and expected changes, the Fraunhofer IFF developed a flexible and customizable methodology to assess a company's maturity level in different dimensions and start a road mapping process to subsequently increase the maturity level. In this way, companies are helped to individually meet the structural change resulting from various external challenges and the advent of Industry 4.0. Furthermore, SMEs are supported to successfully transformation. Maturity assessments proved very successful not only in developing concrete roadmaps for companies to increase their overall maturity, but also in shaping the necessary and underlying mindset to foster change. It was demonstrated that the maturity assessment methodology can be adapted in an international context. Additionally, the transfer of the methodology was piloted in a train-the-trainer concept with international trainees. These maturity assessments provide a significant contribution of the Fraunhofer IFF to the activities of the German Mittelstand Digital Initiative as well as the European Digital Innovation Hub (DIH) Initiative.

Keywords SME · Maturity assessment · Structural change · Support infrastructure

1 Introduction

Structural change can be described as qualitative shift in the business environment or the economy as a whole, which necessitates an adaptation process of actors in the environment or the economy (Schilirò, 2012). The underlying reasons for such a shift

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can be regulatory, political, societal or technological. Structural change and its adaptation processes go together with questioning the fundamental ways of operation, be it in a social, political or business context. In Economics the term "creative destruction" was termed early in the twentieth century to describe these changes (Schumpeter, 1912). A European region, which is marked by continuing structural change are Germany's eastern federal states, the region of the former German Democratic Republic. With German reunification in 1990, the structure of the local economy changed overnight, from large government-owned and -directed enterprises with a set market towards privatized small and micro enterprises, which need to compete nationally and globally.

The adaptation processes led to shifts in the economic make-up of the region. From 1990 onwards, Eastern Germany has had a significantly higher rate of unemployment than the western federal states. Only starting in ca. 2009 the gap between the different rates of unemployment started to close (Röbenack, 2020). Taking the example of Saxony-Anhalt, the unemployment rate between 1997 and 2005 was constantly above 20%, while for western Germany it was below or at approx 10%. Saxony-Anhalt also has a constant, albeit shrinking, outflow of people (Bundesamt, 2021a). The number of companies in Saxony-Anhalt has been in continuous decline since 2012 (Bundesamt, 2021b). Furthermore, Saxony-Anhalt has a very small-scale business structure. SMEs account for 99.3% of Saxony-Anhalt's corporate structure. This is not a large deviation from the average numbers for the German economy. However, looking at the employee distribution it can be seen that in Saxony-Anhalt less people work in larger companies—with more than 500 employees—than the German average (Ministerium für Wirtschaft, Wissenschaft & Digitalisierung, 2019). Within the group of SMEs, microenterprises dominate with a share of 93.3% (Bundesamt, 2021b). Even after more than 30 years of reunification, productivity in Eastern Germany still lacks behind Western Germany (Frei et al., 2021).

Further challenges arose with the emergence of the Industrie 4.0 paradigm, fundamentally questioning the technological and business model underpinnings of, especially, manufacturing companies (Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. Deutschlands Zukunft als Produktionsstandort sichern, 2013). SME in Eastern Germany, which mostly were relatively young, struggling to survive and mostly competing on cost basis, now had to adapt to new market and technology demands. Moreover, in the Eastern federal states companies have a relative unfavorable view about the framework and infrastructure to support their digital transformation (Brockhaus et al., 2020). The current COVID-19 pandemic provides an additional impetus for digitalization. Especially for SME in Saxony-Anhalt the awareness for a necessary digital transformation increased. (Arlinghaus, 2020).

Now, SME are on the cusp of a new structural change towards increased sustainability and less dependence on fossil fuels. This change is again very pronounced in the east of Germany, in which major regions affected by the coal phase-out are located (Bundesanzeiger Verlag, 2020). Additionally, European regulations and legislations, such as the European Green Deal will put additional demands for fundamental change on the economy as a whole and SME in particular (Commission, 2019). All of the changes and challenges described lead to a structural change that requires action on the part of SMEs.

2 Navigating Structural Change with Maturity Assessments

SME, for the most part, are at a loss in defining necessary adaptation measures to the above described changes in their business environment (Heideman Lassen & Waehrens, 2021). Over the last thirty years, companies in Eastern Germany were faced with requirements for adaptations stemming from political, technical and now societal and regulatory changes. With these complex demands on their resilience, companies need a structured approach to be made aware of the current challenges and requirements. This also includes support to necessary shifts in underlying mind-sets and mental models to understand those challenges and requirements in a new context. SME especially need an objective assessment of their current position with respect to defining change characteristics and influencing dimensions. Maturity assessments are valuable tools in this effort. Moreover, the results of the maturity assessments provide a jumping-off point for a subsequent roadmapping process, planning the transition process for the SME to address and overcome the challenges of the structural change. In this respect, maturity assessments and subsequent roadmapping processes help SME, navigating structural changes by providing an individual company focus while contextualizing challenges and requirements for the individual company. Through this, structural change and ensuing requirements for action become easier to grasp. These are broken down from an abstract technical, political or societal level to a concrete actionable level for SME.

The Fraunhofer Institute for Factory Operation and Automation IFF developed a maturity assessment methodology, which is sufficiently adaptable to address various kinds of change requirements of SME. The Fraunhofer IFF is a production-oriented applied research institute of the Fraunhofer Gesellschaft, Europe's biggest applied research organization. Its aim is to provide a holistic perspective on the smart factory as a whole, focusing specifically on challenges at the interfaces of technologies and disciplines.

3 Maturity Models

Companies, especially SMEs, are subject to constant changes, which is further accelerated by the globalization of the economy (Wiendahl & Wiendahl, 2020). This is reflected, for example, by shorter product life cycles, an increased diversity of variants to accommodate individual customer requirements, and shorter delivery times. The advancing digitalization and networking of the production and logistics sectors—short called Industry 4.0—is enabling companies to respond quickly and efficiently to changing market conditions. In order to meet the structural change associated with Industry 4.0, companies must first determine their own positioning in the respective environment for then to derive specific action measures for further development. This will make company-specific road mapping processes possible and help companies to meet challenges of continuous change. The identification of the current positioning is associated with a high degree of complexity, as it involves a set of potentially changing and individual framework conditions. In addition, companies, with their numerous and individual processes, actors and components (people, technology, organization), also exhibit a high degree of complexity.

Maturity models can serve as helpful instruments for countering this described degree of complexity and for assessing a company's own current performance. These models consider the object of investigation with regard to its systematic further development (Becker et al., 2009b). Maturity models are suitable for analyzing, designing and evaluating companies because they understand the development and change process as an inherent component of company design (Mettler, 2010). By applying specific maturity models, the current situation of the company is analyzed and improvement potentials are identified, enabling the target-oriented implementation of improvement measures to achieve a desired target state (Jodlbauer & Schagerl, 2016).

In this respect, maturity models are used as reference models (Kühn et al., 2013), which define, in successive stages, "an anticipated, logical, desired and / or typical development path for objects of a class […] starting at an initial stage up to perfect maturity" (Becker et al., 2009b). In general, these models are characterized by the following properties (Fraser et al., 2002):

- Maturity models have a number of developmental stages (typically 3-6),
- Each level is assigned an appropriate name,
- The levels are characterized by a generic description of the state or by summarizing the associated properties,
- Maturity models have a number of dimensions that create a problem-oriented view of the defined design domain of the model,
- The dimensions are described in detail by a number of elements or activities,
- The activities and element properties are represented per level of development.

The maturity level is determined by observing and evaluating the object of investigation, in our case a company, at a specified point in time, using predetermined assessment methods. The specific level can be determined by either self-assessment or external assessment (assessment by third parties) (Becker et al., 2009b). The object can reach any maturity level as long as the stage-specific elements of the lower stages and those of the current stage are fulfilled (Kohlegger et al., 2009).

In advance of a maturity assessment, the individual target state of the examined object must be determined on the basis of business and organizational framework conditions. The highest maturity level of the model is not necessarily the optimal target state for the object of investigation. To avoid a one-sided assessment, maturity models are usually created as multidimensional assessments, i.e. several design fields of the object of investigation are examined (Becker et al., 2009a).

Maturity models exist in many different disciplines and focus on a wide variety of objects of investigation. Regarding to the object of investigation “company” in the context of Industry 4.0, there are a large number of different Industry 4.0 maturity models, which show different perspectives, focuses and approaches (Silva et al., 2021). A classification and critical analysis of different maturity models, the different requirements for maturity models depending on company size, and international differences have been discussed in detail in previous work (Häberer et al., 2017; Mittal et al., 2018; Seidel et al., 2020; Silva et al., 2021; Williams et al., 2019).

4 The Industrie 4.0 CheckUp by Fraunhofer IFF

The Fraunhofer IFF’s Industrie 4.0 CheckUp developed and described in (Seidel et al., 2020) and (Häberer et al., 2017) addresses companies facing challenges with respect to digitization. Comprehensively addressing all organizational units of a company, it integrates the analysis of the topics of Industry 4.0. The main argument for the Industrie 4.0 CheckUp is, that it will always be adapted to the individual framework conditions of the company, which is analyzed. Through an on-site analyses and interviews of staff and management, new approaches and desired solutions for the integration of Industrie 4.0 are co-developed with the workforce of the company. In combination with a bottom-up integrated improvement process, the top-down initiated management concept provides a holistic view of the company including the determination of the maturity level, a catalog of measures with various action alternatives including success forecasts as well as decision support with regard to investment projects. The aim of the Industrie 4.0 CheckUp is to assign the company to an Industry 4.0 integration level so that concrete and specifically tailored recommendations for action can be developed.

As described in (Seidel et al., 2020) and (Häberer et al., 2017), the Industrie 4.0 CheckUp is carried out in five steps that are individually adapted to the objective of the analysis and to the specifics and requirements of the company. The general procedure is shown in Fig. 1.

Within an initial target focusing workshop, the assessors carrying out CheckUp and the company representatives set objectives jointly and determine the scope of the maturity assessment. The workshop focuses on the transfer potential of current and company-relevant approaches and results from applied research and development projects to raise awareness of innovative solutions and form a common mind-set. After that, expert interviews will be conducted with selected company representatives in order to create a common data and information base that will later form the base of knowledge for the Industrie 4.0 CheckUp. In addition to the many years of experience of managers and employees, the planning competence and technology assessments of engineers will also be recorded. The involvement of value-creating employees has a positive effect in the later implementation phase, as it increases employee

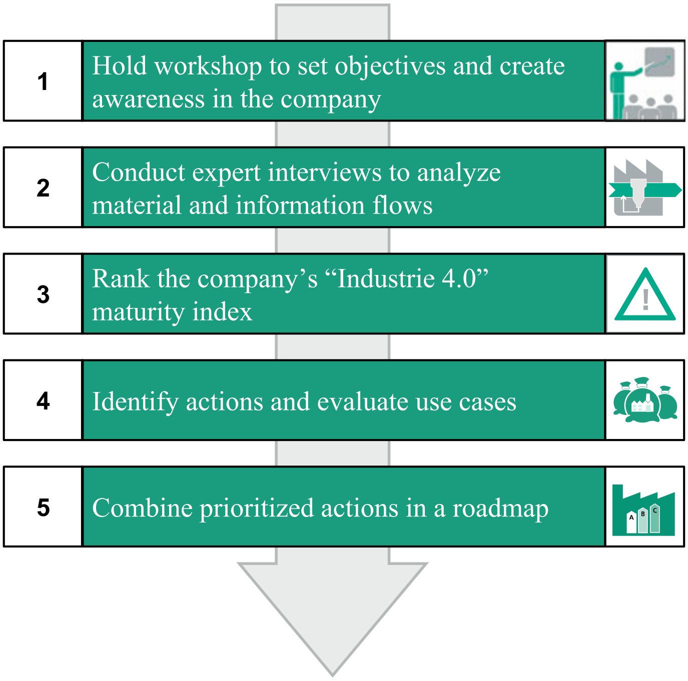

Fig. 1 The Fraunhofer IFF Industrie 4.0 CheckUp

acceptance in this phase. This participatory approach has proven itself, particularly in the implementation of digitization and automation solutions (Seidel et al., 2020).

The results of the company survey as well as the information gathered during the interviews will be recorded by the assessors in a standardized evaluation schema, or questionnaire. Based on the recorded criteria the current maturity of the company regarding to Industry 4.0 can be determined. The basis for this evaluation schema is formed by the functional units for Industry 4.0 as shown in Fig. 2. The Fraunhofer IFF developed a five stage Industry 4.0 maturity model with the following levels:

- Stage 1: Standards

  Partial automation and local solutions with execution of individual actions.

- Stage 2: Transparent Factory

  Networked manufacturing with integrated acquisition of production, quality and logistics data.

- Stage 3: Smart Factory

  Assistance systems and human–robot collaboration with linked product and process data.

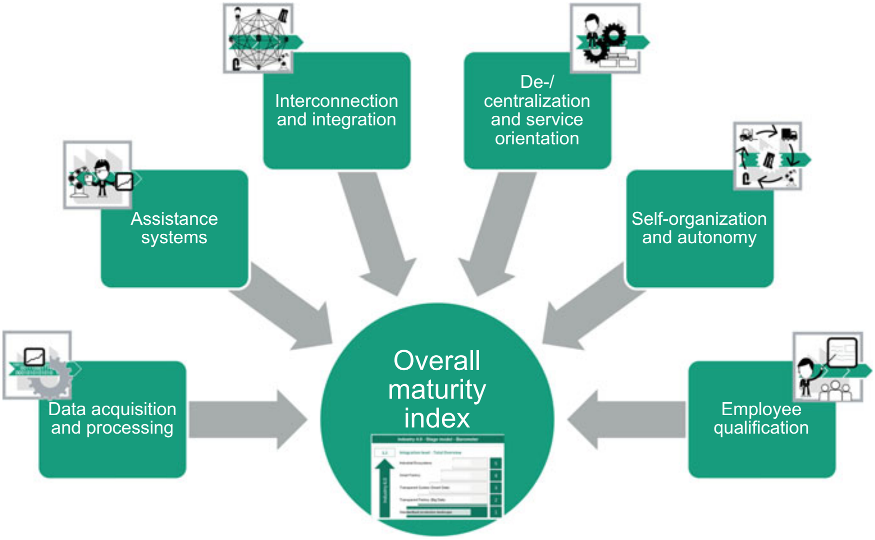

Fig. 2 Overall maturity index assessment derived from an evaluation of the individual functional units of Industry **4.0**

- Stage 4: Dark Factory

  Highly automated subsystems with self-learning control algorithms.

- Stage 5: Factory of the Future—Industrial Ecosystems

  Networked automated production and logistics systems.

The maturity of a company is determined with a specific point value attributed to each functional unit, based on set criteria for the evaluation. The aggregation of the point values over all functional units, determines the overall maturity level of the company.

In the next step, concrete measures are identified for each business unit and placed in the overall focus of the company. In the process, local optima are avoided through interdisciplinary and process-driven planning. Assessment models modified specifically for digitization are applied to evaluate derived measures qualitatively or quantitatively, depending on the companies wishes. Based on this evaluation, a strategy roadmap is developed that provides the company with a digitization strategy with possible migration paths and provides a concrete evolution path.

A modification of the Industrie 4.0 CheckUp is the Industrie 4.0 Quick CheckUp. This modification towards a self-assessment CheckUp was implemented based on the requirements of SMEs for maturity models identified in (Behrendt et al., 2017). The Industrie 4.0 Quick CheckUp serves as an initial self-assessment to identify potential for improvement in the company.

The methodology has been implemented in various manufacturing companies in different industries, from pharmaceuticals to manufacturing, to food, to textiles.

Moreover, the maturity assessment was used to support SME and large companies in countries such Germany, Spain, Kazakhstan, China and Thailand, proving its strength to also address challenges in different cultural contexts. An additional strong point of the underlying methodology is its adaptability so that it can be employed not just in different industries and cultural contexts but also in different thematic contexts. The maturity assessment methodology was developed for contexts such as Industry 4.0, Digital Engineering, the application of Artificial Intelligence (AI) (Schmidgal, 2022) or Workforce Management (Häberer, 2021). Through this methodology it is possible to customize support to a diverse range of SMEs.

The experience of implementing the methodology, shows maturity models to be a proven method for determining the positioning of companies, as well as supporting their strategic roadmap development. However, due to the different types of change, there is a need for continuous adaptation and expansion of the respective maturity assessment models. Furthermore, the objective of the respective maturity model must be questioned and adapted.

5 Provision of SME Directed Services by Digital Innovation Hubs

With the perspectives on digital maturity assessment it is possible to provide SME with continuous support to manage their responses and changes to continuous structural changes in their business environments. It can also be seen as a prerequisite for a further adoption of digital and automation technology. The diffusion of digital and automation technology, especially among SME, has been identified as a major roadblock to increased competitiveness in Germany (Wischmann et al., 2015). Therefore, it is necessary to establish a comprehensive support infrastructure, through which it is possible to provide SME with ongoing support in their digital transformation needs (Lassen & Waehrens, 2021).

The German government established a network of regional competence centers, specifically focusing on the support needs of SME in overcoming barriers to digital transformation. The program Mittelstand Digital currently funds twenty-six regional and thematic competence centers in Germany (Bundesministerium für Wirtschaft & Energie, 2021). These centers follow an ecosystem approach and are led by a consortium of regionally active partners, often from academia, research, technology transfer and/or business services. Through their local knowledge they have the capability to specifically address the needs and requirements of SME in their operational region and develop customized service portfolios to address these challenges. The Fraunhofer IFF is an integral and driving actor in the regional Mittelstand 4.0 Kompetenzzentrum for Saxony Anhalt (Experimentelle Fabrik & ZPVP GmbH—Zentrum für Produkt-, Verfahrens- & Prozessinnovation GmbH, 2021) and the European Digital Innovation Hub Initative (Fraunhofer Institute for Factory Operation &

Automation IFF, 2021; Politecnico di Milano, 2021), bringing in its skills to support SME transformation through maturity assessments.

In collaboration with the region's transfer centers, especially the Mittelstand 4.0 Competence Center, the Fraunhofer IFF researchers have analyzed and will continue to analyze the specific requirements of regional companies, especially SMEs, take them into account in the methodology described above and incorporate them in continuous further development. In particular, it has been determined that the phenomenon of the "extended workbench"—i.e. companies' dependence on higher-level organizational units and/or customers—is a problem for SMEs. Furthermore, there is a need for business model innovation to enable unique selling points in processes and products of SMEs in order to increase technological sovereignty.

In the context of the Industrie 4.0 CheckUp, this means analyzing data acquisition and data processing, identifying potential for improvement and taking measures to unlock the potential. In this way, unique selling points (USPs) of SMEs are strengthened. The method also offers the opportunity to take up the opportunities of the transformation of the value creation systems with the companies and to participate in it. This explicitly means examining one's own necessary adaptation of company processes for the production of suitable products and product components, for example for the mobility and energy transition (battery systems, hydrogen systems, etc.) and thus opening up new supplier networks. The Industrie 4.0 CheckUp shows how digitalization technologies can help to reposition the company in the context of modernization. It identifies the need for adaptation in the production system, sales strategies and the necessary qualification of personnel. In addition, the roadmapping will explicitly show the extent to which suitable funding options can be used within the framework of transformation strategies of politics (calls for funding) and financing models (discussion with banks).

6 Conclusion

Eastern Germany went through significant structural change during the years after the German reunification, leading to mass unemployment and a significant shift in economic activities. Focusing on Saxony-Anhalt, the federal state was able to build on its history in engineering and process industries and establish a regional economy built on these industries. With the necessary shift to make industries and the economy as a whole more resilient and sustainable, companies in Saxony-Anhalt face a renewed structural change. As companies in the region are less knowledge intensive/less research intensive, the necessary change is especially difficult for them. Maturity assessments are a proven method to help companies map their way and steer their transformational activities. These assessments provide companies with a realistic evaluation of their current state within different dimensions. The Industrie 4.0 CheckUp developed by the Fraunhofer IFF and used in practice shows in the form of a maturity assessment how digitization technologies can help to reposition themselves in the context of modernization. The Industrie 4.0 CheckUp identifies the need for adaptation in the production system, distribution strategies and the necessary qualification of personnel and supports individual roadmapping. In combination with a comprehensive evaluation and modelling of companies' underlying business models, considering specifically digital dimensions, such as new forms of subscription business models, SME will be put in a position to take into account current and emerging factors in their business environment and actively and continuously pursue transformational changes to ensure long-term competitiveness.

Here, an SME-oriented support infrastructure built on e.g. on the German Mittelstand Digital Centers or the European Digital Innovation Hub initiative can provide valuable services to assist companies in preparing and carrying out these transformational activities.

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How to Support the Transformation Towards Smart Production by Applying the Digital Factory Mapping: A Case Study

Michele Colli

Abstract The chapter presents and discusses the application of the Digital Factory Mapping approach. This supports production companies in the identification of digital innovation projects to capture performance improvement opportunities and in the quantification of their impact. The approach (introduced in Colli et al., 2022) takes advantage of a synergy between Lean and the continuous improvement philosophy and the Digital Maturity concept. This chapter discusses the application of the Digital Factory Mapping in a case company and reflects on its aftermath, by investigating the translation of the Digital Factory Mapping outcome into actual projects implemented in the company. The chapter ends with reflections and practical recommendations related to the adoption of the Digital Factory Mapping.

Keywords Industry 4.0 · Digital innovation · Production · Continuous improvement

1 Introduction

Although digital innovation became an integrating part of most (if not all) production companies' strategies, research highlights how the journey towards Industry 4.0 and the digitalization of factory and supply chain operations remains a significant challenge. The McKinsey Global Survey investigating digital transformations highlighted how in 2018 only 16% of the interviewed companies managed to translate digital innovation into sustained performance improvement (De la Boutetière et al., 2018). One of the fundamental challenges for manufacturing companies is the ability to formulate an individual roadmap outlining the "right" digital innovation projects (De Carolis et al., 2017). The presence of a clear digital transformation strategy clarifying the goals to be achieved and how to achieve them is, in fact, one of the key enablers for succeeding in digital innovation (Büyüközkan & Göçer, 2018; Hess et al., 2016; Matt et al., 2015). Currently, digital maturity assessments

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are used to support companies doing so. These are built on the maturity concept, which sees an evolution path as the progression of steps characterized by cumulative capabilities. The evaluation of a company's "digital maturity" and the identification of the digital capabilities that need to be built to increase it make possible to formulate a portfolio of digital innovation projects (Colli et al., 2019). Nevertheless, in their extensive research concerning the barriers for succeeding in digital innovation projects, Schmitz et al. (2019) identified two main families of challenges companies are still facing: the lack of competences to execute such projects and, most predominantly, the absence of clear business cases. In fact, the lack of a quantitative understanding of the potentials of digital innovation projects makes it impossible to assess their business case and to allocate funding to perform them. This hits small and medium-sized companies particularly, as they generally have a narrower spectrum of internal competences as well as fewer resources available to dedicate to innovation projects (Mittal et al., 2018).The Digital Factory Mapping is addressing this issue, differentiating itself from the existing digital maturity assessments due its additional focus on the quantification of the potentials of such projects.

This chapter is proposing an in-depth view of the application of the Digital Factory Mapping (already introduced in Colli et al., 2021) in a case company – out of the five where the approach has been applied - and a reflection of its aftermath, reviewing the applicability and effectiveness of the suggested digital innovation projects once implemented by the case company.

2 The Digital Factory Mapping

The Digital Factory Mapping approach, built on top of the Value Stream Mapping 4.0 concept proposed by Meudt et al. (2017) and on the assessment tool from Nygaard et al. (2020), aims at providing production companies with enough knowledge to be able to formulate a digital transformation strategy. Following the perspective provided by Hess et al. (2016), this approach maintains a business-centric orientation: instead of focusing on the implementation of specific technologies, its starting point lies in the identification of the business potentials that can be realized. Because of that, the Digital Factory Mapping structures (1) the identification of the most beneficial production improvement opportunities that a company can capitalize on through the implementation of digital solutions, (2) the quantification of the impacts of such opportunities on production performance, in order for the company to be able to formulate a business case for digital innovation projects and (3) the formulation of specific digital innovation projects to capture such opportunities.

To do so, the Digital Factory Mapping takes advantage of a synergy between the Lean philosophy and the Digital Maturity concept. The approach consists of a "physical analysis", performed on top of a material flow mapping, and a "digital analysis", performed on top of an information flow mapping (Fig. 1).

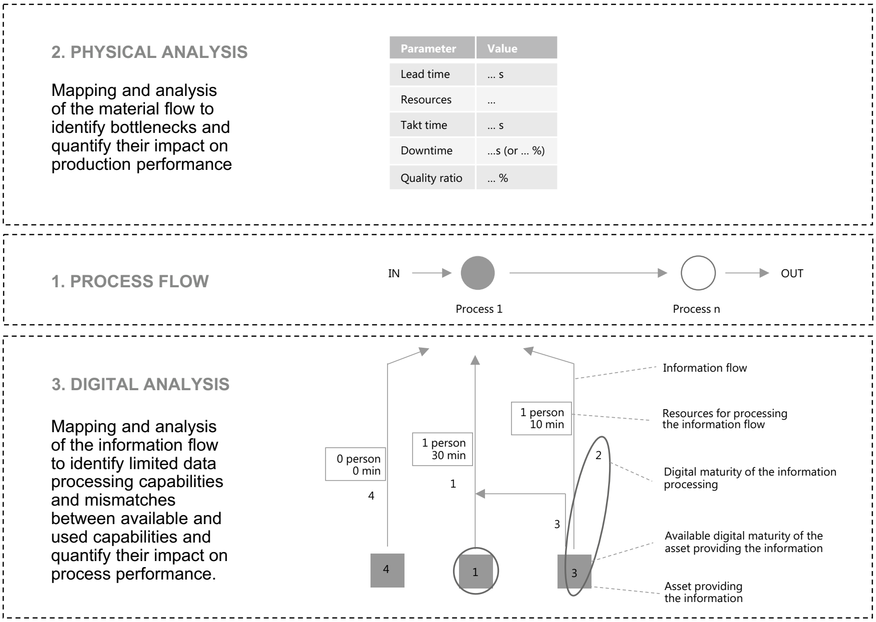

Fig. 1 The digital factory mapping approach (inspired by Colli et al., 2021)

The physical analysis is the analysis performed on the material flow mapping and is operationalized through the performance of a Value Stream Mapping. Production operations are mapped along with their performance indicators. which are then analyzed to make sure that digital innovation initiatives are focused on removing waste and non-value adding activities across bottlenecks—hence, according to the "Law of Bottlenecks" with the potential of generating an overall performance improvement—and to quantify their impact of such bottlenecks on the overall production performance (Rother & Shook, 1999).

The digital analysis is the analysis performed on the information flow mapping. The information flows that are supporting the execution of the mapped operations are mapped along with (1) the assets that are generating the information—whether human or machines—and their digital maturity as well as the resources spent to process such information (human/machines and time) and their digital maturity. The five levels composing the adopted digital maturity scale (from Colli et al., 2021) are:

- 0—*None*: There is no data
- 1—*Basic*: data is collected and it has to be actively searched in case of need
- 2—*Transparent*: data is available according to processes' needs
- 3—*Aware*: data is analyzed to obtain insights for further supporting processes
- 4—*Autonomous*: data is automatically processed to support processes.

The analysis is used to identify and quantify the improvement potentials that can be captured by taking advantage of digital innovation to reduce the resources (time and people) spent for processing the information flow.

The operationalization of the Digital Factory Mapping consists of four workshops, facilitated by two external consultants with experience in the operations management and Industry 4.0 domains and involving, from the case company side, Industry 4.0 and continuous improvement responsible as well as domain-specialists from the mapped processes. The first workshop concerns the provision of an “Industry 4.0 awareness seminar” and aims at inspiring the company representatives with best practices and exemplary cases related to the application of digital technologies in the industry. The second and third workshops concern the actual mapping and analysis of a company’s operations both from a material flow and an information flow perspective (physical analysis and digital analysis). The fourth workshop concerns the provision of the analyses’ outcome, including information regarding the identified operational performance improvement opportunities, the quantification of the related potentials and the formulation of specific digital innovation projects to capture them.

3 Applying the Digital Factory Mapping: A Case Study

3.1 Case Company

The case company is a Danish medium-size manufacturer of high-end furniture. In 2020, after being acquired by a large multinational company, the company experienced a 70% increase in its sales: this generated the need for increasing the production output significantly while maintaining the high-quality standards characterizing its finished products. This sparked the interest of the management in the Industry 4.0 agenda and in the adoption of digital technologies in production to improve its efficiency and enhance its output. As a consequence, the company (represented by the production manager and the change agent) went through a Digital Factory Mapping.

3.2 The Digital Factory Mapping

Workshop 1. The first workshop consisted in providing an “Industry 4.0 awareness seminar”, in presenting the Digital Factory Mapping approach and assigning homework. At first, through the “Industry 4.0 awareness seminar”, the Industry 4.0 agenda, its origin, reasons and enabling technologies as well as a series of best practices adopted to integrate such technologies and exemplary application cases have been presented. This sparked the curiosity of the company representatives, generating questions and discussions about the exemplary application cases and the related potentials, as well as the scope and objectives of the mapping in the case company.

The following presentation of the Digital Factory Mapping clarified the reasons that catalyzed the development of the tool, the rationale behind the tool, the operational aspects concerning the application of the tool (e.g. activities, timeframe, needed data and needed resources) and its deliverables. The presentation of the homework consisted in instructing the company on how to perform a Value Stream Mapping of its production processes focusing on a particularly representative product and was provided with a template indicating (and explaining) the performance parameters to map for each production process according to the scope.

Workshop 2. The second workshop consisted in performing the physical analysis (Fig. 1). At first, the company representatives presented their material flow mapping (i.e. Value Stream Mapping). Its analysis was then performed (Fig. 2) and highlighted three main criticalities:

- Unbalanced flow: Takt times from processes 1 and 2 (0.9 min) were between 200 and 300% compared to the takt times from the following processes. Processes 1 and 2 represented the production flow bottleneck and a potential capacity increase up to 2–300%.
- High level of downtime: Process 2 was characterized by a high level of downtime (i.e. ca. 19%), which was explained by the company as caused by the need for continuous manual loading and unloading during the process.
- Low quality ratio: The quality ratio in process 7 was 83%. By discussing it with the company, this was explained as caused by the equipment age and reduced precision. Currently, a manual quality control is performed once every 10 or 20 items; an increase of frequency would be beneficial—yet expensive—due to the low quality performance of process 7.

After the physical analysis, homework had been assigned to the company representatives. The homework consisted of mapping the information flows supporting the execution of each one of the mapped production processes. The company representatives were instructed to map the assets providing the information required by the process (whether an operator or a machine) and collecting data about the resources (people and time) spent to process this information for each one of the processes. In addition to that, the digital maturity level (i.e. the data processing capabilities) characterizing the assets providing the information and the user of the information had to be assessed according to a digital maturity model.

Workshop 3. The third workshop consisted in performing the digital analysis (Fig. 1). At first, the company representatives presented their information flow mapping, built on top of the material flow mapping that had been previously analyzed. The analysis of the information flow mapping was then performed. The presentation and the discussions around the information flow mapping highlighted that, although the company had an ERP system in place, order information and machine setup specifications were retrieved manually from the ERP system, printed and manually shared for all production processes that are performed (or supported) by an operator

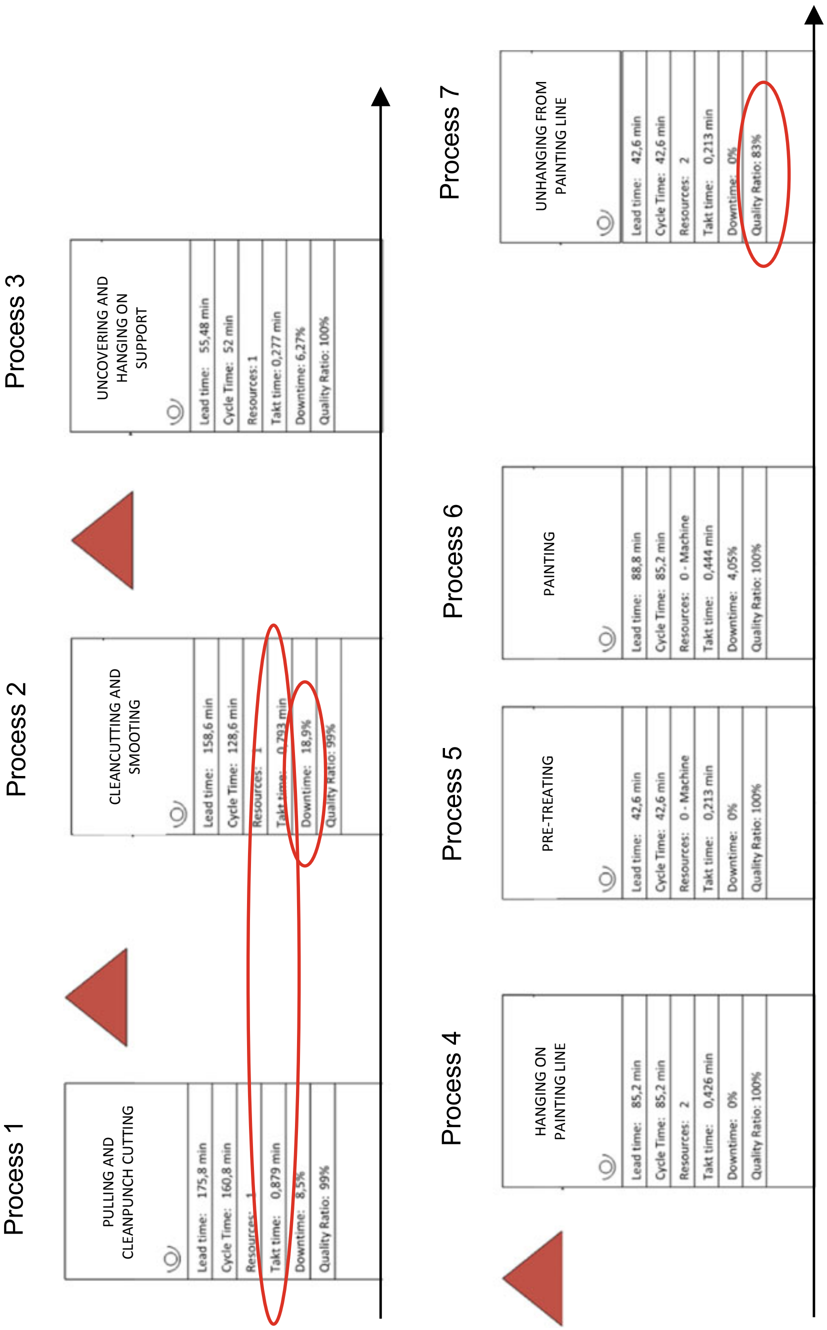

Fig. 2 Physical analysis

(i.e. processes 1, 2, 3, 4 and 7). In the same way, for the same processes, information concerning the quantity and the quality of the produced items were registered manually on the printed paper and copied in the ERP system afterwards (Fig. 3).

If for processes 1, 2 (the bottlenecks) and 3 data registration was automatic, for processes 4 and 7 this was missing (i.e. low digital maturity level): the issue for these processes was not taking full advantage of the available data processing capabilities, which were used in the first three processes (i.e. mismatch between available and used digital maturity level) (Fig. 3).

After the third workshop, the external consultants prepared a report collecting all the findings from the analysis and formulated a selection of project proposal cards. These outlined specific digital innovation projects, based on current state-of-the-art applications and best practices, addressing the most significant issues identified through the analyses, quantifying the related improvement potentials.

Workshop 4. The fourth workshop consisted of a debriefing session. Here, the external consultants presented to the company representatives the report summarizing the outcome of the physical analysis and of the digital analysis as well as the project proposal cards indicating the digital innovation projects suggested to capture the identified improvement potentials. The suggested projects concerned:

- Capacity increase: introduction of additional machines or humans to support machine processing as well as loading and unloading activities, increasing the capacity of processes 1 and 2 (i.e. bottlenecks), reaching a takt time of 0.45 min. This would be make it possible to double the capacity of the whole production line.
- Automatic quality control: automated quality control system to ensure a high-quality output after process 7 (suffering with the lowest quality ratio in the company's production) and enable the increase of quality inspections (i.e. from one every 10–20 items to one for each produced item) without increasing the takt time of the process. This would target a potential reduction of manual work for 42.6 min per batch of products.
- Paperless production: adoption of order identification tags (based on QR/barcodes/RFID/etc.) connected to the ERP system and following the products along the production process. Once scanned by the operator at the beginning of a process, these would automatically provide it with order and machine setup information eliminating the need (and the time required) for manually retrieving such information and for printing them. Once scanned by the operator at the end of a process, data concerning the quantity and quality of the produced products would be automatically registered in the ERP system along with the timestamp, eliminating the need (and the time required) for manually registering such information on the printed paper first and in the ERP system afterwards. This would target a reduction of manual labor of about 25 min per batch of products (a share of the 352.1 min mapped, as these referred also to the loading and unloading processes) as well as a 3% circa overall production performance increase (i.e. circa 5 min reduction of the 160.5 min cycle time).

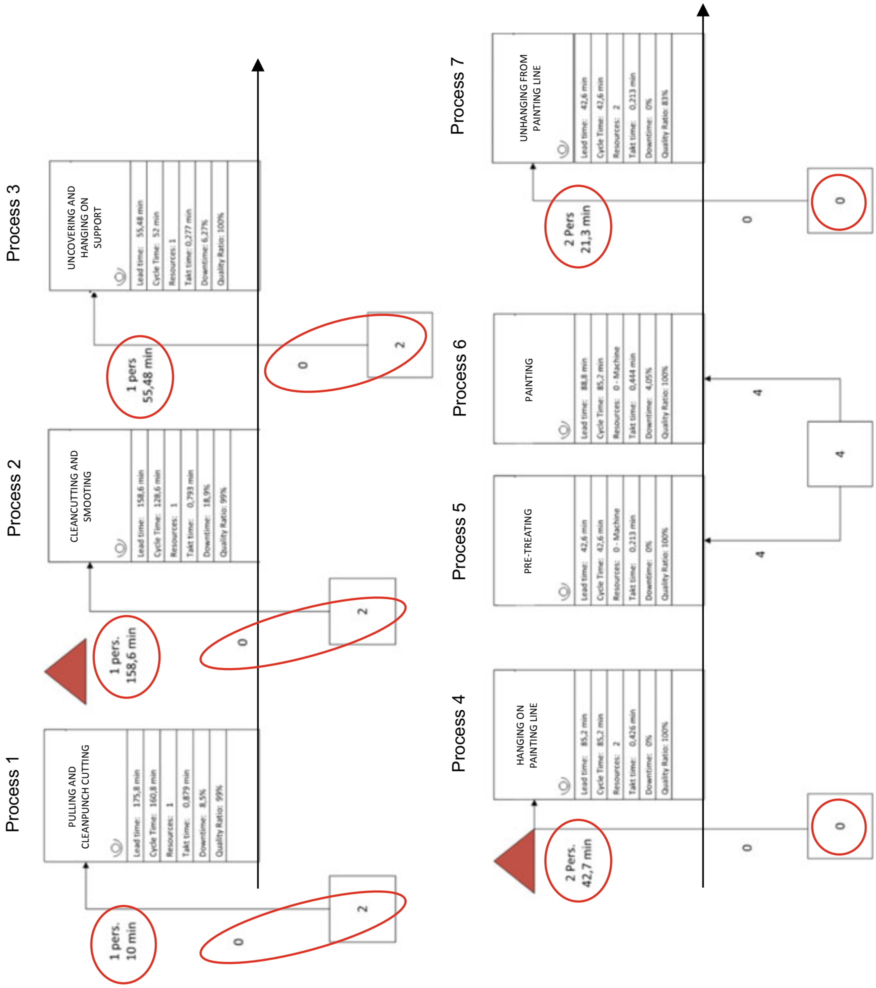

Fig. 3 Digital analysis

- Preventive maintenance: adoption of a preventive maintenance policy (time-based first, condition-based later) to address the low quality ratio of process 7 caused by the recurrent loss of precision of the equipment. This would address a potential quality ratio improvement of 17% and the related potential increase of local capacity, due to the avoidance of waste and reworks.

3.3 The Implementation of the Recommended Digital Innovation Projects

After the conclusion of the Digital Factory Mapping, the case company formulated a roadmap structured around the suggested digital innovation projects, and started working on their implementation in the form of pilot projects. The pilot projects that have been performed after the Digital Factory Mapping concern the introduction and testing, in a small scale, of:

- Capacity increase: collaborative robots to support the loading and unloading of materials in processes 1 and 2 (bottlenecks), partially automating it. This is reducing the manual work required in the processes as well as their lead time, leading to an overall production performance improvement.
- Paperless production: hand barcode scanners and Microsoft Power BI live data reporting solution to provide operators across production with immediate access to the needed information and to automatically register information regarding the produced items and the performance of each production process. This is reducing the lead time of processes 1 and 2 (bottlenecks) as well as of processes 3, 4 and 7.
- Automatic quality control: a quality control solution based on a artificial intelligence-powered vision system to automatically verify the quality of each produced item once this is positioned in front of the cameras. This would ensure a high-quality output after process 7. The solution is being refined to enable the scaling of quality inspections, decoupling it from the increase of manual labor cost as well as reduce the lead time of process 7.

While for the first two pilot projects the case company had been looking for off-the-shelf solutions, the quality control solution implemented in the third pilot project has been developed in a collaboration with a Danish research and technology organization. The reasons behind the collaboration lied in the innovativeness of the technology adopted (and, hence, in the low maturity of the field) and in the lack of internal knowledge, necessary for identifying the most appropriate technologies and technology suppliers for providing such solution. Due to the success of these pilot projects, the case company is investigating the possibility to scale them and starting a new pilot project concerning the transition from corrective to preventive maintenance.

4 Reflections, Implications and Practical Recommendations

The digital innovation projects suggested after the Digital Factory Mapping have been successfully implemented in the form of pilot projects and their scaling is being investigated. This is a good indicator of the applicability and effectiveness of the Digital Factory Mapping outcome. By reflecting on the core mechanisms that led to it in the presented case study, and which are expected to be generalizable to other production companies, it is possible to identify four:

- *Strategic scoping*: it was paramount to define which operations to map (i.e. in this case the operations on the production floor). This had been facilitated by the “Industry 4.0 awareness seminar” during workshop 1 which, by providing information concerning exemplary cases, inspired the company representatives and supported them in scoping the mapping (limiting its complexity) according to their core needs, linked to the company’s overall strategy (i.e. in this case increasing production output due to a 70% increase of sales)
- *Effective data collection*: it was beneficial to have the right data collected by the company right when they were needed for performing the analyses. This was facilitated by a clear explanation of the Digital Factory Mapping and of its mechanisms during workshop 1 as well as of the assigned homework. These provided the companies with the necessary information for gathering the needed data from the right people, providing the necessary foundation for efficient and effective physical and digital analyses.
- *Structured data analysis*: it was beneficial to have a clear model to be followed to analyze the collected data. For the physical analysis, this was the Value Stream Mapping. For the digital analysis, this consisted in adopting the digital maturity concept and of the provided digital maturity model, as well as with the adoption of the approach described by Colli et al. (2021). This provided the foundation for a transparent and replicable analysis as well as a good overview (for the external consultants and for the company itself) of how the analyzed company is operating.
- *Domain experts*: the capability to outline the right digital innovation projects was dependent on the knowledge from the external consultants and to their ongoing discussion with the company representatives, providing information about the company’s strategy and limitations. Because of that, the selection of the digital innovation projects did benefit from the availability of experts in the operations management and Industry 4.0 domain and from an ongoing discussion with company representatives.

Nevertheless, several issues might arise depending on the context where a Digital Factory Mapping is performed. For instance, the mapped company may not have the knowledge or resources to collect data about its material and information flows. In this case, the data collection might be performed by the external consultants, as long as companies prepare and make the right people available to them. In addition to that, a relevant aspect to be considered for the implementation of the suggested digital innovation projects is the possibility to collaborate with research and technology organizations, which can both help in technology solution development as well as in the selection of the most appropriate suppliers. Ultimately, it is important to remark how this approach focuses on enabling continuous improvement through digital innovation, but it is not providing guidance for identifying and achieving disruptive changes—such as the complete removal of some production processes through the introduction of new manufacturing technologies.

5 Conclusions

This chapter presented and discussed the application of the Digital Factory Mapping approach (Colli et al., 2021), developed and adopted to support production companies in identifying digital innovation projects for capturing their performance improvement opportunities and in quantifying their potentials. This case study provided a tangible and in-depth example of how the approach, built on top of the work from Meudt et al. (2017) and Nygaard et al. (2020), is delivering such results by practically linking the Lean philosophy with the Digital Maturity concept. Moreover, having a longitudinal perspective on the investigated case company, it had been possible to validate the capability of the approach in facilitating the identification of both applicable and effective digital innovation projects. Nevertheless, the in-depth study of the application of the Digital Factory Mapping enabled the recognition of four key mechanisms for the successful adoption of the approach and which are considered to be generalizable for all the production companies that have to go through a Digital Factory Mapping.

Further research involving the application of the Digital Factory Mapping is however needed to test the generalizability of the approach and of such mechanisms in companies which do not have the possibility to perform the data collection or to participate in the data analyses processes. In addition to that, the application of the Digital Factory Mapping on a larger sample and the longitudinal study of such sample is needed to verify if the approach is positively affecting the overall digital innovation success ratio, improving the 16% identified by De la Boutetière et al. in 2018.

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Differences Between Small and Medium Sized Companies When Realizing Smart Production – Experiences from Northwest Smart Production Program in Denmark

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Abstract The challenges of utilizing new digitalization and automation opportunities are significantly different in smaller companies compared to larger companies. Most of the literature and experiences relate to larger companies, and approaches for small companies have yet to emerge. Larger companies are internally self-driven in their approaches, but smaller companies need support from outside sources. This chapter summarizes initial experiences of how smaller companies can be supported. The empirical background is a municipal business support program Northwest Smart Production Program (NVSP), which aims to support SMEs in exploiting development opportunities in relation to smart production. Methodologically, the chapter is based on an action research approach, where the development of the individual company has been the aim of the NVSP program. Given the exploratory nature of the chapter, the research results are documented with qualitative observations and supplemented with case studies. The NVSP program has been focusing on both medium sized and smaller companies; however, this chapter will focus specifically on the challenges that have been experienced in the smaller companies.

Keywords Smart production implementation · Small and micro enterprises

1 Introduction

Global competition in general and the demand for increased flexible manufacturing force manufacturing companies to develop and change their manufacturing setup at an ever-faster pace. The changes in manufacturing setup typically include a higher degree of automation and a higher degree of digitalization. Various conceptual frameworks inform and inspire this development. Most importantly, the concept of Industry 4.0 (Chen et al., 2017) and the concepts of Smart Factory, Smart Manufacturing, and

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Smart Production (Kang et al., 2016) provide inspiration for the development of the next generation of production systems.

Implementation of these concepts differs from that of existing technologies. Increasing complexity of emerging technologies generates uncertainty about the needed organizational capabilities and the new technology potentialities as well as adequate strategies. Different timing perspectives of the solution benefits forces companies to prioritize between investments and to understand these investments as highly interrelated (Sjödin et al., 2018). Furthermore, the automation and digitalization opportunities are characterized by being implemented and supplied by increasingly more specialized suppliers.

An important aspect of the perceived increasing complexity is the higher degree of critical interrelationships between the solution elements and the various elements in both the production set-up and the broader organizational set-up. These critical interrelationships often extend also to customers and suppliers.

Larger manufacturing companies can cope with the challenges that arise from the increased complexity by employing more internal specialists. The small and medium-sized (SME) companies experience an urgent need to deal with these challenges in different ways. Methods of how to deal with these challenges are still under development and there are not yet convincing examples of consolidated successful approaches.

This chapter deals with the development of such new methods for the smaller companies in the SME segment to deal with the challenges associated with the successful implementation of automation, Industry 4.0 and digitization opportunities.

2 The SME Challenges

The differences in potential benefits compared to conventional automation solutions and the increased specialization among solution providers pose the largest challenges to the SME Manufacturing companies (Hall et al., 2009). This leads to a high degree of uncertainties in respect to aligning the new solution opportunities with the current market and customer strategies. In many cases the strategies are not even formally expressed but exist mainly as tacit knowledge in the mind of the limited numbers of decision makers within the organization.

The SMEs are in general challenged by the fact that among the employees there are few people with detailed knowledge about the new opportunities that new smart production technologies can offer. For the smaller SMEs there is often only one critical decision maker (in many cases the owner).

To cope with these challenges new methods and approaches are needed. Such approaches are not yet in operation; therefore, the consequences are decreasing efficiency in the implementation process which leads to limiting competitiveness of the manufacturing SMEs.

In addition, the potential solution providers are also experiencing problems that relate to the uncertainties among the manufacturing SMEs. The solution providers experience problems when trying to communicate the potential solution benefits and when trying the specify the interrelations between the many specialized solution components. The consequences are longer decision processes (or no decision) and more complicated sales/specification processes.

The Danish Manufacturing Business Structure

The Danish and European manufacturing business structure is characterized by consisting of many SMEs. In numbers the SMEs count 99.8% of all the companies and employ 66.6% of all company employed persons in EU as a whole (Eurostat, 2022). Eurostat divides SMEs into three categories, Micro (1–9 employees), Small (10–49 employees), and Medium-Sized (50–249 employees). Large companies are one category with 250 or more employees. The number of SMEs in Denmark in 2016 was estimated to be 227,102 companies and the number of large companies was estimated at 727 (European Commission, 2018). Most of the SMEs fall into the category "Small" or "Micro". These categories count for 98.1% of the Danish SMEs.

Companies are not geographically evenly distributed. This creates some geographic areas, typically called "outer areas", with a higher relative percentage of small and micro businesses. The same phenomenon is known throughout Europe.

The roles in the Danish business support system are divided between the Danish state and the municipalities. Geographical differences, as described above, means that the challenges differ significantly between municipalities. The municipalities are dependent on the number and the character of jobs to maintain and increase the attractivity of the area. And not least, the companies and their employees are taxpayers who financially enable the municipalities to maintain their level of service (schools, kindergartens, elderly care, etc.).

The uneven distribution of larger and medium-sized manufacturing companies challenges the Municipalities, especially in the "outer areas", in respect to supporting the local companies to improve competiveness and stimulate growth. To support the municipalities in dealing with these challenges so-called "Business Houses" have been established. These Business Houses develop their own services and at the same time, the business houses form the link between local offers and state offers in the business support system.

One of these municipality initiatives is the Northwest Smart Production Program (NVSP) that have been developed by two municipalities in the northern part of Denmark. This is a typical "outer area" of Denmark with challenges as described above.

3 Northwest Smart Production Program (NVSP)

The Northwest Smart Production Program (NVSP) was initiated by two Danish municipalities (Vesthimmerland and Jammerbugt Municipality) in 2017 and will continue until August 2022. Financially, the project is supported by the EU Regional

Fund, The Danish Business Promotion Board, and the Ministry of Business Affairs' Outer Area Pool.

The executing partners are Foundation Autonomous (a privately owned local consultancy company) and Department of Materials and Production, Aalborg University (AAU). Foundation Autonomous (FA) has strong competencies in digitalization and AAU has strong competencies in product/production development and automation. The local Business Houses (BH) and Foundation Autonomous take care of the needed administrative tasks and therefore keep the bureaucratic work of participants to a minimum.

The goal has been to include 45 SMEs in a structured development process that focusses on improving their competitiveness by developing the degree of automation and digitalization in the participating companies. Of the 45 SMEs the 35 falls into the category SM (Small and Micro sized).

The goal has been to make an outreach innovation effort that is individually tailored to each participating company. It has been a crucial demand that the activities during the development project must take place at the company. This is primarily due to the critical reliance of very few decision makers in the companies. These decision makers are typically responsible for both development and operation and can therefore hardly not be away from the company.

Selection of the participating SMEs is done by the local municipality Business House. This selection is done based on the close local knowledge that the Business Houses possess and includes a first-hand assessment of the company's development ability and development potential.

4 NVSP Approach

In relation to the interaction with the SMEs, a method has been chosen which can metaphorically be described as "building the bridge while walking on it". The first engagement is the only part that is formalized. BH identifies the potential SMEs and take a first meeting where FA participates. If there is a match between the perceived development potential and the ability and willingness of the SME to engage in a development project the next phase is initiated.

The next phase is a so-called "Gemba Walk" where FA and AAU participate. Gemba Walk is an essential part of the Lean management philosophy. In the NVSP project the Gemba Walk has been adapted to focus particularly on potential smart production and digitalization opportunities or challenges in respect to operations or development. The purpose of the Gemba Walk is to allow the project participants to observe the actual work processes, engage with employees, gain knowledge about the work processes, and explore opportunities for development. Typically, the Gemba Walk and the following discussion have a total duration of 3–4 h.

After the Gemba Walk a Design Brief is created to summarize the observations and the initial development proposals. The Design Brief specifies broad objectives and potential directions to go but generally does not specify a precise destination or a specific way of how to proceed.

If the management of the SME agrees on the Design Brief the first iteration of the development process can be initiated. The iterations are kept as focused and as short as possible. This is to ensure that the pace of the ongoing project match the possible effort of the involved people in the SME. New iterations with different or extended focus can be initiated on a flexible basis. Many times, the projects were put on temporary hold or discontinued for various reasons (finances, large orders, missing orders, staff changes, etc.). In one of the SMEs as many as 48 iterations were initiated during the project period.

The engagement in the 45 SMEs has demonstrated that there are significant differences between the medium sized and the small-micro sized companies. The most important differences are summarized in Table 1.

The significant differences between engaging with medium sized and small and micro sized companies (SM) indicate that rather different methodologies are needed.

Table 1 Summary of the observations from engaging with 45 SMEs

Topic	Larger and more matured medium-sized companies	Small and micro sized companies
Background of critical decision makers	Management has formal management training on a university level	Management has vocational training background and no formal management training
Strategy formulation	Formal written strategy approved by the board—yearly updates	Unformal strategy—the formal part is the budget approved by the bank
Product-production development	Separate organizational functions focus on product and production development	Integrated product and production development is handled by one or a few people
Organizational reporting structures	Formal internal reporting structures	Informal reporting structure
Financial function	Specialized financial organizational function	Financial function is limited to bookkeeping
Board Function	Formal board with external professional members	Board typically consists of family supplemented with an external auditor or lawyer
Initiation of development projects	Formal decisions based on budgets and calculation of financial returns and risks	Ad hoc decisions made by the management/owner
Execution of development projects	Development projects are staffed, and timelines approved and followed up upon from management side	Development projects are often put on hold due to limited resources
Networking	Management engages in formal networking activities in various industry association	Networking is limited to contacts with customers and suppliers

In the following the engagement with two SM companies are summarized in short case descriptions.

NVSP Case A

Case A is a small startup manufacturing company that serve as supplier to several large companies within the energy sector. The case is characterized as a pre-digitalization project that focus on creating the best possible condition for utilizing the digital opportunities during future growth and development (Table 2).

During the project there has been weekly meetings between the company and the NVSP facilitators. At the start of the project the owner was likely to respond to the growing sales just by buying new machines. The iterative process has clarified that it has been highly beneficial to get a sufficient overview of the customer and product data before machine investments. Yet, it is not clarified where the real bottlenecks are in the production. This has postponed investments in new machinery until a clear overview and a following formal strategy has been developed.

During the project the company has grown significantly. Both in respect to turnover (1900% compared to 2018) and in respect to number of employees (3–13). The more transparent data structure has enabled more people to participate in operational decision making. In particular, the mapping of the routings and the associated pre-calculation system has made it possible for more people than the owner to accept customer orders and to issue production orders.

NVSP Case B

Case B is a small metalworking company that focuses on small production series of sheet metal components. The main manufacturing processes are laser cutting and edging machining (Table 3).

Initially the owner questioned the benefits of having a long-term vision or strategy. However, the NVSP facilitator proposed a simplified vision that ended up being a powerful driver for a continuing discussion about the potential future development. The new vision especially supported the involvement of some of the younger employees who saw opportunities in using more automated machines. Thereby, the simple vision began to be consolidated and new customers were attracted.

5 Discussion and Methodology Reflections in Hindsight

The two cases illustrate the diversity of the projects running as part of the NVSP project. Case A illustrates fast a growing startup companies that need to focus on the infrastructure and the fundamental data structure to be positioned for growth and full utilization of the digital opportunities. Case B illustrates a small manufacturing company with a stable market that is not aware of the growth potential. They need to engage in a discussion about the future automation vision and to be supported in a balanced implementation process.

Table 2 Summary of the NVSP activities in Case A

Topic	Case activities
Company data	Established in 2017 as a limited liability company, board consisting of owner and family
Facilities	Rented manufacturing and administration facilities
Employees	2017: 2; 2018: 3; 2019: 6; 2020: 9; 2021:13
Turnover in percent	2018:100%; 2019: 199%; 2020: 1122%; 2021: 1900% (expected)
NVSP activities	*Brief after Gemba Walk*: Significant growth experienced in 2020; No clear overview of product portfolio; No clear overview of customer portfolio; No pre-calculation system in place; Manufacturing equipment is a mixture between standard machines and self-made machinery; No automation in production; No administrative systems (but a simple accounting system); No formalized strategy; Owner serves as sales responsible and production manager; Most decision must be taken by owner or approved by owner before execution *Iteration 1*: A short term vision is defined to focus on creating an overview of the product and customer portfolio. The goal is to develop a data structure that can be implemented in an ERP system (planned duration 2 months) *Outcome of iteration 1*: By hiring a parttime student worker it is possible to map the products sold and relate this to customers. The seasonality of the sales is also documented. The results are presented by simple spreadsheet prototypes *Iteration 2*: The vision is expanded to include data for a pre-calculation system and to generate an overview of the raw material stocks. The goal is to implement this in the future ERP system. Scanning for a suitable ERP system must start (duration 4 months) *Outcome of iteration 2*: To make a pre-calculation system it is necessary to map the material flow and the order flow. These analyses form the foundation for the routings that is needed for the future ERP system. The pre-calculation system is prototyped in a spreadsheet program and is verified by the owner. Mapping the raw material stocks initiate a search for new suppliers. It has been decided to implement a cloud-based ERP system *Iteration 3*: With the data foundation in place the implementation of the ERP system can start. The vision is maintained and the confidence that it can be realized is strengthened (duration 6 months) *Outcome of iteration 3*: This iteration is still ongoing, but the tests has shown that the data structure prototyped in spreadsheet programs can be implemented *Iteration X*: The project is still ongoing. With the administrative data flow in place the focus will change towards developing an integrated production planning concept. This will be followed by simulations of potential capacity bottlenecks and plans for automation of the machinery and internal transportation. These activities will go in parallel with developing a new vision and an associated strategy

Table 3 Summary of the NVSP activities in Case B

Topic	Case activities
Company data	The company was acquired by the current owner in 2017 as a part of a group with a total of 4 companies. The board consists of owners and a professional board member
Facilities	Own buildings and a combination of owned and leased machines
Employees	2017:6; 2018:6; 2019:6; 2020:7; 2021:8
Turnover in percent	2017:100%; 2018: 118%; 2019: 125%; 2020: 211%
NVSP activities	*Brief after Gemba Walk*: Small and established company with limited growth over a period of years. Employees have typically been employed for many years and the financial base is stable. The culture is dominantly operational, and the customers have been the same for several years. There is no strategy or plan for future growth *Iteration 1*: The initial discussion revealed that the order processing was time consuming, manual, slow and encumbered with several errors *Outcome of iteration 1*: Efficient order processing system implemented. The dialogue led to a first version of an automation vision developed by the facilitator *Iteration 2*: The newly developed vision facilitated a powerful internal discussion. A process of acquiring a new CNC Edging Machine was initiated *Outcome of iteration 2*: The new CNC Edging Machine was installed. The employees were positive and participatory in this process. Some of the younger employees eagerly engaged in operating the new machinery. The new technical capabilities started to attract new customers *Iteration 3*: The focus changed to consolidating and refining the automation efforts. This included more efficient production control, less waste and extended hours of operation *Outcome of iteration 3*: Several new automation investments have been proposed and is awaiting final accept *Iteration X*: The realization of the vision is still ongoing. The next planned steps involve implementation of industrial robots and a more intensive process of identifying new customers

Even though the participating SMs are very diverse there has been recurring patterns in the approach to support these companies in their effort to adopt new ways of dealing with the challenges related to digitalization and automation. This can be interpreted as an emerging methodology that is continuously being refined and improved.

The recurring elements in the approach can be summarized in the following methodology fragments:

- Defining the vision
- Defining and analyzing the operational tasks
- Defining specific goals
- Defining short term implementation tasks
- Proposing solutions
- Prototyping solutions in an iterative approach

- Identifying implementation challenges
- Initiating a flexible implementation process
- Repeating the whole process (several times).

When the SMs initially are asked to formulate the vision for the future manufacturing setup, they generally express difficulties in doing so. The same goes with defining the tasks and setting specific goals. These goals can be ambitious, but the initial implementation tasks must be short-term. It is experienced as a difficult challenge to define the first implementation task.

If the first implementation task is successful, their ability to be precise and creative about expressing vision, task and goals increases significantly in the subsequent iterations. This has primarily been facilitated by the extended focus on prototyping. It has been an explicit vision in NVSP that the prototypes should be as simple as possible to test specific hypotheses. The simplicity efficiently supports the speed in terms of producing and presenting the prototype. A similar approach is described in the Lean Startup methodology. Here it is introduced under the name Minimum Viable Product (Ries, 2017).

Prototypes made for one SM highly inspire the specifications of prototypes for the other participating SMs. One example is the step-by-step development of an IoT (Internet of Things) Suitcase. The need emerged when one company needed data about the operational conditions of a critical machine. Inspired by the technology available in cheap pedometers a simple accelerometer was combined with a digital datalogger. After the first test it was immediately clear that this represented a very generic need. Over a few numbers of iterations emerged the IoT Suitcase that have thermometers, inductive counters, mechanistic counters, accelerometer, and an ability to cloud log the data. Apart from providing data and testing hypotheses about operational conditions of various types of equipment the IoT Suitcase also demonstrated the value of collecting data and making these data available in a cloud-based data storage. In this respect it provides a hands-on introduction to digitalization for the SMs. Since the data refer to their own equipment in a specific operational context the experience informs and supports the ability to express future visions and set explicit goals about their own digitalization process.

The next important topic is the implementation process. In respect to larger companies the implementation process can be handled internally. It is not only feasible to do so but also highly recommendable since it ensures a grounded ownership that can support the continuous scaling and improvement of solutions.

In SMs this implementation approach is often not possible. This is because responsibility for operations and development in most cases relies on one or very few people. Therefore, most of the existing theory about implementation processes must be supplemented with new approaches that recognize the characteristics of the SMs.

Another aspect that challenges the SMs is the increasing complexity of the solutions. Due to increasing complexity more specialized suppliers are needed, and the traditional one-to-one buyer–supplier relationship is no longer sufficient. Experiences from the NVSP program indicate that there is a need for a new role throughout the process consisting of analysis-ideation-search-negotiation-implementation. This new role can best be named “integrator”. In the NVSP project the facilitators from FA and AAU in many cases play the role as integrators, but there is yet no unambiguous and comprehensive description of how the role is best handled.

One element of the integrator role is frequently raised by the SMs. This is the psychological aspect “trust”. If there is not a sufficient sense of trust between the responsible person in the SM and the integrator, the role cannot be fulfilled satisfactorily. The strong personal/psychological elements of this observation show that it is a very difficult role to fill in.

One important reason for the importance of trust is that the responsible person in the SM (often the owner) basically is investing his or her own money in the project. This also explains why integrators from outside have better chances of initiating a successful development process with an SM if they can bring external/public funding with them.

In most cases development processes and implementation also include organizational changes. If this topic is brought up during the initial discussions it has a significant impact on the shaping of the solution. In cases where the introduction of the organizational change dimension takes place late, it is more likely that the planned solution need adjustments before it can be implemented. It has also proved that a planned re-implantation can have a positive impact.

The characteristics of the SMs have a strong impact on their implementation capacity. This means that most projects benefit from being broken down to smaller steps when implementing. It is argued from an implementation effort perspective but often there is additionally an important financial perspective.

6 Conclusion

The chapter reports the initial experiences from a business support initiative focusing on supporting small companies in their effort to benefit from new digitalization and automation opportunities. Small companies need a specific type of support to getting started and continuing implementation of such opportunities.

The initial experiences still only generate fragments of methodologies, but some observations are frequently repeated. There seems to be an urgent need to define and fill the role of an “integrator”. The integrator must ensure that a vision makes an earning potential visible. For the small companies it is important that the engagement takes place at the sites of the company. Furthermore, the integrator must ensure that the implementation plan being designed with critical consideration of the company’s ability to carry out the implementation of the solutions.

The interaction between the integrator and the company seems to be organized best with an extensive use of prototypes of various kinds. These prototypes take very different forms, but the mindset “Test before investment” seems to be the best guide to ensure confidence and basic understanding of both the solution and the importance of the solution for the company.

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Innovation Factory North: An Approach to Make Small and Medium Sized Manufacturing Companies Smarter

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Abstract This chapter presents the Innovation Factory North (IFN) as a platform for a collaborative approach to trigger and accelerate industry 4.0 based innovations in small and medium sized manufacturing enterprises. The potentials for SME becoming 'smarter' are huge and well-recognized. However, 'how' to approach this is difficult. In IFN, manufacturing companies, technology vendors, and academia join forces to trigger digital transformation. The IFN approach has been developed during an ongoing regional research and innovation project in a collaboration between industry, academia, and the government. This chapter presents the generalized approach and discuss the preliminary findings from more than 60 cases of applying the approach as steps towards making the participating companies smarter.

Keywords Industry 4.0 · Smart production · Innovation factory · Collaborative learning approach

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1 Introduction

For an SME, the journey towards industry 4.0 and digitalization can be difficult. SMEs are often challenged with resource scarcity, such as lack of financial instruments and digital skill sets. Furthermore, the immediate value of the transformation may be difficult to identify and the steps that should be taken are unknown.

To demonstrate the potentials of smart production, AAU has established a Smart Production Laboratory (Smart Lab (Madsen and Møller, 2017)). The Smart Lab is a full-scale production system built on the FESTO CP Factory platform. The Smart Lab has been used as a learning factory (Abele et al., 2015) and can be used to build demonstrators of various new manufacturing applications and solutions in a realistic manufacturing context (Nardello et al., 2017). However, the ambition is also to have this knowledge spur innovations in industry.

The local region has tasked AAU to build an ecosystem around the Smart Lab to support the local SMEs with knowledge and activities that help the companies identify and realize the potentials of I4.0 in their own context. To do so, Innovation Factory North (IFN) was established. The purpose of IFN is to build a local ecosystem of industrial companies, technology providers, and knowledge institutions, and to develop new competences needed for I4.0. In the IFN ecosystem, qualified companies can participate in collaborative activities aimed at increasing the awareness of industry 4.0 and getting guidance in creating innovative industrial solutions.

Digital transformation towards I4.0 is characterized as a business transformation having IT as an enabler and as a strategic intend. Consequently, most of the frameworks for business transformation are primarily top-down approaches driven by a strong managerial vision and supported by large-scale investments and enablement projects or programs. These approaches do not fit the local industry of Denmark very well as it is characterized by a majority of small and medium sized manufacturing companies with a low level of digital maturity. At the same time, the region has some technologically advanced companies, especially within the area of Internet of Things (IoT). However, many of these companies do not understand how their technologies can provide value in the industrial domain, and consequently they need to evolve their offerings towards I4.0 and smart production.

In summation, the IFN project was established based on the assumption that given resource constraints (financial, competence, market uncertainties, etc.), SMEs must become smarter by embarking on a stepwise digitalization journey where the direction and insights are created along the way. The approach is planned as a step wise industry-academia engagement process spanning three steps: (1) awareness, (2) demonstration, and (3) anchoring. The approach is build based on a set of initial hypotheses regarding the interactions between industry and academia and the impact. The hypotheses reflect the planned transformation cycle around the Smart Lab: Manufacturers become smarter by (1) engaging in fast innovation cycles; where companies explore new opportunities by; (2) building prototypes of new digital solutions; and (3) learning from taking small, incremental steps and finally consolidating and scaling small scale experiments and solutions from the Smart Lab into the factories. Thus, IFN are preparing the participants for the digital transformation journey towards industry 4.0 and smart production.

The first IFN hypothesis is regarding the innovation process, and why the companies need to innovate. The assumption is here that the technology is out there, and that it is just a matter of identifying the right knowledge/competencies and adopting it to the specific needs and apply it to the right problem. The second hypothesis is on the development process, and how to organize. The assumption is that we can build new solutions by *co-locating* relevant stakeholders in the lab and jointly and in close collaboration with the solution providers build the solution, thus *co-creation.* The third hypothesis is on how to create new knowledge and competencies through an iterative and experimental learning process. The learning process is facilitated partly by a structured approach and partly facilitated by the researchers involved in the process. The development and the shape of this structured process is the topic of this paper, where we so far have more than 60 companies engaged in the project.

Next section presents the background for the project, followed by a description and motivation of the generalized approach. After this, the findings are discussed and finally the conclusion provide the wider perspective of the approach.

2 Background

The researchers behind the IFN project have been involved in a larger number of industrial development projects over the last decade (Global, MADE SPIR, MADE Digital and MADE FAST). The projects spanned globalization and digitalization topics and involved both large and medium sized Danish manufacturing companies such as Royal Greenland, Danish Crown, GPV, Linak, and Novo Nordisk. The engagements were mainly one-to-one, meaning the research group worked with one specific company over a limited time-period, and engaged with them through workshops combined with in-depth studies. The research approaches ranging from systematic academic approaches such as action research (AR), action learning (AL) and future workshops, to what may be characterized as advanced consulting approached guided by an approach developed at the department (Coughlan, 2002; Müllert & Jungk, 1987).

At the same time, the research group has been working on developing the Smart Lab as a physical learning environment where I4.0 technologies can be tested and demonstrated in the context of what we call a learning factory. A learning factory is a well-established concept (Abele et al., 2015) mainly focused on teaching and training, but recently also considered to be a potential pathway towards I4.0 transformation (Baena et al., 2017). However, using a learning factory to prototyping/piloting industrial solutions with the purpose of innovating across multiple stakeholders has been given little attention (Abele et al., 2019; Larsen et al., 2019).

The IFN project proposal was built on these past experiences and the realization, that if smaller companies should get started and succeed with digitalization, there is a need to simplify the approach. This was the reason why the IFN project was built as a three-step process taking place in the Smart Lab: (1) Awareness activities, where the aim is to formulate the vision and to identify the potentials of industry 4.0 for the individual companies; (2) Demonstrator activities, where potential solutions are prototyped and demonstrated in the lab; and (3) Anchoring activities, where the organizational capabilities and competence gaps are considered and addressed. The approach was guided by the strategic road-mapping approach developed by Cambridge University (Kerr & Phaal 2015), the SCRUM methodology and the Toyota Kata approach (Rother, 2009). The main difference is the collaborative nature of the approach and the learning factory context.

The IFN project proposal was the foundation for a regional grant where the contractual conditions determined the research setup and industrial collaboration. This project provides a setup where the project finances six Ph.D. researchers supported by four senior researchers and administrative and lab support resources. Furthermore, the project is supported by an advisory board with regional industrial managers who provide inputs for the IFN team on the strategic direction of IFN.

The context of the IFN project is regulated in the contract between the University and the Danish Board of Business Development (DBBD) that administer the grant. The IFN project contract stipulates specific requirement to company location and size, and a limitation on which activities that can be supported by the grant. The stipulated collaboration between industry and researchers is aimed at establishing an innovation ecosystem based on Industry 4.0 technologies. The purpose of the ecosystem is to strengthen innovation and productivity of the region's SMEs through the creation of new knowledge and joint applications of knowledge. The industrial partners do not pay cash to participate, but they commit a certain number of development hours as in-kind payment.

The contract of the IFN project covers support for activities to establish and operate the ecosystem for three years, after which the project is expected to become financially viable. Consequently, planning the continuation and developing a sustainable business model is thus also part of the expected IFN deliverables.

In the following chapters, the IFN approach is elucidated by describing the activities performed at three levels as illustrated in Fig. 1.

3 IFN Ecosystem

The goal of the IFN project is building a regionally based innovation ecosystem consisting of relevant stakeholders. IFN operates with three types of stakeholders: Industrial SMEs, Industry 4.0 technology providers, and knowledge institutions from which both researchers and students are actively engaged. The knowledge institutions include a university and a local university college. There will be around 80 industrial partners, and approximately the same number of students involved in the project (Table 1).

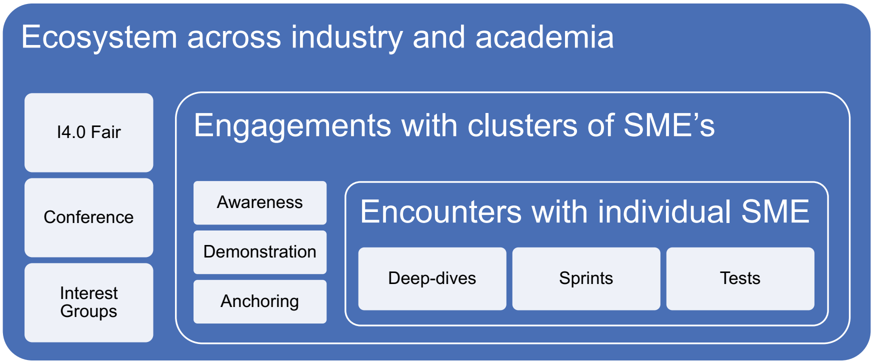

Fig. 1 IFN activities

Table 1 IFN stakeholders

Stakeholder	Primary role	Benefits	Constraints
Industrial companies	Problem owner	Innovation capabilities and new knowledge	Hours to participate, develop, and implement the solutions
Technology provides	Solutions owner	Prototyping and testing specific solution, based on own technology	Hours to participate, develop, and implement the solutions
Students	Knowledge owners	Learning a problem-solving approach and testing theoretical knowledge	Fit with curriculum and timing of projects
Researchers	Process owners	Testing research propositions by engaging with the problem and by supervising the students	Specific research interest and focus
DBBD (region)	Sponsors and innovation experts	Practical experience with industry 4.0 innovation, access to PBL-project	Company cluster configurations (size, location) and supported activities

The key activities of the project cover activities intended to establish and sustain the *ecosystem* such as conferences, seminars targeting all participating stakeholders, and a set of repeated collaborative activities referred to as the IFN engagement. The IFN engagements are organized into three steps, and each step involve several collaborative events (workshops) and individual encounters to support the collaborative activities. A company sign up for one or more steps, and both joint activities and the individual encounters are facilitated by researchers and follows a general schema.

4 IFN Engagements

An IFN engagement is defined as a collaborative process where a group of stakeholders from the ecosystem, referred to as a company cluster, collaborate to create new, shared knowledge related to Industry 4.0 solutions. Due to the nature of the regional contract, the project cannot sponsor formal competence development or implementation. However, these add-on activities are obviously also studied.

The engagement is organized as a journey in three stages: (1) awareness; (2) demonstrator; and (3) anchoring, and between each stage, there is a "pivot" seminar where the cluster is formed, direction is set, companies commit to the next stage and the content is scoped. A cluster consist of 3–5 SMEs, one technology vendor, researchers, and students.

The total engagement spanning a little less than a year, with monthly joint workshops in the Smart Lab supplemented with company specific analysis and diagnosis activities carried out in the individual organizations (encounters). However, a company can also chose only to participate in one or two stages.

The workshops in the Smart Lab are all structured according to the same template: (1) Explore; (2) Exposé; and (3) Experiments and (4) Evaluate. This means all workshops have a similar agenda: investigate options, demonstrate in the lab, and actively try out things in the lab and later in the companies. The activities in the individual companies (encounters) run in parallel to the joint activities, and they are scoped and evaluated at the joint workshops.

The awareness stage is generalized for all participating companies and by large driven by a set of tools and models shaped specifically for this project. The demonstrator stage is themed according to selected topics within smart production (e.g. paperless production, data driven decision making, or predictive maintenance), and the anchoring stage is customized for the specific company cluster. The IFN approach is illustrated in the "Triple Diamond" model below (Fig. 2).

The companies are recruited and onboarded based on the constraints and requirements set out by the DBBD and the goal is to have 94 companies through Awareness, 25 through demonstrators and 13 through anchoring. The 10 technology providers are onboarded based on the technology fit. The tentative time consumption for a company is 150 h for awareness and 600 h for both demonstrator and anchoring. The companies are assigned a student as a coach throughout their engagement.

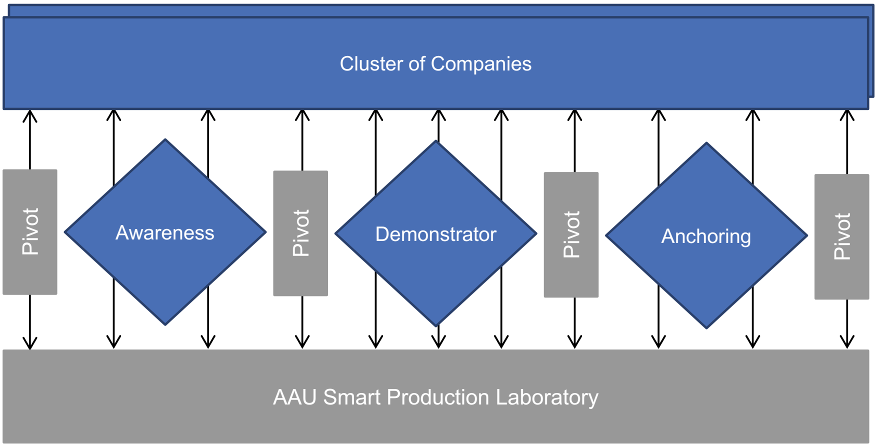

Fig. 2 The IFN Triple Diamond approach. Arrows illustrates monthly events

4.1 The Awareness Stage

The Awareness stage is kicked-off with a pivot seminar where expectations are aligned, and the administrative framework is presented. During the awareness stage, the objective is to develop a strategic roadmap for implementing industry 4.0. Strategic roadmapping is a widely used workshop-based approach for supporting innovation and strategy development (Phaal et al., 2015). In the IFN approach, the search stage in an innovation process aims to formulate a concept of the innovation and consists of activities such as idea generation and selection, concept development, and project definition (Boeddrich, 2004; Kurkkio, 2011). The stage contains the following activities:

- An introductory presentation to Industry 4.0 along with three presentations of Industry 4.0 enabling technologies by local researchers
- Participation in an Industry 4.0 awareness game
- Formulation of an Industry 4.0 vision for their own factory
- A digital maturity assessment is performed
- Evaluation of the economic potential of their Industry 4.0 strategy
- Formulation of a conceptual idea leading to the innovation in the context of Industry 4.0.

From these activities, the companies obtained future vision to strive for, overview of their current level of digital maturity, and a plan for how to achieve their future goals. The output of this step is a simplified visual roadmap (Kerr & Phaal 2015) for becoming smarter. Furthermore, the conceptual ideas formulated in this stage are used as inputs for the next stage of the approach, the demonstrator stage.

4.2 The Demonstrator Stage

The Demonstrator stage is kicked-off with a pivot seminar where the expectations are aligned, and the joint demonstrator is scoped based on the conceptual ideas from the awareness stage. The purpose of the demonstrator stage is to transform the conceptual idea from the search stage to a tangible solution ready for implementation in the organization (Ahlskog et al., 2017). Consequently, the demonstrator stage in the IFN centers around building a prototype of the conceptual idea defined in the search stage.

One of the challenges related to Industry 4.0 innovations is that they are constructed by recombining existing technologies (which thus may not be novel themselves) into new combinations (Brynjolfsson et al., 2014), that match the potentials of the technologies with productive applications in industry (Lassen & Waehrens, 2021). However, the technologies that Industry 4.0 rely on have not been widely applied in the production, and experience in combining the technologies into extensive systemic innovations may also be limited in industry. IFN therefore aims to assist in building this knowledge in the industry by establishing collaborations between researchers, manufacturers, and technology vendors in demonstrator projects.

Based on the assumptions underlying hypothesis on organizational learning and existing research findings (Li, 2020, Møller & Hansen, 2006, Rycroft & Kash, 2000, Sjödin et al., 2018) the original design of the demonstrator stage used an iterative, experimental approach inspired by development process designs such as scrum and agile. Furthermore, the prototype was built and tested in our smart production lab which is a small-scale manufacturing system equipped with state-of-the-art technologies and solutions. Thereby, we avoided interfering with the daily operations of the manufacturers while at the same time allowing for learning by doing in an environment which resembles a real production facility (Leonard-Barton, 1992). We have experimented with different configurations for coupling the company specific demonstrator to the generic joint demonstrator, and a close synchronized approach is preferred.

Each demonstrator is organized around a common theme like paperless production, data driven decision making, or predictive maintenance. E.g. in a paperless production demonstrator, the shared problem is to digitize and automatize indirect business processes that involve manual and paper based operations. An example of an IFN demonstrator on "Paperless Production" can be found in this book (Palade & Møller, 2022).

4.3 The Anchoring Stage

The Anchoring stage is kicked-off with a pivot seminar where the expectations are aligned, and the anchoring stage is scoped based on the prototypes from the demonstrator stage.

The anchoring stage aims to implement the prototype and thereby exploit the idea by transforming it into an operable solution through full scale implementation in the company. Tasks related to organizational change are important in this stage (Karlsson & Larsson, 2016). The implementation stage consists of the following activities:

- A theoretical introduction to change management in digitalization projects
- Competence mapping
- Developing implementation plan
- Execute on the plan for successful implementation
- Continuously monitoring progress and redesign if needed.

This design of the anchoring stage is the foundation from which we have initialized the first round of activities in this stage. As in the design of the two other stages evolves, we will continuously be analyzing and evaluating the companies' progress and outcomes of the process and improve its design if needed. Further discussion can be found in part 5 later in this book (Lassen, 2022).

4.4 The IFN Events and Encounters

The IFN engagement is essentially a sequence of monthly joint workshops with company specific encounters in between the workshops (deep-dives, sprints, and tests). Each engagement stage is organized in two or three distinct steps with a joint pivot seminar as a transition between the stages.

Between the events, there is an encounter in each of the participating companies coached by students (a deep dive analysis, a prototype sprint or test of a prototype). The outcome of this encounter is the basis for the following joint workshop.

Each of the workshops follows the pattern described below. The pattern consists of four phases to be covered in a half to a full day workshop. This template has been found to create a good group dynamic, and to trigger the emergence of new shared insights. This new insight is then used to scope next workshop in detail.

4.4.1 The Exploration Phase

The balance between exploration and exploitation has been discussed by March (March, 1991) as an approach generate new knowledge in the organization (Argyris & Schön, 1978).

Each of the workshops start with bringing in relevant new external knowledge and/or technologies into the joint workshop. Either as invited guests, researchers or as a technology demonstrator in the Smart Lab or other cases.

4.4.2 The Exposé Phase

The most important part of the workshop is the exposé stage where all participant presents the results from the encounters between the workshops, and where the more tangible results are demonstrated in the Smart Lab. In some cases, also external cases are used to demonstrate the principles and ideas.

One of the cornerstones of the I4.0 movement is the development and implementation of new technological solutions that have the potential to disrupt the status quo of business and manufacturing traditions. However, these technologies are not unidimensional, but are rather often the result of collaboration between partners from different domains and are somewhat interrelated with one another. This leads us to refer to these technologies as "boundary objects" which are described as objects that refer meaning to more than a particular domain and are the result of a cross-boundary collaboration (Barley et al., 2012).

When talking about solution development it doesn't refer particularly of a specific physical product or instantiation of a technology, although that is often the case, but it can also refer to methodologies or frameworks, which are part of the knowledge spectrum. The co-creation of new solutions, which is at the core of the IFN approach, is the activity of sharing knowledge from different domain spectrums in order to explore the development and implementation of a boundary object.

4.4.3 The Experimentation Phase

The experimentation phase is where the joint ideas and demonstrations are transferred to the participants own company and context as an experiment intended to reinforce learning (Kolb, 1984).

Experimentation is an acknowledge approach for developing in an uncertain environment (Cannon & Edmondson, 2005, Garvin, 1993; Thomke, 2020) also in the context of Industry 4.0 (Li, 2020). Experiments enable opportunity seeking and expanding horizons and thereby shifting the focus away from problem solving (Garvin, 1993). Experiments are carried out as a systemic search for and testing of new knowledge which result in several changes (both small and large) which combined foster extensive benefits. Experiments may take on different forms and may be small or large (Garvin, 1993; Thomke, 2020).

Experiments in the IFN approach evolves from the awareness stage, where the experimentations are limited to probing the organizations using several different model templates to assess the organization and the strategic direction, over testing prototypes in the demonstrator stage to validating prototypes in the anchoring stage.

4.4.4 The Evaluation Phase

The evaluation phase is related to both the practitioner's perspective (Lidón et al., 2011) as well as the research perspective (Møller et al., 2022a). Evaluation and reflection are critical elements in both perspectives and evaluation must lead to re-adjusting the scope and approach. In particular from the research perspective, this is where sense-making of the entire process is formed, leading to a better understanding of the process and the project.

5 Discussion

The continuous design and redesign of the approach is part of the research, but for the most recent engagements the format and content have proved to be stable. Later in this book, we will discuss the research approach applied in the project (Møller et al., 2022a, b).

The empirical findings from the first part of the research support the augmentation of the original three assumptions into six key findings that may be corollary be put forward as propositions for the remainder of the project. Furthermore, discussing these three propositions on: (1) fast innovation cycles; (2) prototyping new solutions; and (3) scaling prototypes, we have identified three additional propositions to be explored in future redesigns.

Context switching of problem/solutions (the innovation perspective): We have observed that one of the most powerful mechanisms for sparking new ideas is the idea of systematically switching context for a problem or solution. This both means using a generic solution (e.g. a written or live case) and transferring this into the context of the participating companies. Or this could be to investigate how the same generic problem manifest itself in the participating companies.

The implication of this could be, that we should try to build up an inventory/repository of generic industry 4.0 problems and solutions to be re-used across engagements. You could also argue, that bringing in vendor with experiences from outside manufacturing also is a context switching mechanism. The bottom line is that this is a way of getting new knowledge into the engagements.

Storytelling as a way to allow for co-creation across engagements (the build perspective): In the learning factory, the emphasis is on creating authentic environment for the participant to immerse into. We have observed that the technical details are less important to the participants but the story telling around a particular setup take precedents. We also saw that participants across different runs kept referring to the same stories. This could also imply that we should work on making this story telling more explicit, using more techniques that we originally did. Again, this could be kept in an inventory to be reused.

Guided reflection as a way to support learning (the learning perspective): When presenting companies with new concepts and tools we have originally approached this a conventional PBL project, where we assumed that the participant would be able to absorb knowledge on their own. We have found that we needed to organize this better and to provide the participants with simplified operational models to guide them through the preparation.

So, going forward, we will be experimenting with packaging knowledge into re-usable patterns and to create a standardized learning tree and learning path.

Unfortunately, the COVID-19 situation mandated moving activities from on-site to off-site online. This were not optimal, and we have focused on identifying activities that were least damaging to the process to execute online. Also, we have been experimenting with ways to replace company visits with online video tours and other online formats.

Another challenge to be addressed in the next research cycles, is to make the value proposition explicit to the individual participants.

This paper set out with an ambition to refine the IFN approach and frame and elaborate on the initial hypothesis. We have managed to recruit and keep the companies engaged which is an indicator of the project being value-adding, but we have not seen any major performance leaps or completely innovative solutions. What we have seen are companies continuing the journey on their own.

For small companies, we have seen that the industry 4.0 is not triggering a digital transformation in the short time perspective, but rather work as a vehicle for smaller improvements that might lead to digital transformation in the long run. However, we would need to follow the companies for a longer period to support this claim.

However, this supports the initial understanding of Industry 4.0 as a concept that provide a vision but not the way. In our conceptualization, Smart Production (Møller et al., 2022b) provide a way for smaller companies to work on identifying their own personalized pathway towards Industry 4.0 together with colleagues, vendors, students, and researchers.

We sat out specific objectives for identifying didactical principles and operation model for the smart lab as a learning factory. The generalized IFN approach can be considered a class of didactics and an operating model aimed at research and innovation based on the learning factory.

However, the learning factory can also be considered for applications inside a single organization. How can a company leverage a learning factory for internal innovation projects? This would basically be like the learning lab [], and the potentials and managerial implication could be studied further.

6 Conclusions

In this chapter, we have presented the IFN as a platform for a collaborative approach to trigger and accelerate industry 4.0 based innovations in small and medium sized manufacturing enterprises. The IFN approach is iteratively shaped by very specific conditions and constraints from the project context, however, we believe that the approach can be generalized and re-used for other similar academia/industry collaborations, aimed at advancing industry 4.0 in SME.

We have developed the approach using a systematic research approach (Møller et al., 2022a, b) and we have developed content that are reused across several engagements. We have collaborated with more than 80 companies, and we have evaluated the impact of the engagements on all the stakeholders, and the empirical findings have been discussed.

Going forward, we still need to finalize engagements with additional 10–20 companies and are moving into the final stage of the project where we will be institutionalizing the approach in the region and ensuring the continuation of the activities.

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Digitalization and Automation in Small and Medium-Sized Enterprises: Challenges, Needs, and Solutions in Brandenburg, Germany

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Abstract Digitalization and automation represent both a major challenge and a long-term opportunity for SMEs to secure their business success. They often lack specialist knowledge and a sufficient financial scope and therefore need external support in meeting these challenges. This is of particular relevance and political interest as Brandenburgs economy is determined by SMEs. Knowledge and technology transfer between scientific institutions and companies is seen as a possible solution. However, different goals, approaches and expectations of researchers and companies inhibits or complicates a successful cooperation. Therefore, transfer intermediaries are needed as mediators.

The book chapter uses the example of IMI Brandenburg to show how knowledge and technology transfer can be implemented by intermediaries and what key findings were obtained in the process. Furthermore, possible success factors for both the digitization of Brandenburg's SMEs and successful knowledge and technology transfer are discussed.

The chapter addresses decision-makers in SMEs as well as research institutions and transfer intermediaries and is intended to raise awareness of the opportunities, challenges and solutions in the cooperation between science and industry.

Keywords SME · Digitalisation · Knowledge and technology transfer · Challenges · Services · Use case · Model factory

1 Introduction

Securing long-term competitiveness is currently and will be one of the greatest challenges for small and medium-sized enterprises (SMEs) in the future. Especially in

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connection with the changes in operational processes and restrictions triggered by the pandemic, digitalization is less of a challenge than a decisive success factor, which offers a multitude of innovation opportunities and possibilities for optimizing operational processes through to the development of new business processes.

The spread of digital value creation activities has gained enormous momentum in recent years (Brink et al., 2020). The focus has shifted from a pure use as an innovation driver to a concrete design of digitalization, with the strategic handling of digital transformation moving into the foreground (Lundborg & Schrade, 2020). However, it also shows that SMEs regularly fail to generate and transfer knowledge (Brink et al., 2020) and only a few challenges can be met by companies alone. The reasons for this are usually a lack of specialist knowledge and financial scope, which result from the size of the company (Failed, 2018). Policy intervention is needed to support businesses (Brink et al., 2020).

In this context, a variety of support structures have emerged in recent years to help companies actively confront change processes and find solutions that meet their needs. Using IMI Brandenburg (Innovation Center Modern Industry Brandenburg) as an example, this chapter shows the role played by university research institutions in this context and how companies can benefit from working with them.

In order to create a basic understanding, essential information on the economic structure and status of digitalization in Brandenburg is first provided. This is followed by a description of the contribution that research institutions can make and the challenges that go hand in hand with this. Based on the experience gained from supporting and assisting SMEs in their innovation projects, we will conclude by outlining the factors and mechanisms that determine the success or failure of digitalization projects and collaborations with research institutions.

2 General Conditions and Status of Digitalization in Brandenburg

The corporate structure in the rural and comparatively sparsely populated state of Brandenburg, Germany is strongly determined by SMEs, whereby all companies with fewer than 250 employees subject to social insurance contributions are subsumed under SMEs. If the employment size criterion is applied, 99.5% of the companies belong to SMEs (Bericht der Landesregierung, 2014).

The industrial focus regions located primarily in the south of Brandenburg are predominantly in the optical industry, mechanical engineering, and the manufacture of electrical equipment and metal products (Schröder et al., 2021). Accordingly, the economic structure is characterized by companies that do not handle their value creation exclusively digitally but provide services locally as craft businesses, manufacture, or transport goods. Although only a few companies have been fully sensitized to the topic (Kilimis et al., 2019), digitalization has arrived in all sectors of the Brandenburg economy. The skilled trades in particular are proving to be the drivers of

Table 1 Digitalization processes by business unit (Kampe & Walter, 2018)

Business unit	Use of digital technologies	
	Number	Percentage (%)
Administration	66	78.6
Production and service process	64	76.2
Purchasing and sourcing	56	66.7
Interface to suppliers and customers	56	66.7
Cross-divisional networking	47	56.0
Networking of production steps	46	54.8
Market development	28	33.3
Other	4	4.8

digitalization. A large proportion of companies are actively addressing the issue of digitalization, and there is no indication of any state-specific digitalization lag (i-vector Innovationsmanagement GmbH & Regionomica GmbH, 2018).

According to a study by the Brandenburg Economic Development Corporation, two corporate sectors in particular are involved in digitalization processes (Table 1). Digital technologies are used primarily in administration (78.6%) and in the value-adding production and service sectors (76.2%).

The most important motives for digitalization include the optimization of internal processes and the further development of supplier and customer interfaces. The focus is on process-related functions, so that the back office is largely digitized.

Overall, the level of digitalization in Brandenburg can be classified as advanced. A large proportion of companies use networked digital solutions or at least resort to stand-alone solutions. Based on these technological developments, enormous leaps in development have been realized in terms of growth and market development. However, there are significant differences in the degree of penetration (Kampe et al., 2018). There is no widespread implementation, so there is still a great need for action. In rural areas in particular, SMEs repeatedly prove to be laggards (Schröder et al., 2021). In the production and manufacturing sector in particular, the opportunities arising from the use of digital technologies are only being exploited to a limited extent. Accordingly, a certain digitalization backlog can be identified here. Studies suggest that there is a residual number of companies that are resistant to digitalization, which in turn means that relevant digitalization potential is lying fallow (Kampe et al., 2018).

SMEs continue to find it difficult to meet the challenges associated with digitalization processes due to limited resources (Kampe & Walter, 2018). In addition to a lack of capacity to deal with the necessary change processes in a structured manner (Schröder et al., 2021), ignorance of technical possibilities, potential (Andulkar et al., 2018) and difficulties in assessing risks and benefits are limiting factors (Kampe et al., 2018). Of particular importance here are the factors of time and sufficiently qualified personnel, which are needed for the planning and implementation of digitalization projects (i-vector Innovationsmanagement GmbH & Regionomica GmbH, 2018).

3 Research Institutions as Knowledge Providers

Targeted Knowledge and Technology Transfer (KTT) is essential to ensure that companies have a high level of innovative strength in the long term to cope with the digital transformation. The term is understood to mean "the targeted transfer of technological and technology-related knowledge between partners (individuals, institutions, organizations and companies)" (Meißner, 2001), which also includes the transfer of explicit and implicit knowledge about the application and use of technology (Bozeman, 2000).

Transfer service providers are usually considered to be universities, colleges, and research institutions (Meißner, 2001). They act as knowledge and technology providers, provide extensive know-how, are solution providers for concrete tasks, helpers in the process, networkers and often initiators (Rauter, 2013). In addition to a broad reservoir of factual, process, action and procedural knowledge, as well as knowledge that is required for the conception, production as well as use of technology, universities also offer to use part of their facility. For example, regional economic actors can benefit from sports and cultural facilities, patent information centers or laboratories (Hamm & Koschatzky, 2020). In this context, so-called learning factories should be highlighted, which represent a promising approach for the acquisition of specific competencies with regard to the digital transformation of the economy (Rehe & Gebauer, 2021). Also often referred to as demonstration, model, concept, experimentation or efficiency factories, these feature basic laboratories, industrial and interlinked machine systems, and a didactic concept for problem- and action-oriented learning (Heinze et al., 2021).

Although the cooperation between research institutions and companies that enables access to the resources just mentioned and thus addresses the limiting factors mentioned in the previous chapter, fundamental market mechanisms as well as conflicts of interest and goals make cooperation between universities and companies more difficult.

Explicitly worth mentioning here are, for example, the different time horizons they both use in planning and working. Companies often approach universities with acute problems. Bound to the semester rhythm, the immediate processing of these and thus a short-term problem solution is hardly possible. From the point of view of the university, whose main task is primarily defined by research, teaching and study, the scientific value is relatively low. This results in a conflict of interest between academic research and practice-oriented transfer, which is associated with a high level of administrative effort. Also fundamentally problematic is a different assessment of the value of the service as well as the difficulty of specifying the result precisely from the outset (Hamm & Koschatzky, 2020). From the point of view of companies, on the other hand, the lack of maturity of technological solutions (Kurz et al., 2022) and the low application relevance of academic research are a limiting factor (Hamm & Koschatzky, 2020).

Divergent objectives also have an inhibiting effect on cooperation between players from business and research. While universities aim to make knowledge accessible to the public and strive for scientific thoroughness, which is associated with a high expenditure of time, companies focus on the expansion of economic advantages through scientific findings. Accordingly, short-term solutions are essential here, which, however, are only available to a limited audience.

Other inhibiting factors are language discrepancies and differences in expectations and information levels. The latter leads to a lack of knowledge of suitable contacts, research profiles and transfer services on the part of companies and of the needs of industry for specific transfer services on the part of research institutions (Kurz et al., 2022). As part of the market mechanism, these information asymmetries, associated high search and transaction costs, as well as a lack of overlap in the social networks of companies and knowledge-producing organizations, lead to an inefficient allocation of knowledge providers and demanders (Rauter, 2013). As a result, there is still sufficient untapped potential for cooperation (Heinze et al., 2021).

Especially in the context of the latter points, so-called intermediaries play an important role. These are are individuals or organizations that initiate and keep knowledge transfer going. They support innovation processes and facilitate decision making, negotiations as well as interactions between transfer partners from different knowledge domains (Kaufmann et al., 2021). According to Lehmann and Preissler, the functions or service categories (Preissler, 2016) shown in Fig. 1 can be distinguished.

Using IMI Brandenburg as an example, the following chapter illustrates the design of such KTT services based on specific measures and findings on enabling and limiting factors regarding successful KTT regarding digitalization and automation in SMEs are discussed.

Fig. 1 Knowledge and technology transfer services

4 Example: Innovation Center Modern Industry Brandenburg

4.1 Objectives and Services

Based on the economic situation described in Sect. 2, there was a need to create an offer for SMEs that would support them in mastering the digital transformation (BTU Cottbus-Senftenberg, Regionomica GmbH & Fraunhofer IFF, 2013). The transfer of scientific results was considered to be immanently important, so science should act as the transfer provider. Therefore, IMI Brandenburg was founded at BTU Cottbus-Senftenberg in 2015, aiming to increase the degree of digitalization of the Brandenburg economy by initiating cooperation projects between SMEs and research institutions.

Faced with the challenges and difficulties of facilitating successful technology transfer, an offer was created that is available to all SMEs in the region with as few barriers as possible. This has been continuously adapted to the needs of SMEs since 2015 and meets the requirements of modern science and technology transfer (Preissler, 2016).

Provision of resources: In order to communicate digitalization concepts in line with needs, instruments are required that create awareness of the benefits of digital technologies, convey the basics of application and provide approaches for the use of digital technologies in companies (Wank et al., 2016). This is done by industry-oriented demonstrators in a Model Factory that provides a physical space for meetings and events, enables access to expertise and joint work on projects and tasks. It covers important topics of automation and digitization, fulfills the functions indicated in Fig. 2 and thus contributes to a reduction of barriers for SMEs. Here, for example, technical feasibility studies on the use of robots or the applicability of digital assistance systems can be carried out.

Transparency: IMI Brandenburg aims at reducing information asymmetries between research or technology providers and SMEs. To create awareness, reduce concerns and overcome language barriers, relevant research results are presented appropriate to the target group, e.g. demonstrators, lectures, information brochures or blogposts. In order to create an overlap of the social networks of companies and knowledge providers, networking events were established, e.g. Colloquium of Industrial IT and TransferDay, which link information technology branch and production sectors or science and industry. The prerequisite for this is a continuous scouting for new technologies and research results as well as suitable partners.

Marketplace: A network of more than 200 partners from science and industry who offer solutions to manage the digital transformation provides companies with access to potential partners and needed competencies. Networking events create opportunities for exchange between solution providers and inquiring SMEs; contact with industry associations also expands the group of addressees. In addition, SMEs are actively supported in their search for partners to solve specific problems. Frequently

Fig. 2 Topics and functions of the model factory of IMI Brandenburg

occurring use cases are prepared as demonstrators and published as written reports to serve as a source of ideas for other companies.

Competence building: Since SMEs are usually unable to develop sufficient skills in new technologies due to their limited human resources (Taurino & Villa, 2019), IMI Brandenburg aims to impart or compensate for missing skills. Therefore, relevant learning goals and content are defined for the corresponding target group of manufacturing SMEs and conveyed in the form of workshops on methodological and skills and basic knowledge of digitalisation and automation technologies according to the principle of "helping people to help themselves". The content conveyed serves as an impulse for further knowledge acquisition and the development of innovations.

Administration: Due to lacking knowledge both in methodological approaches to digital transformation and general digital technologies SMES need support in defining and preparing the projects (Doyle & Cosgrove, 2019). A step-by-step approach enables SMEs to initiate innovation projects. The starting point is a potential analysis (i.e. a maturity model), which determines the degree of automation and digitization and compares it to other companies. Possible measures to improve the degree of maturity can be derived from this. These are developed into a specific project and suitable partners can be found for implementation. Success stories of other SMEs and existing technology demonstrators can serve as inspiration. In addition, information about funding can be provided to overcome financial restrictions.

4.2 Findings

So far, more than 250 companies from the manufacturing sector have been supported by the innovation center. The company size varies greatly from 3 to more than 250 employees, the majority covering between 30 and 150 employees. Since 2015, almost 100 projects have been initiated directly by the innovation center; a lot more were initiated by the companies on their own initiative. The network of IMI Brandenburg, in which companies were put in contact with suitable solution providers, played an important role here.

Since IMI Brandenbur has been founded, a change in the inquiries of companies that requested support for the first time could be observed. At the beginning of IMI, the focus was primarily on informing and raising the awareness in SMEs regarding digitalization and automation, since there was a great deal of ignorance of the technologies and a lack of clarity about the benefits (IMI Brandenburg, 2021). It could be observed that the implementation of new technologies mostly took place under pressure from business partners who had special requirements in terms of process quality, documentation or data exchange. Another digitalization driver were legal requirements, which could not be implemented with analog procedures. In both cases, there were no radical innovations, but usually only incremental improvements to existing processes.

Furthermore, the direct implementation of smart production turned out to be difficult, since many SMEs still lacked basics in planning, organization and automation.

Common digitilization concepts such as IoT, IoS, CPS and smart factory cannot be easily transferred to SMEs, as they lack the necessary infrastructure and usually have to make extensive investments first (Andulkar et al., 2018).

The focus was therefore to support prioritization of the various projects. First of all, technological basics, such as the introduction of a leading system (e.g. ERP) in the company and afterwards the realization of projects in production and logistics, which are suitable for achieving the greatest possible efficiencies (Kilimis et al., 2019). Due to financial and personnel restrictions which SMEs are subject to, it is important for the success of possible projects to consider possible funding and involve employees at an early stage.

While at the beginning the uncertainty regarding the possibilities and benefits of digital solutions prevailed, starting in 2019 the question of the right approach came to the fore. Digitization was increasingly recognized and implemented as a strategic option to ensure the long-term success of the company. The benchmark with other companies through the potential analysis and inspiration from successful examples were a motivating factor. The results of the offered potential analysis show that SMEs that follow a digitalization strategy, define responsibilities, invest continuously and esp. maintain cooperation with research institutions are above average in all other evaluated indicators and able to master the challenges of digital transformation (IMI Brandenburg, 2021).

In addition, it could be observed that the personal relationships between the transfer managers and the companies is a decisive factor for successful knowledge and technology transfer (O'Reilly & Cunningham, 2017). A successful collaboration depends on the number of years a scientist has spent in academia ("university effect") and in industry ("understanding effect"), whereas times in academia tend to have a negative impact and industry experience has a positive contribution (O'Reilly & Cunningham, 2017). As a result, an interdisciplinary project team was formed that was able to contribute both scientific and industrial experience.

5 Conclusions and Implications

Due to their prerequisites, SMEs need support in mastering the digital transformation. Universities and research institutions are often seen as providers of knowledge and technology, but different goals, interests and approaches can make cooperation difficult. Intermediaries of knowledge and technology transfer play a major role as mediators between companies and universities to close this gap. The example of the Innovation Center Modern Industry Brandenburg was able to show that intermediaries can support and promote the digital transformation in SMEs by creating a target group- and topic-oriented offer. This offer should create transparency on the topic, serve as a marketplace to connect the different interest groups that support knowledge creation, provide resources and administrative support for the SMEs. The Innovation Center's model factory facilitates an introduction to digital technologies by using physical objects to demonstrate, discuss, learn and network.

Due to limited human and financial resources, companies prefer easily accessible offers that are free of charge and in close proximity to the company. The exchange with reliable contact persons on a par makes a long-term cooperation more likely, a stable network leads to further innovation processes. Companies' needs in automation and digitalization change depending on the level of maturity they have reached, external conditions and internal innovation processes.

In the Innovation Center, it was observed that companies that were willing to collaborate with universities had better chances of mastering the digital transformation. They benefited both from the direct offers and from the implicit knowledge they learned in discussions. Further success factors were an initial assessment and a roadmap based on it, which enabled the prioritized implementation of the individual goals.

Nevertheless, there are still barriers that prevent SMEs from considering universities and research institutions as knowledge providers with regard to automation and digitalization. In addition to the transparent presentation of opportunities and the sensitization of researchers to the needs and language of companies as recipients of research results, a certain persistence of the transfer intermediaries is probably required so that further potential can be tapped here.

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ARENA2036: A Collaborative Space for the Future of Mobility and Production

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Abstract The disruptive impact of digital technologies opens the opportunity to redefine the innovation ecosystems across (and between) several industries. To respond to this challenge, several initiatives were funded all over Germany. The Research Campus ARENA2036 at the University of Stuttgart oversees the platform for research and innovation on the topic of mobility and production of the future. This article describes the creation of ARENA2036, its organizing mechanisms, and its function as a catalyst for collaborative innovation. The article ends with a summary of the lessons learned in its first years of operation and an outlook on the future challenges.

Keywords Collaboration · Mobility industry · Smart production · Innovation spaces

1 Introduction

The evolution of the automotive industry has been driven by constant improvements in production technologies and systems. The region of Baden-Württemberg has been home of leading automakers for decades, creating a rich and complex supply chain network of SMEs in the region. As a result, the region accumulated advanced technological knowledge and production capabilities that sets it apart from any other region in Europe. However, the accelerated transition to the new electric mobility

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Fig. 1 ARENA2036 interior (authors)

paradigm and the omnipresent digitalization created an urge to accelerate innovation across the whole ecosystem.

To respond to this challenge, ARENA2036 was founded in 2013. The Active Research Environment for the Next generation of Automobiles (ARENA2036) is a highly flexible platform for research and innovation on mobility and production. It is a Federal Ministry of Education and Research (BMBF)-supported Research Campus that brings together partners from science and industry in a co-creative and open research environment. The building itself (see Fig. 1) received support from the European Fund for Regional Development (EFRE) and the University of Stuttgart. To ensure that it successfully connects science and industry research, ARENA2036 is built as an association with members from both communities. To add to the co-creative mindset on site, ARENA2036, the University of Stuttgart, and Daimler AG co-founded the open innovation platform STARTUP AUTOBAHN in 2015.

We take three perspectives to explain how ARENA2036 is contributing to the digitalization of SMEs and accelerating the response of the whole innovation ecosystem to the ongoing challenges in mobility and production.

First, we take the innovation organization perspective to describe the distinct types of projects that have structured the activities in the ARENA2036. We then describe the key projects that defined ARENA2036 and how they have contributed to what the collaborative space is currently.

As second perspective, we describe the profiles of the different partners and active members that engaged in the initial set up and the further evolution of the ARENA2036 collaborative space. We explain the motivations and roles that start-ups, SMEs, large companies, and university/research institutes have taken. We take advantage of the five years perspective to reflect on how the network of partners has co-evolved and matured.

Finally, we take the technology perspective to explain how the projects and partners have been organized around the production and mobility challenges. We go in-depth with the technology perspective to explain how the innovation ecosystem has been integrated in ARENA2036, deciphering how the projects have covered aspects related to building the future digital platforms and their integration with existing mobility and production infrastructures and technologies.

We conclude by sharing the four lessons learned in these first two phases of ARENA2036 and the upcoming challenges to keep driving innovation across the automotive supply chain and the broad innovation ecosystem.

2 Organizing for Innovation in Mobility and Production

The ARENA2036 defines itself as a space to co-create innovations and it has a strong focus on the automotive industry. The 2036 suffix in the name is the year that the automobile industry will celebrate its 150th anniversary. Given the ongoing transformation in the automotive industry (Llopis-Albert et al., 2021), the innovation focus includes aspects related to electrification, modern production, and interconnectivity. It resembles other similar international initiatives like the research campus of the Manufacturing Technology Center (MTC) in Coventry, UK, effectively bridging industry and academic research on the future of manufacturing.

To better understand how ARENA2036 works, we first describe the rules and institutional values of the space, to then go in detail on the different projects that agglomerate the different innovation activities.

2.1 The Core Values of the Collaboration Space

An essential aspect of ARENA2036 is that it is defined as an active research environment. In this context, active means that research is done by exploring and testing solutions that can be easily transferred to the industrial production context. For this to happen, a core value of the space is that industry (large companies, SMEs, and startups) and academia work on an equal footing, under the same roof. This means that when engaged in a research project, both sides have an equal role in the generation and experimentation of viable solutions addressing the research challenge.

This core value is translated in the legal form used to organize projects, ARENA2036 promotes the activation of bilateral agreements that involve academic and industry partners. The ambition is to establish an initial framework that reduces the distance between the industry and academia researchers, making it more likely to trigger cross-boundary innovations where ideas coming from science and technologies in a specific research field can be adapted and translated for an industrial research challenge and vice versa.

A second core value of the space aims to strengthen the expected benefits of physical proximity. Besides ensuring proximity by placing industry and academic research units close, in the same space, special attention is given to foster cognitive proximity. This is done by promoting trust within the partners of ARENA2036, by facilitating informal exchanges in the space (workshops, thematic events, open seminars), but even more importantly by putting in place a mandatory non-disclosure agreement (NDA) that every partner's member must sign. Interestingly this NDA mimics an established corporate formality to protect knowledge and secrecy, however ARENA2036 drafted this NDA to create a different effect. It is an open-ended NDA where partners commit to exchange and protect each other's interest in the scope of the innovation projects that are being developed in the space. This NDA contributes to reinforce the core value of trust among partners, it offers a legal space to work together and explore without being constrained by the operational—and intellectual property—boundaries of each organization.

2.2 An Innovation-Oriented Project-Based Space

To drive active research collaborations, ARENA2036 established that it will run its activity around innovation projects. For this, it established three distinct types of projects that would also reflect the scope and resources of the challenge being tackled. The first category is the publicly funded joint projects, these have a duration of 5 years and each of them defines a collaboration pillar inside the ARENA2036 (see Table 1). Over the course of 5 years, the listed projects receive aggregated funding of 10 m€ from the German Federal Ministry (BMBF). In addition to the before mentioned projects, 17 projects were initiated in 2021. These are supported by 261 m€ in total, with a share of 19 m€ for research conducted at the ARENA2036 facilities.

At a second level, the focus projects have an equally ambitious goal but in a shorter time horizon (see Table 2). They are 3-years projects that complement the larger joint projects and help to bring the future visions to solutions that can be implemented by the industry. This category opens additional options to SMEs and startups to collaborate with larger players that usually work with longer time horizons.

Table 1 Description of the publicly funded joint projects at ARENA2036

Project name	Project objective
Agile innovation hub	Understand and further develop the cooperation and innovation process of collaborative research spaces
Digital fingerprint	Develop and visualize the structure for an intelligent value chain
FlexCAR	Develop and promote an open vehicle platform for the mobility of the future
Fluid production	Develop and implement a human-centered cyber-physical production concept

Table 2 Exemplary description of some focus projects at ARENA2036

Project name	Project objective
Catena-X	Promotion and implementation of a secure and standardized data exchange for the automotive industry
DIRECT	Development of a digitally reconfigurable, sensory-supported production environment for high-performance fiber compositive components
GrantSLAM	Interdisciplinary optimization of the SLM process, from the original component concept to the intelligent material composition, and to the desired process result
SynergieRegion	Development and testing of 5G applications for modern production systems in the urban area of Stuttgart
Management shell for the line set	Development of shared digital twins along the value chain to improvement the management overview

Finally, there is a third level for projects that have a duration below one year. These projects are built around very narrow and clear challenges. They are directly funded by the industrial partners, particularly fitting for SMEs needs and capacities. Those projects are meant to also work as pilots that provide some initial evidence to support a larger focus project or joint-project type.

The distinct project types are established to facilitate that ARENA2036's partners can get involved in multiple ongoing projects, as well as join new projects as they complete them. The ARENA2036 management actively seeks to re-engage existing partners in future projects, as well as to bring in new partners into the research campus.

2.3 Managing a Diversity of Collaborative Projects

To understand the approach that ARENA2036 has followed to organize the collaborative innovation projects it is imperative to describe how it is formally established. It is a business association, meaning that each member (currently over 50 organizations) pays an annual fee to be part of ARENA2036. The members' fees help to cover the project management and other running costs of the association.

Consequently, the function of the management of ARENA2036 is not only to look after the physical space—the building—but also to activate, facilitate, and guide the interactions between active partners in the projects and the rest of members in the association. Its function goes beyond the building management role to then become an innovation intermediary that can broker between members to trigger and expand the impact of their activities.

These responsibilities that the management takes, also become visible at project level, where ARENA2036 introduces key performance indicators for each publicly funded project to monitor its respective progress. These indicators are then used to learn and report externally, how the space is operating and how it is contributing to transform the mobility and production ecosystem.

3 Partners and Ecosystem Development

The ecosystem concept has emerged as a popular topic among management scholars in strategy, innovation, and entrepreneurship and is gaining increased attention in practice and policy (Dedehayir et al., 2018; Gomes et al., 2018; Scaringella & Radziwon, 2018; Tsujimoto et al., 2018). Digitalization is the major trend driving business model innovations, open innovation, and ecosystems. Experts frequently refer to today's world as the VUCA world, characterized by volatility, uncertainty, complexity, and ambiguity. Ecosystems are formed when organizations collaborate to create a value proposition that would be impossible for a single firm to create on its own (Adner, 2017). Ecosystems are characterized by participant heterogeneity (large companies, SMEs and other actors), ecosystem outputs, partner interdependence and non-contractual governance.

To further understand how ARENA2036 works, in this section we examine the partner ecosystem and its evolution over time. We have included profiles of the various partners and active members that contributed to its initial setup. We use a longitudinal lens to examine how the network of partners has co-evolved and matured.

3.1 The Ecosystem Blueprint at ARENA2036

ARENA2036 partners join the ecosystem for different reasons. In some cases, they aim to influence the future vision of manufacturing, in others (e.g., SMEs), they try to learn and gain insights on how the industry can evolve. To get a better picture of these different aspects we take the perspective of Lingens et al. (2021) on what constitutes an Ecosystem blueprint and how to design it based on surrounding conditions. We will analyze the ARENA2036 Partner ecosystem and its development and how ARENA2036 defines the architecture of its ecosystem focused on mobility and production using this approach. Ecosystem design entails defining an ecosystem's structure and activities (Lingens et al., 2021). Orchestration is critical for the ecosystem's effective governance and performance, and it encompasses activities at four distinct layers: technological, economic, institutional, and behavioral (Autio, 2021).

In this case, ARENA2036 plays a critical role as the ecosystem orchestrator to bring together all the partners around the shared value proposition. The orchestrator in an innovation ecosystem does not have to be the largest firm with the most resources; it can also be an organization capable of bringing the ecosystem's partners together around a value proposition (Lingens et al., 2021). Thus, we define ARENA2036 as a unique innovation ecosystem in which the orchestrator is not a large corporation but a neutral organization that connects science and industry and is backed by policy and government.

3.2 Ecosystem Partners and Evolution

Now, let us take a closer look at how ARENA2036 has evolved over time. We explore how the network of partners has co-evolved and matured over time using a longitudinal perspective. Among the ecosystem's partners are large enterprises, small and medium-sized businesses, start-ups, research institutes, universities, and accelerators. In 2013, ARENA2036 was founded with the objective of engaging with research and industry in an atmosphere that fosters innovation and creativity. In 2014, the founding partners included large companies such as Bosch, Daimler, and BASF, as well as the University of Stuttgart and research institutes such as Fraunhofer, DLR and Deutsche Institute für Textil und Faserforschung (DITF). A little later, SME's such as BÄR, developing AGVs and automation technologies, as well as FARO, specialized in 3D measurement and imaging technologies, joined the ARENA2036.

We can observe that the ARENA2036 has been successful in drawing new partners over the years, with 54 members today representing large businesses, small and medium-sized enterprises, research institutes, universities, start-ups, and accelerators. Most ecosystem's partners joined to capitalize on opportunities for collaborative work with other ecosystem partners established through projects, benefiting from shared knowledge, and contributing to new innovations by examining problems that no single organization or entity can solve alone. From the standpoint of research institutes and universities, it is an excellent opportunity to market their technology research and contribute critical inputs, as seen by the formation of new spin-off start-ups from universities and research institutes. This way, all ecosystem players benefit from one another, making the entire mobility and production ecosystem more resilient to disruptions caused by digitalization and increased collaboration.

The timeline in Fig. 2 summarizes ARENA2036's evolution from 2013 to 2021, as well as that of its numerous partners. The collaborative projects began to bear fruit in 2018, when the ecosystem's first startup, ThingOS, emerged. Due to ARENA2036's unique position in the ecosystem, which enables it to have a bird's eye view, initiatives such as the Innovation Initiative Wiring Harness (IILS), a first-of-its-kind project to digitalize the wiring harness in the automotive sector, began to emerge in 2019. This has resulted in the addition of new partners to ARENA2036, as stakeholders in ecosystems recognize the value of bringing all parties together to address specific digitalization challenges. The year 2021 saw the highest number of partners join ARENA2036, with 14 organizations.

ARENA2036 has shaped its ecosystem over the years around the future of mobility and production. Additionally, it emphasizes the value of a collaborative innovation space that enables all partners to collaborate on a common value proposition while also developing capabilities for small and medium-sized businesses and start-ups. The current partner ecosystem of ARENA2036 is depicted in Fig. 3, which showcases

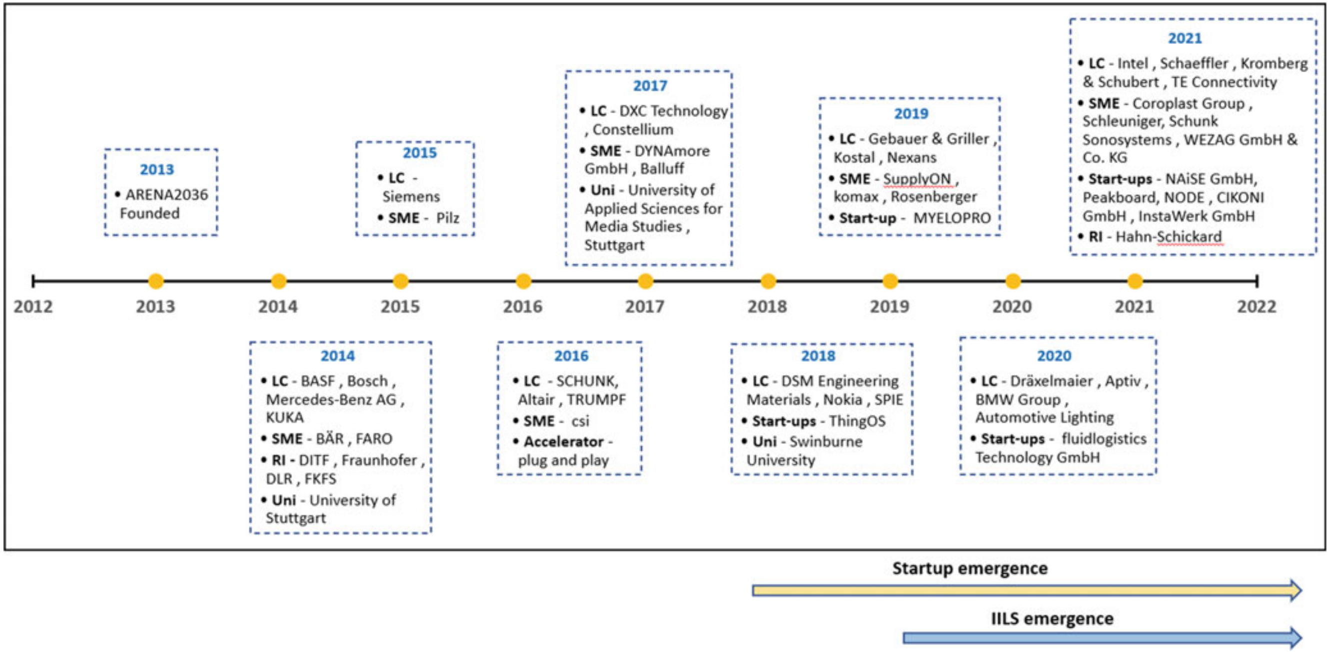

Fig. 2 Evolution of ARENA2036 partners large companies (LC), SMEs, start-ups, academic partners (Uni) and research institutions (RI)

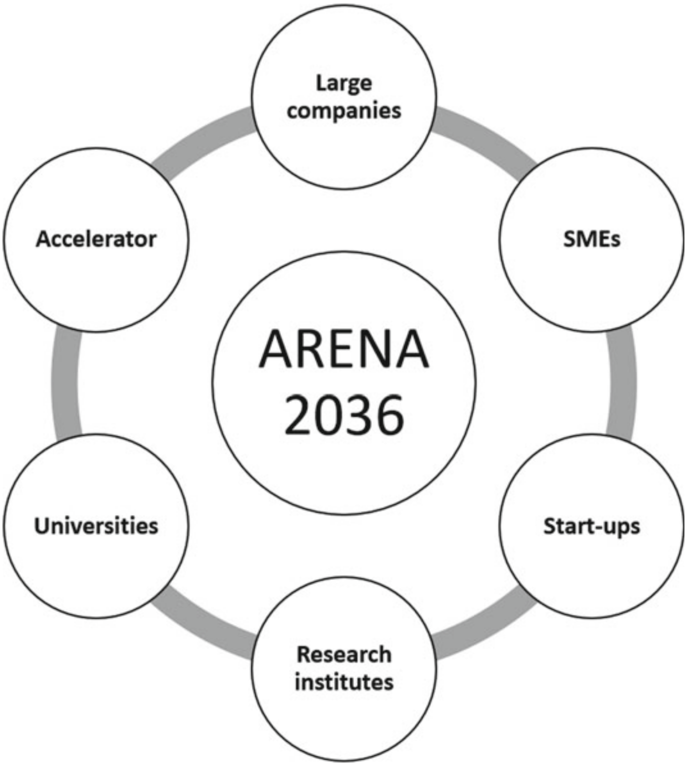

Fig. 3 ARENA2036 Partner Ecosystem

the diversity of stakeholders that are active actors. ARENA2036 has successfully orchestrated the ecosystem to work collaboratively thus far and is still navigating the various orchestration mechanisms as the ecosystem evolves further.

4 Technology View Development

Given the weight of the car manufacturing industry in the regional economy, it is no surprise that the ARENA2036 project defined the transformation of mobility and production as their core goal. This overarching topic defines the central motivation of individual projects carried out within the ARENA2036 framework. Understandably, this goal is too broad and intangible to allow all members to contribute constructively. As a result, "*tech areas*" were introduced, which each portray an underlying, enabling technology. Each *tech area* represents an umbrella for ongoing, crossdisciplinarity and project independent work around a given technology. All *tech areas* are led by

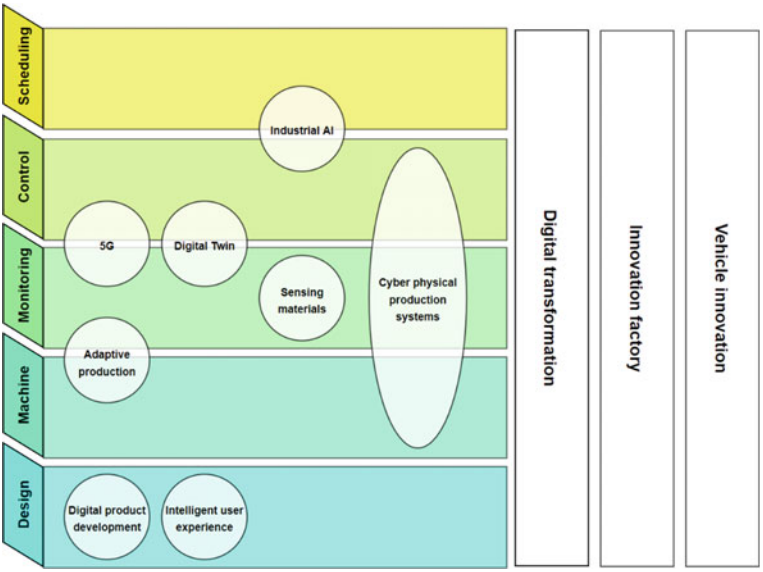

Fig. 4 Categorization of the different tech areas of the ARENA2036 project following Zhong et al.'s (2017) dimensions

one or more experts in the field, who supervise the projects and serve as the main contact person.

The ARENA2036 project is closely related to the concept of Industry 4.0. To visualize how ARENA2036's activities relate to the technologies of Industry 4.0, we bring in Zhong's (2017) framework to map the research topics of the *teach areas*. Their proposed framework allows categorization of intelligent manufacturing systems research topics into five distinct categories: Smart design, smart machines, smart monitoring, smart control, and smart scheduling (see Fig. 4).

- **Smart design** covers all attempts to rethink traditional design processes by introducing cyber physical systems into the process. Especially technologies like augmented reality and virtual reality have the potential to better connect traditional digital design processes such as computer aided design to the real world.
- **Smart machines** describe all efforts to elevate robots and manufacturing machines from passive devices to sensing, fully connected and collaborative equipment. This lays the foundation for digital twins.
- **Smart monitoring** summarizes all research related to obtaining relevant data from individual processes. Those range from process related to generic information surrounding the process. Based on this the operation, scheduling and maintenance of the production site can be optimized.
- **Smart control** deals with the controlling mechanisms of cyber physical production-control systems.

- **Smart scheduling** builds on top of the data obtained from the smart monitoring, building data driven advanced modelling and scheduling algorithms for decision making processes.

In the diagram we can see the positioning of all the *tech areas* defined. Production specific areas have been placed within the framework, while accompanying areas have been placed alongside.

Looking at the *tech areas* and their positioning, it becomes apparent, that a wide variety of production related topics are covered by the research conducted at ARENA2036. However, given the strong emphasis on the car manufacturing sector, it is not surprising that the focus lies on optimizing and rethinking production processes. Especially the smart scheduling category has not received as much attention as other categories. Improving the supply chain management will without a doubt be as relevant as the production itself in the future.

In addition to production related areas, three more topics complement the research at ARENA2036. These intend to foster innovation surrounding vehicles of the future and business model innovation through digital transformation. While these topics do not directly contribute to the production itself, continuously questioning current products and business models means that the research does not only focus on doing things right but is also concerned with doing the right things.

Overall, it can be concluded, that the research consortium covers all relevant aspects of the industry 4.0 technologies, while not losing sight of more impactful changes to the car manufacturing industry. The subdivision of the core goal into smaller areas with autonomous projects and leadership results in the projects being more agile and focused, while at the same time allowing greater specificity of the individual projects. However, effective communication between the different areas becomes imperative, since most if not all areas are interconnected and should benefit from the learnings of others.

5 Lessons Learned on Orchestrating a Production and Mobility Innovation Ecosystem

Having started out in 2013, ARENA2036 is now looking back at nine years of precompetitive, collaborative research. The BMBF has set the scene for the Research Campus initiative with a headline that shape the every-day work of everyone involved: (1) it is an industry on campus scheme that enables, (2) science and industry to, (3) work together on an equal footing in, (4) a precompetitive environment.

Beyond these guidelines, the actual implementation of the cooperation varies amongst the nine Research Campuses in Germany. Hence, this is also an interesting opportunity for companies, and in particular SMEs, to gain more insights into the different interpretations of these guidelines.

As for ARENA2036, there are numerous learnings that show us how to enable collaborative innovation. At the same time, there is still quite some room for improvement when it comes to systematizing the serendipitous nature of cooperative ideation.

First, we will discuss those experiences that we still pursue and that we plan to further develop for the years to come. After that, we will turn to those areas, where we still see room for improvement. The backbone of everything that follows is always the goal to speed up the process from idea to project to transfer. Finally, we close with concrete suggestions for practice.

ARENA2036 is conceived as an ecosystem platform, i.e., management serves as platform operator and simultaneously functions as a catalyst, whilst the partners on the platform are the ones involved in the actual research projects. In other words, one partner that joins the platform benefits from the experience and expertise of 50+ other partners, instead of having to repeatedly seek individual partners for bilateral research relationships. This is especially valuable for SMEs and Start-ups, since ARENA2036 offers them an ecosystem that guarantees immediate access to large corporates as well as research institutes that they would otherwise not be able to approach. Knowing this, ARENA2036—secondly—puts an emphasis on projects that have a similar platform character. This means that the larger ARENA2036-projects are conceived in a way that they are architecturally open to enable other partners to join into a discussion with the project owners and to potentially add to the project with their respective expertise. This is in line with earlier research highlighting the role of innovation ecosystems orchestrators, the value of common standards, and the strategic approach which is necessary to develop ecosystems further (Brem et al., 2016). For this, it is also important to consider at which levels different projects operate. Utilizing the Technology Readiness Level (TRL) helps to assess the different stages projects are in. Here, the challenge emerges that projects at early levels (TRL 1–3) must be combined with projects at applied levels (TRL 4–6) up to industrial projects (TRL more than 7), ideally in combination with other readiness levels such as demand, regulatory, etc. (Hjorth & Brem, 2016; Vik et al., 2021). The experience in the ARENA2036 context, indicates that a mix of such TRLs fosters collaborations to a certain extent, but also hinders project evolution, requiring for ARENA2036 interventions to realign the collaboration between projects. Otherwise, this creates problems when project partners' expectations do not match or have not been explicitly discussed before. For instance, if you get a 5G network installed in the factory floor, but the accuracy of the network is not as assumed by the project partners, this requires revision and redeployments of expensive technical equipment in the collaborative area of the research campus. In conclusion, there is high potential, yet it is necessary to have management interventions to make sure that it is exploited.

That said, there are still vast, partly untapped potentials. Over the past eight years, we were able to observe that chance plays a crucial role in the ideation and innovation process. Turning mere chance into serendipity is one of the management-tasks that needs further attention. For example, ARENA2036 offers an open research environment that enables researchers and developers from diverse backgrounds to move around freely and without structural barriers between the different companies of institutes. This openness creates chances for random meetups, for inspiration, and an exchange of ideas. However, increasing the frequency of these meetups, hiding inspiring prototypes in plain sight, and creating more spots for productive exchanges of ideas is a challenge that shall be tackled soon. To do so, we plan to redesign the entire shopfloor in such a way that the researchers and developers are forced to take detours on their way from a to b, to increase the number of accidental meetups, inspiring moments, and insightful conversations. In other words, we aim at finding a way to structurally help with the transformation from mere chance to serendipity. This highlights the role of formal and informal communities of practice, which typically undergo several phases in their development (Brem & Maier, 2014). The first phases are like the one of startups, where the focus lies on building up structures, bringing in partners and acquisition of customers, with the overall aim to have a solid foundation for growth. Later, the focus shifts towards managerial issues since the growth of an organization is generally higher than the adaption of related processes (Picken, 2017). These dynamics can also be seen in the ARENA2036 setup. Here the challenge remains to develop the setup further, including new partners and ending projects which are beyond their project deadline and scope. Such renewal processes come also with a kind of pain, since established routines are always difficult to break in any organization with new configurations and business models (Volberda et al., 2021).

In this context, the COVID-19 pandemic with all the related restrictions in 2020 and 2021, and beyond, showcases how critical personal interactions are. Even though there were digital technologies available as alternatives, this could not substitute human interaction one would have meeting in person. Especially when it comes to new projects and project execution in these years, the negative effect of the pandemic is apparent.

Lastly, management has a privileged teichoscopic position that allows for a bird's eye view on the entire portfolio of partners. This enables management on the one hand to take on a seismographic role, which informs the general strategic process, thus allowing for the improvement of the ARENA2036 platform. Simultaneously, however, it offers a chance to formulate future topics at the intersection of interests of a variety of partners that we are only now beginning to turn into high profile projects such as the Innovation Initiative Wiring Harness (IILS) or Catena-X, that will create common standardized platforms for the automotive industry. Going forward, formulating, implementing, and proactively managing such lighthouse projects, is an area that we have only begun to explore. ARENA2036 partners such as the STARTUP AUTOBAHN can provide an international platform for collaboration with startups, while partners within the University of Stuttgart can potentially increase the range of fields covered. Finally, growth of such ecosystems naturally leads to more competitive situations. To overcome such challenges, a mindset of coopetition might help in the future (Luo, 2007).

In conclusion, what are the learnings of this research campus setup, framed as implication for managers? In a nutshell:

- Bring both companies (industry) and research (academia) institutions together in a joint, managed open space.

- Assemble multiple companies (and include SMEs and startups) with distinct knowledge and specialty areas within the same physical space
- Start only projects that have a common interest and a clearly defined goal, duration, and end
- Create a culture of "give and take" beyond cultural and disciplinary borders
- Take your project partners serious, stick to deadlines, and deliver as per the made commitments.
- Enforce promised commitments from the partners

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Subscription Business Models as Accelerators for the Adoption of Industry 4.0 by SMEs

Nils Burgmann, Markus Burger, and Andreas Krüger

Abstract As the implementation of Industry 4.0 challenges current business models, subscription-based models enter the market. Frontrunners offer subscriptions, e. g. for printing machines, compressors or vehicles and promise various benefits to their customers. While SMEs struggle with the implementation of Industry 4.0 due to lacking technology awareness and missing financial or knowledge resources, the use of subscriptions for industrial goods is scarce. Thus, SMEs with limited digital capabilities face a broad range of different subscription models, offered by larger providers. We contribute to this issue, by exploring how different characteristics of subscription offers correlate with benefits and challenges for SMEs. Based on both a multiple case study and expert interviews beyond the cases, we identify three moderating dimensions of a subscription offer. While comprehensive fulfillment related to these dimensions promise the most benefits, it requires certain technical requirements and increases SME's dependency on the provider. This article helps SMEs to assess the suitability of subscription offers based on their given capabilities.

Keywords SME · Subscription business model · Industry 4.0 · Digitalization

1 Introduction

Technology trends such as automation and the Internet of Things, subsumed under the term Industry 4.0, enable new forms of digital business models. Machines and equipment are increasingly interconnected and fitted with sensors. Production and machine data can be accessed and analysed in real time. This enables new digital services for industrial products (Ibarra et al., 2018). However, Industry 4.0 also puts companies in an increasingly competitive environment. The application of Industry 4.0 technologies is therefore very critical for them. That is especially demanding for SMEs. They face challenges in adapting to Industry 4.0 that can be condensed into three main

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categories: limitations in financial resource, knowledge resource and technology awareness (Masood & Sonntag, 2020).

Subscription business models are a promising form of digital business models. In recent years, providers in the industrial context have supplemented their existing business model with these. For example, *Intuitive* offers its robot-assisted surgical system to hospitals and *Heller* offers its machine tools (*Heller4Use*) as part of a pay-per-use model (Engel et al., 2021). Such pioneering projects were researched by academics in the form of case studies. They focus on the implementation of these models by the provider and identified different types (Rudolph et al., 2017). From a customer's point of view, the use of subscription has not been considered extensively in the literature. The many forms of such models make the portfolio difficult to survey. A structured overview for subscribers is missing. The requirements for the realisation of such a model in the procurement of production machinery and equipment, and the challenges that arise are not well understood.

While facing various hurdles related to the implementation of Industry 4.0, different forms of subscription models are offered in the market. These offers differ, e.g. in the form of payment (periodic or usage based), or in the allocation of responsibilities (who operates the machine—provider or customer). Are there different requirements and challenges due to different forms of these models? Which benefits are driving the usage of these models? To answer these questions, we explore the following research question:

> How do different characteristics of subscriptions correlate with challenges and benefits for SMEs using these offers?

In order to answer this question, we conduct an exploratory study. We examine 5 cases where subscription business models have been successfully implemented. To support the findings, we also conduct 11 expert interviews beyond the cases.

2 Theoretical Background

2.1 Subscription Business Models

The first types of subscription business models were used as early as the fifteenth century. Navigators and explorers not only bought a current version of a map, but also the service of always having the latest version available. As the discovery of the world progressed, the map material quickly became outdated. By subscribing, the navigators and explorers ensured that they received the latest update (Warrillow, 2015).

In the last century, the model also gained importance in the private sector. To this day, customers receive their newspapers at home via subscriptions. At the beginning of this millennium, digitalization opened up new possibilities for subscriptions. Streaming services such as Netflix or Spotify use the internet to give their customers access to content such as movies and music for a monthly fee. Such services are still growing today.

The success of digital subscription in the private sector in recent years and the increasing opportunities presented by Industry 4.0 are prompting more and more companies to look at this business model. Academia is also increasingly investigating subscription business models in an industrial context. One research stream is concerned with the definition. Here there are very general approaches that understand subscription business models across industries and independent of the sector. E.g., Gassmann et al. (2021) defines the recurring provision of products or services and the associated regular payments as the core of subscription business models (Gassmann et al., 2021).

In the industrial context, Schuh et al. (2019) focuses on the bundling of products and services and their continuous improvement (Schuh et al., 2019). Schuh et al. (2020) defines four main characteristics of subscription business models in the machinery and equipment industry: periodic payments based on results, continuous improvement of customer value, knowledge of changes in individual customer value and a long-term, cooperative partnership (Schuh et al., 2020). Riesener et al. (2020) names a product-service system as the basis for a subscription business model and sees customer-centricity as an essential characteristic (Riesener et al., 2020). Liu et al. (2020) additionally emphasises in the definition that the values are not transported by the physical product alone, but by the entire scope of services (Liu et al., 2020).

2.2 Dimensions of Subscription Business Models

There are various approaches to characterising the different forms of subscription business models, some of which take the sector or industry into account. Rudolph et al. (2017) presents three archetypical categories for the B2C sector, which are differentiated according to the degree of surprise of the offer: predefined subscriptions that ship commoditized items, curated subscriptions that ship products of a certain category selected in accordance with consumers' preferences and surprise subscriptions that ship boxes with content that cannot be controlled by consumers (Rudolph et al., 2017).

Liu et al. (2020) presents a structure for categorising subscription business models in manufacturing. The structure consists of six categories, some of which build on each other. A physical product is the basis for all subscription offers. All services in the categories serve to increase the productivity of this product (Liu et al., 2020).

In Burgmann et al. (2021) developed three dimensions to differentiate the various forms of subscription business models in the industrial context. The underlying model is a product-service system (PSS). An output is generated for the customer via the dimensions scope of services and process coverage. The scope of services can include, e.g. services such as the continuous monitoring of a machine, the required procedural adaptation during operation, the maintenance or the actual operation of the machine. The process coverage describes which process steps, preceding and succeeding processes as well as ancillary processes are covered by the subscription. This can include, e.g. the provision of consumables or the feeding of manufactured parts to the next process. The quantification of the output is the foundation for the third dimension, the billing logic. On the basis of, e.g. the number of units produced, kilometers driven or the amount of compressed air supplied, the provider continuously generates invoices. The customer, referred to as a subscriber in the context of the subscription, attends to these invoices in regular payments. Figure 1 illustrates the relationship between the three dimensions *scope of service*, *process coverage* and *billing logic*. For the purpose of our study, we define these dimensions as follows:

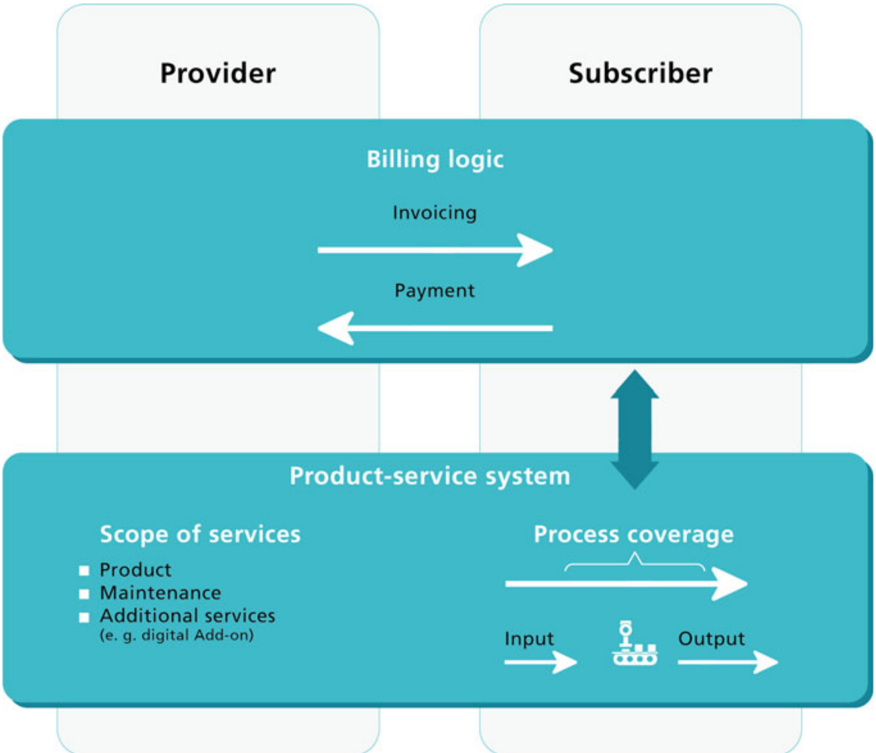

Fig. 1 The relationship between the three dimensions *scope of service*, *process coverage* and *billing logic* of subscription business models in an industrial context

Process coverage: Share of all upstream and downstream processes and activities that are required to generate the defined output and are carried out by the provider, e.g. machine operation, maintenance, procurement of consumables or transport on the shop floor.
Scope of service: Is the set of services provided to a customer within the scope of its subscription. Additional to the output generation, services like digital add-on, consulting activities and trainings may be included.
Billing logic: Is the mechanism by which output is billed and paid for. Payments can range from fully periodic to fully output-based. As a rule, a combination of both variants is used in various degrees.

We use the term output to describe the result that is created as part of the defined processes. It includes physical results, e.g. parts, and provided performances.

2.3 Benefits and Challenges in the Transition from One-Time-Buy to Subscription

The idea of enriching physical product with additional services is known as servitization. Servitization plays an important role in the adoption of subscription business models. Many publications have examined the transformation from a product-oriented to a service-oriented provider and highlighted both benefits and challenges. Rymaszewska et al. (2017), for example, presents a framework in which servitization brings out benefits from IoT-based solutions (Rymaszewska et al., 2017). A similar idea is outlined by Frank et al. (2019). In their conceptual framework for business model innovation, the two transformation trends Industry 4.0 and servitization are connected (Frank et al., 2019). Parida et al. (2019) combine digitalization with business model innovation and sustainable industry in a framework (Parida et al., 2019). Kohtamäki et al. (2019) investigating the impact of servitization of a company on its ecosystem (Kohtamäki et al., 2019).

To date, only a few papers have directly addressed benefits and challenges in the transition to the subscription business model. Some work examines the benefits and challenges in the context of the underlying product-service system. This usually happens with a focus on the provider. Mont presents in Mont (2002) two lists that classify barriers and benefits of PSS in a theoretical framework. The barriers are challenges that a supplier faces when introducing these models. Benefits, on the other hand, are categorized by stakeholder. For the customer, the article lists the benefits: added value through more customized offers of a higher quality; changing needs and conditions can be better satisfied by the flexible service component and consumers are relieved of responsibility for the product as it stays under the ownership of a producer through its entire life span. These benefits and challenges are also revisited by Helo et al. (2017a). Lah & Wood, (2016) also compile financial motivators for customers from the perspective of a provider in a guide: cost savings through reduced operating costs for the customer, revenue generation through increased revenue the customer can generate, and risk avoidance by preventing the loss of revenue or assets (Lah & Wood, 2016).

A guide for machinery and equipment manufacturers to develop a customized subscription offer is presented by Liu et al. (2020). It includes an overview and structure for potential offers for customers, as well as success factors and requirements. As a starting point for this framework, potential offers and value propositions were collected from all industries and success factors were derived. These success factors were then examined in terms of their transferability into the machinery and equipment industry. Finally, the requirements specific to this industry were defined.

Like Liu et al. (2020), Burger et al. (2022) define requirements and success factors within a transformation framework (Burger et al., 2022).

We assign the success factors together with the motivators and benefits to the supercategory *benefits*. The requirements, obstacles and risks form the supercategory *challenges*. In these two supercategories, we summarize the challenges and benefits from the various sources in literature (Burger et al., 2022; Helo et al., 2017b; Lah & Wood, 2016; Liu et al., 2020; Mont, 2002). We then grouped these in turn as follows.

Benefits

- *Better plannability, more accurate procurement and sales calculation*: Benefits that have an impact on a company's administrative processes.
- *Bundling and customization*: All the benefits that come with subscription configurations.
- *Enabled digitalization, gaining know how and recources*: All the benefits that address digital transformation, the transfer of knowledge and competence carriers.
- *Increase utilization, availability and productivity*: All benefits that enhance important KPIs for the evaluation of production.
- *Investment, operational expenditure shift* (*opex-shift*)*, flexibility and risk transfer*: All benefits relevant for strategic alignment of the business.

Challenges

- *Connectivity, manageable process complexity and urgency*: Challenges that arise due to the specific initial situation of a company.
- *Contracting and trust-based partnership*: The challenges that arise in collaboration on both a business and relationship level.
- *Cyber security, data ownership and transparency*: The challenges presented by sharing data across corporate boundaries.
- *Loss of contact to market, dependency and locked-in effect*: Challenges arising from strengthened risks and dependencies in procurement.

Using these groups, we analyzed, within the study described below, cases for the benefits and challenges.

3 Methodology

In order to investigate the influence of the different types of subscription business models on subscriber's challenges and benefits, we conducted an exploratory study consisting of two parts: five case studies and eleven additional expert interviews beyond the cases.

A case study explores a certain phenomenon in a real-life context (Yin, 2018) and allows to understand the dynamics present within single settings (Eisenhardt, 1989). For the case studies, we interviewed providers of industrial products. Wherever possible, we supplemented the interviews with research from secondary sources. For gathering insights beyond the cases, we interviewed third-party providers involved in the realisation of subscription offers, such as consulting, IT or insurance providers. With the help of the different perspectives, we validated the findings from the case studies. We selected the participants of the study according to the following criteria: For the case study, the companies had to offer or been using a subscription service for at least one year. The expert interviews were conducted with persons who have at least three years of experience in their industry and are involved in the decision-making process for the realisation of subscription business models.

At the time of the study, the participating companies had staff numbers between 300 and 49,000. Their annual turnover ranged from 70 million to 50 billion euros. Table 1 lists these figures in detail.

The interviews were audio recorded and fully transcribed and subsequently analyzed in two steps. In the first step, three experts independently analyzed each interview individually. In the second step, the individual analyses were discussed and combined.

4 Findings

Table 2 shows the correlations between dimensions and benefits and challenges of subscription business models as identified in Sects. 2.2 and 2.3.

In the course of our study, we were able to identify that top management support, willingness to learn, internal transformation as well as culture and internal resistance are main challenges in the adoption of a subscription business model across the dimensions. The changes that result from the implementation of this model in procurement extend to many areas of the company. They are changes in the company's own business model, e.g. the cost structure, and thus fundamental for the company. These changes can only be driven by top management and a comprehensive change management throughout the company.

We too discovered challenges and benefits in using subscription business models, which vary in their degree of severity depending on the dimensions considered. Not every dimension has an influence on specific challenges or benefits. Nor are these

Table 1 Overview of the study data sample

No.	Study type	Business segment	Role	Employees in k (2020)	Revenue in mill. € (2020)
1	Case	Locomotives	Provider	40–50	> 10,000
2	Case	Printing presses	Provider	10–20	1000–5000
3	Case	Machine tools and laser systems	Provider	10–20	1000–5000
4	Case 4	Core shop systems	Provider	< 1	< 100
5	Case 5	Compressed air stations	Provider	40–50	> 10,000
6	Interview	Aircraft turbines	Provider	> 50	> 10,000
7	Interview	Locomotives	Subscriber	< 1	100–500
8	Interview	Locomotives	Subscriber	< 1	100–500
9	Interview	Printing presses	Subscriber	1–5	100–500
10	Interview	IIoT	3rd party	< 1	< 100
11	Interview	Healthcare	Provider	> 50	> 10,000
12	Interview	Custom equipment	Provider	< 1	< 100
13	Interview	IIoT	3rd party	1–5	100–500
14	Interview	IIoT	3rd party	< 1	1000–5000
15	Interview	Consulting	3rd party	< 1	1000–5000
16	Interview	Insurance	3rd party	1–5	100–500

influences explained by individual challenges and benefits. For the challenge groups developed in Sect. 2.3, we can derive the following relationships as sub-conclusions.

- *Connectivity, manageable process complexity and urgency.* Connectivity is the basic prerequisite for a broad scope of services and high process coverage. The better the existing connectivity, the easier it is to implement a subscription business model with corresponding degrees of coverage.
- *Contracting and trust-based partnership.* In all the case studies, there existed a trust-based relationship between the supplier and the customer already before the joint introduction of a subscription. This trust was strengthened in all cases during the course of the realization.
- *Cyber security, data ownership and transparency.* A high process coverage and a large scope of services increase the points of entry for cyber attacks, make authorization issues more complex, and the subscriber more transparent to the provider. Accordingly, the aspect of cyber security is gaining in importance.
- *Loss of contact to market, dependency and locked-in effect.* Higher process coverage increases the subscriber's dependence on the provider. Switching providers becomes more complicated, and contact with subcontractors is lost.

In summary we can derive that a high process coverage and the use of additional digital add-ons extend existing technical challenges and at the same time increase

Table 2 Correlations between dimensions and benefits as well as dimensions and challenges of subscription business models

		Dimensions of subscription business models				
		Product-service system				
Category	Group	Billing logic	Scope of service	Process coverage	Conclusion group	Conclusion category
Benefits	Better plannability, more accurate procurement and sales calculation	With the help of purely outcome-based contracts, former machine-based fix costs that have been broken down to specific products by calculation, can now be directly linked to the products as variable costs. E.g., the subscriber in case 2 announced to increase the accuracy of its internal calculation	Digital add-ons like the analysis and visualization of data help to determine the demand from previous processes and for consumables more precisely. Additionally AI features may help to predict demands based on historical data		The higher the variable cost share and the more data evaluated by the provider (not only the data used for the billing logic, but also data available via e.g. digital add-ons), the better the predictability for the subscriber	**Process coverage as a multiplier of benefits.** A high level of process coverage can reduce the number of suppliers and make as many investment costs as possible variable. Also, the corresponding processes must be digitally linked. Often, the provider contributes the know-how for setting up these digital connections and thus supports the SME's digital transformation. A broad scope of service with digital add-ons also contributes to digitization. The higher the usage-based cost share in the model, the more easily goals such as the OPEX shift or a more accurate calculation can be realized
	Bundling and customization		Which processes the subscriber wants to cover influences the minimum scope of service. In case 5, for example, compressed air systems are provided and billed via delivered units. The scope of services also includes the maintenance of the system to ensure the guaranteed performance	The greater the process coverage, the more suppliers can be replaced by the provider. In case 2, the provider supplies the consumables in addition to the printing press	An all-in-one solution can be achieved through high process coverage and a large scope of service. The larger the process coverage, the more the subscription offering must be tailored to the subscribers needs	

(continued)

Table 2 (continued)

		Dimensions of subscription business models				
		Product-service system				
Category	Group	Billing logic	Scope of service	Process coverage	Conclusion group	Conclusion category
	Enabled digitalization, gaining know how and resources		By including digital add-ons for analysing and visualizing data, or using data for predictive maintenance activities, the provider pushes digitalization approaches at subscriber's shop flor. Further providers can educate the subscriber's employees by consulting activities. E.g., in case 2 the provider supports with the qualification and training of subscriber's employees	For comprehensive process coverage, processes need to be linked and process data must be exchanged along the overall process. Thus, providers might help to digitalize processes by the installation of sensors and by the interlinkage of related data	In-depth process coverage and a wide range of services support digitalization, as expertise in more business processes can be gained through training and consultancy	
	Increase utilization, availability and productivity			It is particularly valuable to investigate machines with low utilization or availability. Here, on the one hand, the potential for an increase in productivity is high. On the other hand, productivity increases for neighboring processes may be limited by this machine	The higher the process coverage, the more process-related and technical interfaces are involved. The more interfaces involved, the more inefficiencies are potentially present and can be eliminated by an all-in-one solution. It should be noted that there are interfaces that hinder efficiency as well as enable it. An all-in-one solution is the desired ideal, but often not feasible due to cost and high complexity	

(continued)

Table 2 (continued)

		Dimensions of subscription business models				
		Product-service system				
Category	Group	Billing logic	Scope of service	Process coverage	Conclusion group	Conclusion category
	Investment, opex-shift, flexibility and risk transfer	Achieving fully variable total costs, as there is no initial capital expenditure and costs are only incurred when the machine is in operational use, such as in case 3, where billing is carried out per produced component This increases the flexibility of the subscriber		The higher the process coverage, the greater the investment savings. In case 4, e.g. additionally to foundry cores the provider also operates core shooter systems. The subscriber also saves the cost of an employee to operate the machine	The higher the process coverage, the more "investment demand" is variabilised and the less capital is tied up in capex. (strong variabilisation of costs through a 100% pay-per-use model)	
Challenges	Connectivity, manageable process complexity and urgency		Comprehensive process coverage, i.e. the processes are interlinked and process data can be exchanged across the overall process, enabling the provider to integrate further digital add-ons in the offer	For comprehensive process coverage, processes need to be linked and process data must be exchanged along the overall process. Although providers may help to digitalize related processes, consisting process connectivity is beneficial and eases to archive a high process coverage of subscription	Connectivity is the basic prerequisite for a broad scope of services and high process coverage. The better the existing connectivity, the easier it is to implement a subscription business model with corresponding levels of coverage	**High process coverage and digital add-ons extend existing technical challenges and at the same time increase dependency**. Both factors require a certain digital "pre-maturity" on the part of the customer. Processes should already be linked to a certain degree to avoid IT-based risks. Billing logic is of minor importance

(continued)

Table 2 (continued)

		Dimensions of subscription business models				
		Product-service system				
Category	Group	Billing logic	Scope of service	Process coverage	Conclusion group	Conclusion category
	Contracting and trust-based partnership			The higher the process coverage, the more responsibility the subscriber hands over to the provider. This requires a corresponding basis of trust between subscriber and provider, e.g. in case 2 a need was stated for joint problem solving throughout the implementation	In all the case studies, there existed a trust-based relationship between the supplier and the customer already before the joint introduction of a subscription. This trust was strengthened in all cases during the course of the realisation	
	Cyber security, data ownership and transparency		While digital add-ons are based on the analysis and visualization of data, setting up these services requires a high level of control for access rights and data security. These demanding legal requirements for security hinder digitization approaches, for example in case 6 for logbooks in the aerospace industry	As a deeper process coverage requires the linkage of processes and data, the number of potential attack points and lost data increases in case of higher process coverage. While the provider in case 2 covers e.g., the management of inbound materials, the company puts emphasis on cyber security efforts	A high process coverage and a large scope of services increase the points of entry for cyber attacks, make authorization issues more complex, and the subscriber more transparent to the provider. Accordingly, the aspect of cyber security is gaining in importance	

(continued)

Table 2 (continued)

		Dimensions of subscription business models				
		Product-service system				
Category	Group	Billing logic	Scope of service	Process coverage	Conclusion group	Conclusion category
	Loss of contact to market, dependency and locked-in effect		In a broad scope of service, a subscriber outsources actives as, e.g., maintenance or data analysis to the provider. Consequently, the subscriber's ability to built up these capabilities by himself might be limited. E.g., one subscriber in case 1 depends on the provider's fulfilment of technical and legal requirements, while its own ability to control the provider is limited	While the provider takes care about pre-processes e.g., procurement of consumables, the buyer looses the contact to related suppliers. E.g., the subscriber in case 2 depends on provider's procurement activities and thus can hardly influence quality or benefit from price discounts	Higher process coverage increases the subscriber's dependence on the provider. Switching providers becomes more complicated, and contact with subcontractors is lost	

dependency. Both factors require a certain pre-requisite level of digital maturity on the part of the customer. Processes should already be linked to a certain degree to avoid high IT-based risks. The billing logic is of minor importance. Sub-conclusions for the benefits groups are:

- *Better plannability, more accurate procurement and sales calculation.* The higher the variable cost share and the more data evaluated by the provider (not only the data used for the billing logic, but also data available via e.g. digital add-ons), the better the predictability for the subscriber.
- *Bundling and customization.* An all-in-one solution can be achieved through high process coverage and a large scope of service.
- *Enabled digitalization, gaining know-how and resources.* In-depth process coverage and a wide range of services support digitalization, as expertise in more business processes can be gained through training and consultancy.
- *Increase utilization, availability and productivity.* The higher the process coverage, the more process-related and technical interfaces are involved. The more interfaces involved, the more inefficiencies are potentially present and can be eliminated by an all-in-one solution. It should be noted that there are interfaces that hinder efficiency as well as enable it. An all-in-one solution is the desired ideal, but often not feasible due to cost and high complexity.
- *Investment, OPEX-shift, flexibility and risk transfer*. The higher the process coverage, the more investment demand is variabilised and the less capital is tied up in capital expenditures (capex). A 100% pay-per-use model can achieve a high degree of cost variabilization.

In our study, we discovered process coverage as a multiplier for benefits. A high level of process coverage can reduce the number of suppliers and make as many investment costs as possible variable. Also, the corresponding processes must be digitally linked. Often, the provider contributes the know-how for setting up these digital connections and thus supports the SME's digital transformation. A broad scope of service with digital add-ons also contributes to digitization. The higher the usage-based cost share in the model, the more easily goals such as the OPEX shift or a more accurate calculation can be realized. In general, the dimension process coverage has the broadest influence on challenges and benefits, followed by scope of service. While the billing logic still has an influence on a few benefits, it no longer affects the challenges at all.

5 Conclusion

Our findings show a moderating effect of the dimensions of subscription business models on the challenges and benefits when using these models. SMEs can generate the greatest benefits in a comprehensive model, where the provider takes responsibility for the output and all downstream processes by offering digital dashboards, consulting services and providing consumables. However, such a model requires the following:

- The subscriber must be able to meet the technical conditions. Often the provider can support, but a low Industry 4.0 maturity level of the subscriber increases the implementation time.
- The subscriber increases its dependency on the provider. Data releases should be clarified in advance, own employees comprehensively taken along. Management-driven change management is just as relevant as a proper weighing of the objective of handing over as much risk as possible to the provider and the resulting higher dependency on the provider (locked-in effect).

The billing logic as a factor increases the variablization of costs and the plannability, but it also presents additional challenges. A complete variabilization of costs is a goal that is rarely achieved. This corresponds to a 100% risk transfer, which in most cases is not shouldered by the provider. Provider and subscriber negotiate a mixed form that combines periodic and variable shares to varying degrees for the payments. The subscriber has two adjustment levers concerning the knowledge resources for the adaptation of Industry 4.0 via the dimension. It can obtain consulting and training services as part of the scope of services and thus have its employees empowered. Alternatively, it can hand over the processes that require a high level of expertise in the area of Industry 4.0 to the provider. In both cases, an SME can mitigate the limitations with regard to knowledge resources and technology awareness. Financial limitations can be mitigated by three levers. Subscription is based on the idea of continuously increasing productivity. This increases the profit. Through the shift from capex to opex in procurement, an SME needs to tie up less capital in production machinery and equipment. Thus, more capital is available for other investments. And in addition, fixed expenses are reduced by the variabilization of costs.

6 Limitations and Further Research

The results we have developed are built on case studies. In general, these studies are criticized for examining a specific phenomenon in a specific context and for being limited by the number of cases studied. Although we attempted to address this by conducting additional expert interviews to gather information beyond the five cases, a limiting factor is the dependency on qualitative data. In addition, qualitative research can be influenced by researchers (Stake, 2005). Further surveys or Delphi studies need to be conducted to develop, validate and quantify the impact of the subscription switch, such as in terms of performance.

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Part 3
Solutions

Introduction to Part 3

Integrated Solutions for Smart Production

Charles Møller

Abstract This part will contain a collection of papers that all describes general solutions for Smart Production (e.g., CPS, collaborative robots, IIoT, reconfigurable manufacturing systems, paperless production, predictive analytics, additive manufacturing etc.) which integrates several enabling technologies to be presented in Part 4 into applications of relevance to SMEs. The general concepts will be presented and illustrated by examples and case studies. The benefits and challenges for SMEs associated with realizing the concepts will be discussed. This could include aspects such as: which opportunities do the concepts/applications provide the SMEs; can the SMEs do the implementation themself; which managerial and decision capabilities are needed.

Keywords Industry 4.0 · Smart production · Integrated solutions

1 Introduction

Industry 4.0 (I4.0) has been proposed as a vision of a technological driven transformation of industry towards a highly competitive digitized ecosystem (Kagermann et al., 2013). The concept of I4.0 started out as the framing of a strategic initiative in the German industry to support re-industrialization, and later I4.0 was adopted by the World Economic Forum as the Fourth Industrial Revolution (4IR). The 4IR is mainly an explanatory story telling around the impact of new technology in society, and it has been widely accepted in business as a new vision to pursue even bigger agendas, such as sustainability, equality, etc. (Schwab, 2016).

In general, both I4.0 and 4IR, is driven by technology related concepts like cyber-physical systems, digital twins, artificial intelligence, blockchains, advanced robotics, new smart materials etc. In a much-cited report from Boston Consulting Group, the nine key technologies that are transforming industrial production are named as: Big Data and Analytics, Autonomous Robots, Simulation, Horizontal and

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Vertical System Integration, The Industrial Internet of Things, Cybersecurity, The Cloud, Additive Manufacturing, and Augmented Reality (Colotla et al., 2016). Most of these technologies will covered in the next part of this book (Schou, 2022), and in this part of the book, we will cover solutions with potentials for SMEs. Potential solutions for SME's are not characterized by state-of-the-art technologies, but rather the combination of new affordable technologies and the knowledge and dedication of engaged employees to deliver value.

Defining specific technologies as I4.0 seems inappropriate. In principle any technologies may enable I4.0 solutions—new or old! But what seems to have happened is more related to the availability of the advanced technologies in terms of usability and cost. Cost is obviously a major driver of the adoption of technology in industry, and what we have seen is a massive commoditization of advanced manufacturing technology, because of the increasing digitalization.

Another driver of the availability is the standardization of connectivity, promoted by the large vendors, who share the interest of increasing availability. Connectivity is often enabled by applying widely used Internet technologies to the industrial technologies.

In the beginning of this book, we formulated the I4.0 vision in an SME context as Smart Production. Smart Production capture the conditions and constraints from small and medium sized enterprises (SME), who are both challenged and gifted in other ways than large multi-national companies with huge investment budgets. To an industrial manufacturing company, the I4.0 vision points towards improving operations by enabling new and better ways of working and collaborating with partners and customers. There are at least five mechanisms to make production smarter as illustrated in Fig. 1.

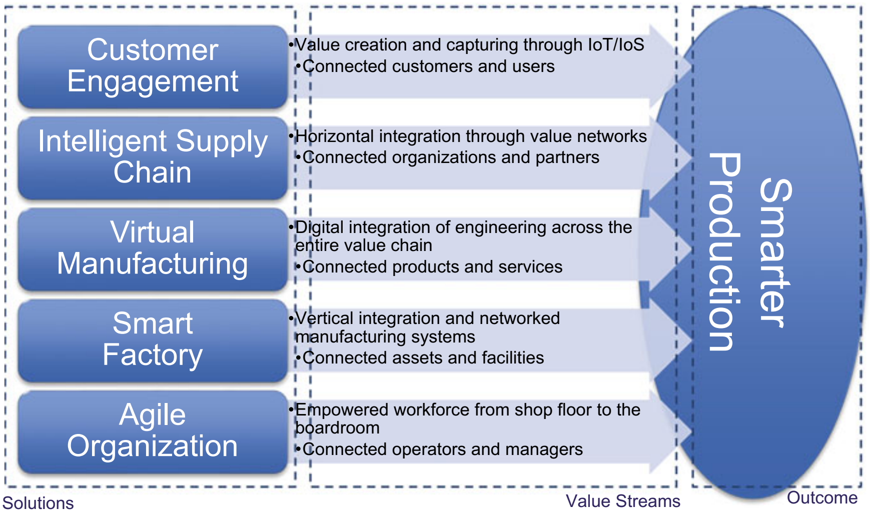

Fig. 1 Five mechanisms to make production smarter

Smart Production means that the production activities are instrumented, interconnected, and intelligent, but the main impact on business emerges when it enables the SME to communicate and collaborate with customers and partners in better ways. The impact on the business from improving operations is not linear but the value is generated in stages leading to sustained competitive advantages (Hammer, 2004).

Production needs to be integrated with the customers, and other users. As a result, relevant data can be available throughout the organization for automated decision making or human decision support. This is what we call an integrated production system which goes beyond well beyond digital twins by considering stakeholders and socio-technical aspects. The challenge of making production smarter is thus to integrate the relevant components of the system and to reap the operational benefits by enabling the organization to work smarter or to pursue new business models, like digital servitization based on smart products.

For an SME, availability of a technology is determined by access to low-cost applications and access to knowledge partner such as vendors. Only in few cases SME will turn to immature and expensive technologies. But for an application to create value, it must be integrated in the organization and accepted by the users.

2 What Are Integrated Solutions?

An integrated solution is the application of an instrumented, inter-connected and intelligent system that is serving a business purpose by enabling the end-to-end value chains in an organization or in a supply chain.

- Instrumented solutions can be enabled by cyber-physical systems. Most new equipment is already data-enabled, but it can also be e.g., assistance systems enabled by AR or VR.
- Inter-connected solutions can be enabled by Industrial IoT, but it can also be new wireless communication, that also enable the company to communicate outside of the organization, and thus supports new business models.
- Intelligent can mean both “real” intelligence (humans) or it can mean artificial enable by cognitive intelligence, that is available to industry as standard tools via the cloud.

Integrated solution can be partial and spanning certain aspects of the value chain. As an example, a Smart Factory is a generic solution concept that may be instantiated into a particular solution, that assist operators and management in their work.

Corollary, an integrated solution is an amalgamation of technologies, applications that support the user or the business in achieving their objectives. Thus, an integrated solution is more that its components.

In this part of the book, we present examples of general integrated solution concepts, demonstrate how they can be developed and is being applied, and discuss the potentials for SME.

3 Integrated Solutions

In the first paper, Napoleone et al. (2022) argue that SME's may improve responsiveness by increasing changeability and reconfigurability in their manufacturing system. The authors demonstrate the benefits at three SME's from implementing the proper level of flexibility. In the three cases, a combination of new technology and re-design of control principles is applied to tackle the challenge.

In the second paper, Raza and Bilberg (2022) address collaborative robots' implementation in SMEs and the role of computer simulations. They argue that collaborative robots are an attractive tool to deal with the High-Mix Low-Volume challenge faced by many order-producing SME's. However, in particular SME's are challenged in the deployment of these solutions and the paper discus how computer simulations may be applied as a tool to help in the deployment process.

Intelligent Assistance Systems for Assembly Tasks is the third paper (Lehmann, 2022). This paper provides an overview of the emerging assistance technologies and demonstrate a scenario where an intelligent assistance system based on data gloves, independently of cameras can understand and to classify complex gestures of operators.

Borck et al. (2022) outlines the challenges and opportunities of IIoT and smart sensors in human-centered manufacturing. In the paper they present three scenarios where IIoT and Digital Twins enable human-centered manufacturing which is relevant for SME's due to less advanced and fewer machines that larger manufacturers, which ultimately makes batch-size one challenging.

Palade and Møller (2022)presents the experiences from developing paperless production as an integrated solution for Smart Production. The paper reports the collaborative approach taken in a research and innovation project aimed at acceleration the digital transformation in small danish manufacturers. The essence of the approach is to build solutions through small iterative steps, using the smart factory vision to guide the journey. This is demonstrated in the Aalborg University Smart Production Laboratory and exemplified in a small number of SME cases.

Chaudhuri et al. (2022) presents a new concept in the journey from direct and indirect additive manufacturing of individual parts to virtual warehousing of the parts portfolio: lessons for industrial manufacturers. The paper frames a virtual warehouse as a new supply chain solution that is enabled by additive manufacturing, and they illustrate the new concept using a case study.

In the paper: "A Modular Engineering Pipeline for Mixed Reality Environments", Böhnke et al. (2022) presents an approach where SME's can build an low-cost pipeline for visualizing industrial 3D data in Mixed Reality (MR). The paper explains the considerations for each of the tool and stages in the pipeline and conclude with a demonstrator.

One of the most potential solutions for SME's is predictive maintenance, and in "Predictive analytics applications for small and medium-sized enterprises (SMEs)—A mini survey and real-world use cases", Bøgh et al. (2022) reviews literature, methods, and industrial applications. The authors claim that predictive analytics is progressively becoming more mature, and it starts to gain traction in smart manufacturing around the world.

Finally, in "SMEs and the Sustainability Challenge", Løkke and Madsen (2022) introduce the challenges SMEs are facing when working with sustainability, and present a vision for a digital double twin, which extends the digital twin into the sustainability realm, building the ground for operational sustainable smart production.

4 Summary

In this part, we have introduced the mosaic of the examples of integrated solutions for SME's to be presented in this book. An integrated solutions is a comprehensive combination of knowledge and technology designed to address an industrial problem.

The selection, demonstrate a large variety of different solutions, immediately suited for applications in SME's. The solutions cover various aspects of the mechanisms for making production smarter, see Fig. 1. The solutions presented can be seen as examples of application of the technologies that will be presented in part 4 in this book (Schou, 2022).

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Improving Responsiveness in SMEs Through Changeable and Reconfigurable Manufacturing

Alessia Napoleone, Thomas Ditlev Brunoe, Ann-Louise Andersen, and Kjeld Nielsen

Abstract Many Small and Medium Enterprises (SMEs) are facing challenges in their manufacturing systems due to rapidly evolving and unpredictable customer requirements. To meet these challenges ensuring both responsiveness and cost-efficiency, SMEs may increase changeability by embedding appropriate levels of flexibility and reconfigurability in the design of manufacturing systems. In addition, the rapid diffusion of digital and smart technologies due to Industry 4.0, provides SMEs with new opportunities to increase changeability. This chapter details how flexibility and reconfigurability could be used to meet different change drivers; moreover, the related benefits are described and associated to Key Performance Indicators (KPIs). Finally, three industrial examples from SMEs are provided. The three cases highlight that changeability can indeed create benefits in SMEs, especially for adjusting manufacturing towards frequent variants changes, mix changes, volume changes, and new product introductions.

Keywords Changeability · Reconfigurability · Change drivers · Industrial cases

1 Introduction

Compared to Large Enterprises, Small and Medium Enterprises (SMEs) have been traditionally more responsive in terms of delivery, but this was mainly the result of a rather narrow product range and a simpler product structure that allowed SMEs to take advantage of shorter manufacturing and assembly times (Belvedere et al., 2010). Today, many SMEs are facing challenges in their manufacturing systems due to rapidly evolving and unpredictable customer requirements. Not only product personalization, resulting in reduced product lifecycles, uncontrolled increase of variety in product portfolios, as well as decreasing lot sizes, but also the increasing need to take an active role in the Green Transition, affecting product portfolios (e.g.

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replacing conventional materials with recycled or sustainable ones) and production processes (e.g. transforming conventional manufacturing processes in green and reusable ones as well as establishing take-back programs) challenge SMEs. These factors inevitably determine the increase of internal complexity in manufacturing systems, such as more complex logistics and production processes. In addition, the frequent introduction of new products, which might differ from previous product generations, requires fast adaptation in the production capacities and functionalities offered by manufacturing systems and factories.

A solution for SMEs to meet these challenges and increase responsiveness while remaining cost-efficient is to increase changeability and reconfigurability in manufacturing systems. Moreover, the diffusion of Industry 4.0 technologies supports SMEs to increase these capabilities (Grube et al., 2019; Torn & Vaneker, 2019). In this chapter, the concepts of changeable and reconfigurable manufacturing are introduced in terms of the fundamental aspects and related benefits and potentials. This chapter is structured as follows; first, changeability, flexibility and reconfigurability are introduced and defined. Second, the benefits associated with changeability are described and associated to Key Performance Indicators (KPIs). Finally, three industrial examples from SMEs are provided.

2 Changeability, Reconfigurability, and Flexibility

Changeability is the capability of manufacturing to accomplish early and foresighted adjustments of the factory's structures and processes on all levels in an economically feasible way in response to different change drivers (ElMaraghy & Wiendahl, 2008). Change drivers are those factors, such as competition on new markets, product customization, introduction of sustainable materials, etc., which directly affect the features of the manufactured products, determining (Tracht & Hogreve, 2012):

- Variant changes (usually shorter-term requirements): Variants are instances of a certain product (or, alternatively a certain part, i.e., a component or subassembly of the end-product), which are similar in shape/geometry and technological features. They determine the same or very similar requirements along the production processes.
- Volume changes (usually mid-term to longer-term requirements): Production output varies across variants or product/part families.
- Product/part changes (usually longer-term requirements): Product/part families are groups of product/part variants. Different product families determine different requirements along the production processes.

Usually, companies' product portfolios change over time due to the evolution of product families, i.e., the introduction of new generations of product variants over time. Over longer time horizons, new product families might be introduced in replacement or combination of the existing ones. Affecting manufactured products, change drivers introduce the need for changeability within manufacturing systems. Specifically, to be changeable, companies should design manufacturing systems embedding appropriate levels of flexibility and reconfigurability (Azab et al., 2013). In this regard, flexibility is the capability of the manufacturing systems to ensure fast adaptation within specific, often narrow, corridors of change, thus requiring low time, cost, and number of steps necessary to implement modifications (Azab et al., 2013; Terkaj et al., 2009). Therefore, flexibility allows addressing shorter-term requirements, i.e. variant-changes (Napoleone et al., 2021). For the changes having more long-term impact, reconfigurability is usually more appropriate. Relying on built-in hardware and software modularity of manufacturing equipment, reconfigurability is the capability of the manufacturing system to accommodate changes in product/part volumes (i.e. mid-term requirements) and to accommodate changes in product families (i.e. longer-term requirements) (Napoleone et al., 2021). Figure 1 highlights the main differences between flexibility and reconfigurability.

One of the most relevant enablers of changeability is the modularity of manufacturing equipment, which facilitates the reuse of equipment in different manufacturing settings (Bejlegaard et al., 2016), thus reducing the effort (i.e. the time and cost) needed for reconfigurations, in terms of either duplication or conversion of functionalities. In the product domain, the concept of modularity has for long been applied for effectively introducing a high number of product variants while maintaining economies-of-scale and reducing variety-induced complexity (Brunoe et al., 2020). In the manufacturing system domain, the concept of modularity is more recent.

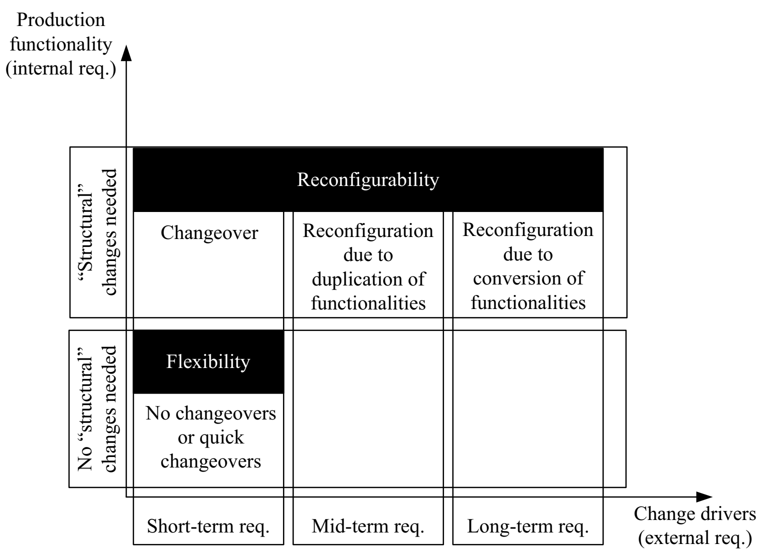

Fig. 1 Flexibility and reconfigurability: two changeability capabilities to address different change drivers

In manufacturing systems, modularity means that two different kinds of modules are designed and introduced these are “process platforms” and “specific modules”.

- “Process platforms” are those modules that are shared by multiple process variants, thus they are designed to be reused in different manufacturing settings (Brunoe et al., 2020). As processes evolve based on product evolution, platforms should be designed based on expected product evolution—in this way, they can be effectively (with respect to cost and time) reused when new generations of products/parts are required (thus to meet long-term requirements), or when the required volumes for specific variants are growing while the required volumes for other variants are decreasing (thus to meet mid-term requirements);
- “Specific modules” are those modules that have distinct features and functionalities compared to other process variants. Therefore, these modules should be designed to allow quick changeovers across variants (thus to meet short-term requirements).

3 Benefits of Changeable Manufacturing

From a general and broader perspective, SMEs can benefit from changeability in terms of increasing responsiveness towards increased variety on the manufacturing systems, while maintaining cost efficiency. Indeed, the design of manufacturing systems embedding appropriate levels of flexibility and reconfigurability allows a reduction of needed changes in the manufacturing system when switching across product/part variants or families. This is primarily due to the reuse of equipment in different manufacturing settings, which also reduces the internal complexity. Other related benefits are better utilization of resources, increased lifetime of systems, as well as reduction of the cost for handling product evolution (Brunoe et al., 2020).

In terms of KPIs, the benefits of changeability can be described in relation to the three changeability requirements: variant changes (short-term requirements); volume changes (mid-term requirements) across variants or product/part families; and product/part changes (long-term requirements). A summary of benefits is provided in Table 1.

In the following sections, different SME cases are presented, in the first case changeability was introduced with significant benefits; in the second and third case the company was already changeable to some extent, thus the level of changeability was increased for additional benefits. The cases are also summarized in Table 2.

Table 1 Three types of benefits of changeability and reconfigurability

	Variant changes	Volume changes	Product/part changes
Time horizon	Short-term	Mid-term	Long-term
KPIs	Changeover time Changeover cost Lot size dimension Range of variants Lead time and inventory level	Capacity utilization Reuse of assets	Time to market New product introduction cost

Table 2 Summary of the SME cases

	SME case 1	SME case 2	SME case 3
Product	Construction machines	Sporting goods	Sporting goods
Type of change	Variant changes Product/part changes	Volume changes Product changes	Variant changes
Initial KPIs	Time consuming changeover for replacing fixtures Significant investments in new fixtures for new parts' introduction Storage space and cost for holding fixtures	Flexibility towards materials changes Limited size of manufactured products	Unbalanced assembly times due to variety, affecting inventory levels and lead times
Solution	Reconfigurable fixture	Modular fiber laying process	Data-driven prediction of process times; reconfigurable workstations and multi-skilled workers
Final KPIs	Changeover times reduced by 80% Cost and time for introducing new parts drastically reduced	Reuse of assets Optimal capacity utilization in transitioning product generations	Reduction of waiting times, inventory levels, and lead time

3.1 SME Case 1: Reconfiguration for Frequent Variant Changes

This case concerns a medium sized manufacturer of construction machines located in Denmark. The production involves mainly precision welding and machining of large steel components, making up the structural parts of the machines, and the assembly of the machine, where the welded components are assembled with other sourced components such as engine, electronics, fittings, etc. The company has a large product portfolio with four main product families, each with high variety. This, combined with a low volume production, with a few machines produced per day, caused the company to implement a one-piece flow rather than batch production. This however implied frequent and time-consuming changeovers for replacing and setting up welding fixtures. In addition to this, the company had to make significant investments in new fixtures every time a new product requiring new welded parts was introduced to the production, implying an increase in capital expenses and longer time to market. Finally, the company was reaching a point where the storage space needed to hold the fixtures for all product variants was becoming a significant expense. Based on these challenges, the company investigated different alternatives to the previous dedicated fixtures, with a one-to-one relationship between new parts and new fixtures. Hence the company had short-term requirements to accommodate variant changes, avoiding time consuming changeovers and high capital expenses for dedicated fixtures, as well as long-term requirements related to introduction of new parts for new product families. To address these requirements, two different scenarios were developed.

The first scenario was the introduction of a hyper flexible robot welding cell, where two large robots and magnetic jigs would hold the parts in place while being welded by a third robot. This concept was validated through a simulation and would completely remove changeovers, significantly reduce the variable cost of welding as it was automated, and finally remove the need for developing new fixtures when introducing new products. However, the initial investment necessary for this concept rendered the investment infeasible, as the utilization with the current volume would only be around 20%.

The second scenario was the introduction of a modular, reconfigurable tack-welding fixture. This fixture would replace a number of dedicated fixtures, and also allow for instant short-term changeovers and introduction of new parts with a minimum effort and investment. The reconfigurable fixture was developed by organizing the different welded steel parts into part families based on similarities of their geometrical features. A proof of concept was developed for one part-family consisting of six different parts. These parts were roughly the same size and had similar geometrical features, allowing for the parts to be fixates using similar mechanisms. A fixture platform was developed and fitted with a number of electrically actuated supports. This system could be reconfigured by computer control to fit any of the existing products in the product family and new products with similar features. In this way, the company was able to reduce changeover times by 80%, because the operators no longer had to replace the fixture with a forklift. The cost and time for introducing new products could also be drastically reduced, as this involved mainly programming and validating the settings of the fixture for new dimensions of the components, possibly purchasing additional actuated supports (Fig. 2).

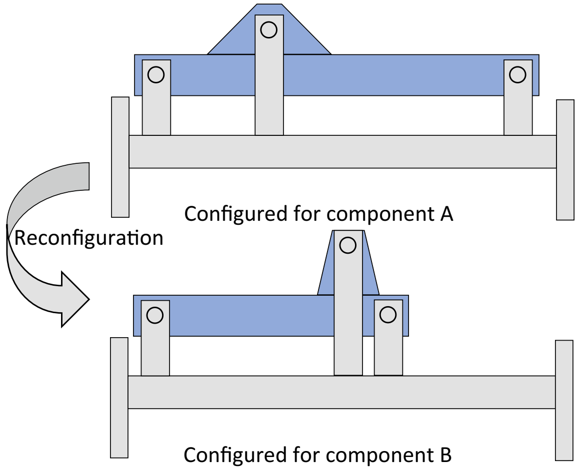

Fig. 2 The reconfiguration of welding fixture to accommodate different components sharing similar geometric characteristics

3.2 SME Case 2: Reconfiguration for New Product Introductions

The second case is a Danish medium sized company producing sporting goods. The products manufactured by the company are very different in terms of shape, material and size (area), ranging from a few square meters to over thousands square meters. The company is one of the two market leading companies selling premium products and needs to introduce new products and technologies regularly to sustain this market position. One main process step is an additive manufacturing process where fibers are laid out in customer specific patterns to obtain specific product properties. This is one of the processes where the company needs to renew the technology to maintain its position as first mover in new materials. The process is performed on a large platform providing the base for doing the process, while the additive process is a module that is attached on top of the platform. The platform only contains functions that are "exactly" the same regardless of material or additive process. Thus, whenever a new material is introduced or the additive process is changed, this can be done by just replacing the module performing the fiber laying process, that goes on top of the platform.

When the company started out with the first generation of the product, a smaller base was established, with the fiber laying process on top of the base. After a few years when the technology matured and demand grew, a larger base was constructed, and the fiber laying equipment was moved to the larger base, thus increasing the maximum size of products as well as the actual manufacturing capacity. At the same time, the company was developing a second generation of the product and technology, which at first was immature and needed further development before running smoothly. This was done on the smaller base, thus not taking up capacity for the main product, the first generation. Once the second-generation technology was matured and able to

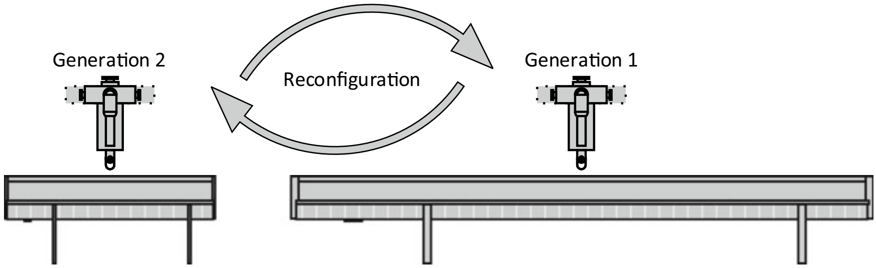

Fig. 3 The reconfiguration of a manufacturing system to accommodate the introduction of new processes and new products

perform at a stable quality, it was introduced to the market, after which the demand moved from the first-generation product to the second-generation product. When that occurred, a reconfiguration was made, moving the second-generation fiber laying equipment to the larger base, thus supporting more variety and a larger volume. The first-generation equipment was moved to the smaller base as demand was declining for these products. This was possible since the interfaces between the base and the fiber laying equipment was common across the two bases and the two generations, as well as the functions in the base being stable, whereas the functions in the fiber laying equipment was changeable (Fig. 3).

3.3 SME Case 3: Reconfiguration for Mix Changes

The last case concerns the same company as the case described above, however a different process is considered. Whereas the first case referred to a process producing materials to be used in the final assembly of the finished product, this case describes the assembly processes. The assembly of the product consists of six consecutive processes. The processes are largely manual, with some specialized workstations being able to perform one process, and some workstations being able to perform multiple processes after a swift changeover. As described in the previous case, the products are very different in shape and size, as well as material and accessories. The process time for each process depends on the characteristics of the product, which implies that given the products are very different, the process times also vary greatly. For the most time-consuming process in the assembly, the process time ranges from one hour to 135 hours for an extreme case, and the less time-consuming processes show a similar variation in process times. Since each product is personalized in terms of materials, accessories and dimensions, no standard times exist for products that would allow for balancing the production.

The company had a goal of reducing the lead time from customer order to shipping the finished product, and they found that the assembly system had a significant potential for lead time reduction. Indeed, the unbalanced load on the different processes led to inventory building up before each process, implying waiting times before each process and long lead times through the assembly system. However, a traditional approach to reducing inventory and reducing lead times by, e.g., introducing takt times and line balancing to balance process capacity with process load was infeasible due to the large variations in process times. Therefore, it was necessary to develop a concept that would allow reconfiguring the assembly system on a short-term basis to match the resources available for each process with the time needed for each process for performing each individual process given the specific configurations being produced.

To this end, a method was introduced which allowed predicting the process times for each product, and by aggregating this, and allocating one day for each process, it was possible to calculate the number of hours needed each day for each process. This information could then be used to make a daily reconfiguration of the assembly system, where workstations could be reconfigured, and workers could be reallocated so that the capacity for each process would match the products going through that process each day. The implementation of this reconfigurable concept was possible thanks to the workstations being reconfigurable by replacing tools and reallocating workers dynamically, also thanks to the workers having competences to operate different workstations. By developing this concept, the waiting times before each process could be reduced to a maximum of 24 hours, which would effectively reduce the total lead time through the assembly system by one week, potentially giving the company a significant competitive advantage, since delivery time is a major order winner in the market which the company operates in (Fig. 4).

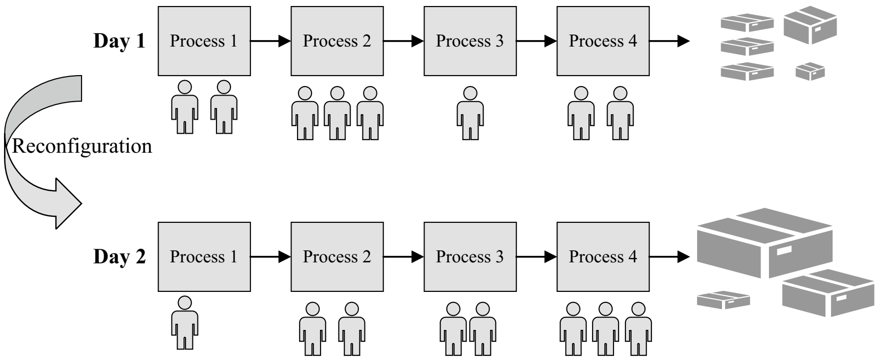

Fig. 4 The reconfiguration of an assembly system to accommodate daily differences in mix and process load

4 Summary

In this chapter, the concepts and benefits of changeable and reconfigurable manufacturing was introduced alongside 3 SME cases illustrating the implementation in real manufacturing settings. While many SMEs are facing increased product variety and more rapid introductions of new products/variants, manufacturing systems are often too rigid/dedicated to accommodating for this or are too cost-heavy to produce variety in a competitive manner. Therefore, the concepts of changeability and reconfigurability are attractive, i.e., providing exact functionality and capacity when needed through modularity and reuse of processes and equipment. The three cases presented in the paper highlight that reconfigurability can indeed create benefits in SMEs, especially for adjusting manufacturing towards frequent variants changes, mix changes, volume changes, and new product introductions.

With Industry 4.0, the relatively inexpensive introduction of digital and smart technologies in manufacturing systems and factories, provides SMEs with new opportunities to enable reconfigurability and changeability, especially with regard to short-term requirements, as shown in the third case, where a data-driven prediction model has been introduced.

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Role of Computer Simulation in the Collaborative Robot Implementation Journey of SMEs

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Abstract Collaborative robots (cobots) market is emerging rapidly since the last decade, and SMEs- small-medium-sized enterprises have the opportunity of dealing with High-Mix Low-Volume (HMLV) production by deploying collaborative robots. However, SMEs are facing certain challenges that may affect the cobots' deployment process. In this chapter, the main challenges for SMEs regarding cobot implementation are highlighted and it is discussed how computer simulations can be a vital tool to cope with these challenges.

Keywords Collaborative robot · Simulation · Small-medium enterprises

1 Introduction

For a long time, industrial automation has been a difficult choice for SMEs as the traditional industrial robots were expensive and require a substantial knowledge base (Workers, 2021a). But cobots have made robotics and automation more accessible as cobots offer an economical and more easy solution to automate manufacturing processes (Workers, 2021a). Cobots are an attractive option for a small-scale manufacturer looking for flexible solutions to deal with a High-Mix Low-Volume production without having a high investment capital (Peterson, 2020).

SMEs can gain several benefits like an improved work environment for humans, increased productivity, improved workflow, and the wellbeing of human workers. But SMEs are facing several cobot implementation challenges regarding work cell design, safety, and decision making. In this chapter it is discussed in detail how SMEs can overcome some of these challenges using computer simulations during the cobot deployment process.

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2 Collaborative Robots

Collaborative robots or cobots are designed and developed to perform tasks in collaboration with human operators. The word cobot is a short term for a collaborative robot. The very reason for deploying collaborative robots is to use the best of humans and robots. Humans are strong in certain areas and robots are better at performing certain tasks. Humans and robots can in other words complement each other in a collaborative environment based on the best capabilities of each. Sherwani et al., (2020) have given a comparison of humans and robots to explain the strength and weaknesses of each as shown in Table 1.

The first collaborative robot is credited to J. Edward Colgate and Michael Peshkin back in 1996 (Workers, 2021b). Since then, cobots have gained importance both in industry and academia. Some of the main manufacturers of collaborative robots worldwide are Universal Robotics, Rethink Robotics, ABB Inc. Robotics, KUKA Robotics, and Omron (Sherwani et al., 2020). Now a day's collaborative robots are being used in different industries to perform a variety of tasks for example; picking, packing, palletizing, welding, assembly, material handling, machine tending, and inspection (Sherwani et al., 2020). Some of the distinguishing benefits of deploying cobots are (Sherwani et al., 2020):

- They provide an economical opportunity to automate production processes and support human operators.
- They are smaller in size, safe, and able to perform different tasks along with humans.
- They are lighter in weight can be easily moved and placed according to the requirements.
- They offer relatively better productivity and flexibility.

The collaborative robots' market is increasing, and more and more industries are adapting to the human–robot collaborative operations. According to Statista, the cobot installation increased by almost 100% worldwide from 2017 to 2020. Statista also states that the 594 million US dollars current global revenue (in 2020) of cobots is projected to increase to 1.5 billion U.S. dollars in 2026 (Statista, 2021).

Table 1 Human versus robot adopted from (Sherwani et al., 2020)

Human		Robot	
Advantages	Disadvantages	Advantages	Disadvantages
Dexterity	Weakness	Strength	No process knowledge
Flexibility	Fatigue	Endurance	Lack of experience
Creativity	Imprecision	Precision	Lack of creativity
Decision making	Low productivity	High productivity	No decision power

3 Collaborative Robots in SMEs

3.1 Why Cobots?

SMEs can get several benefits by introducing collaborative robots into the production processes. Kadir et al., (2018) have discussed three important benefits of introducing collaborative robots in the production setup: (1) Cobot can take over the repetitive and non-creative manual work which enables the human to focus on more creative activities. (2) Implementation of cobots helps to improve the workflow. They have argued that human and robots teams are more efficient compared to human teams only. Robots can handle repetitive and physically tough tasks while a human can work on more versatile and flexible tasks. (3) Cobots implementation may substantially contribute to the health and wellbeing of the human workers as the robot will take over the repetitive and boring work. Hence it will lead to the good health and mental conditions of the workers.

Darrell Adams, Head of Southeast Asia and Oceania, Universal Robots, has given some reasons that make cobots a suitable and affordable option for SMEs, also in comparison with traditional industrial robots (Adams, 2021).

- Setting up traditional robots can take several days which is not an affordable option for SMEs. Conversely, cobots can be set up within hours and learning is also comparatively fast.
- Traditional industrial robots can limit the SMEs that produce in small batches and need fast changeovers and thereby frequent robot programming. In contrast, cobots are easy to move and can be easily redeployed to perform new tasks. They can be easily programmed to new activities also by shop floor workers themselves.
- One of the distinguished benefits that cobots offer is typically a fast return on investment compared to traditional robots.

3.2 Cobot Implementation Challenges

One of the main cobot implementation challenges for SMEs is to plan and decide the right time for deploying a cobot solution and what is the right application. Fast-Berglund and Romero (2019) have also mentioned this problem in their study, they have argued that SMEs are missing clear strategies for when and where to implement cobots. The selection of the most suitable cobot solution that fits exactly the organization's needs and objectives is also one of the important issues for SMEs (Schnell, 2021). Though collaborative robots are thought to be safe still organizations are concerned about the safety of humans while working with a robot side by side. Safety is one of the main concerns in the implementation of collaborative robots in SMEs (Mirit CKL, 2021; Glas, 2021). Integration of the cobot into the production processes may be complicated and also one of the main barriers to the adoption (Brown, 2021).

In a nutshell, for SMEs, three main cobot implementation challenges are evident in the literature:

- The challenge of effectively integrating the cobot into the existing process and optimized design of a cobot work cell.
- The challenge of deciding when and where to implement the cobot solution.
- The challenge of safety in cobot work cells where the cobots are getting close to humans.

3.3 Cobots Implementation in SMEs

How can SMEs effectively implement collaborative robots and get competitive benefits by utilizing them? The Cobot Knowledge Lab has an answer to this question. The Cobot Knowledge Lab was a project funded by The Danish Industry Foundation and the project was aimed to develop and test some tools that may be very useful for the SMEs to realize a collaborative robot solution and get the maximum benefits out of it. The tools developed by the Cobot Knowledge Lab and their respective benefits have been described below:

- Knowledge gap analysis tools
- Clarification tool
- Business case and cycle time estimation tool
- Computer simulations.

3.3.1 Knowledge Gap Analysis Tools

Danish Technological Institute (one of the project partners of the Cobot Knowledge Lab project) has developed a Microsoft Excel-based tool that can help organizations to determine where they are now and where they wanted to be (CKL, 2021). The tool is based on determining the gap regarding the eight specific parameters and can help organizations to identify the core competencies they need to strengthen to exploit the maximum potential benefits associated with the cobot deployment.

3.3.2 Clarification Tool

Microsoft Excel-based tool to assess the qualitative benefits from cobot implementation (CKL, 2021). The purpose of the tool is to quickly investigate whether the cobot is a good solution for a particular company or not? Furthermore, it is argued that some qualitative factors are also important to consider while implementing cobots and the tool helps companies to assess those qualitative factors.

3.3.3 Business Case and Cycle Time Estimation Tool

Once you have assessed the qualitative benefits and performed the gap analysis and the next logical step would be to find out the business case and monetary benefits associated with cobot implementation. The business case and cycle time estimation tool will help you to estimate the investment cost and cycle time of the cobot operations in the respective use case (CKL, 2021).

3.3.4 Computer Simulations

You have decided to deploy a cobot in your organization. Now you want to know about cobot work cell design and optimization. Computer simulation can particularly help you at this stage. Using computer simulation, you can evaluate and decide on the optimal layout of the cobot work cell, verify the cycle time, and get an idea about the optimal and safe distribution of human and robot tasks. In the Cobot Knowledge Lab project it was found that a simulation is an important tool that SMEs can use to design an optimized cobot solution (Mirit Glas, 2021).

Note: All these above-mentioned tools can be accessed through the following link: https://cobotlab.dk/vaerktoejer.

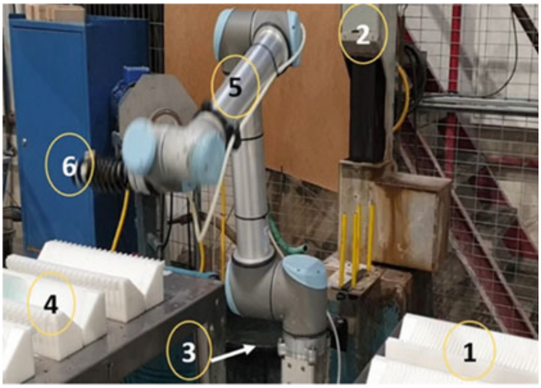
4 Simulation and Cobot Implementation in SMEs

In this section, it is discussed how simulation can be used as an important tool to overcome the cobot implementation challenges for SMEs highlighted in the previous section. Several literature pieces of evidence have been given to highlight the importance of computer simulations to overcome the cobot implementation challenges regarding work cell design, safety, and decision making.

4.1 Cobot Work Cell Design

Wang et al., (2019) have discussed that an optimized work cell design is crucial to achieving the right balance between human safety and comfort and process efficiency and cost of robotic operation. They have shown that simulation can help to design and optimize cobot work cells and to achieve the right balance between cycle time and ergonomics.

Raza et al., (2021) have discussed that SMEs can design an optimized cobot work cell using computer simulations. Through a practical case example of a small-medium enterprise, they have highlighted that how simulation can help not only to optimize the current cobot operation but also to design a future work cell with better utilization of the resources. They have discussed a case of a Danish SME struggling with the underutilization of cobot (UR10) deployed for performing the grinding operation on glass components. The current work cell as shown in the Fig. 1 was designed by an internal system integrator as the organization does not have the in-house ability to do that. A simulation study of the current work cell revealed opportunities for improvement in the design of the work cell. The simulation study helped to design an efficient future work cell as shown in the Fig. 2.



1. Feeding trays
2. Vertical grinder
3. Water tub
4. Finished parts trays
5. UR 10 robot
6. Vacuum gripper

Fig. 1 Current work cell adapted from (Raza et al., 2021)

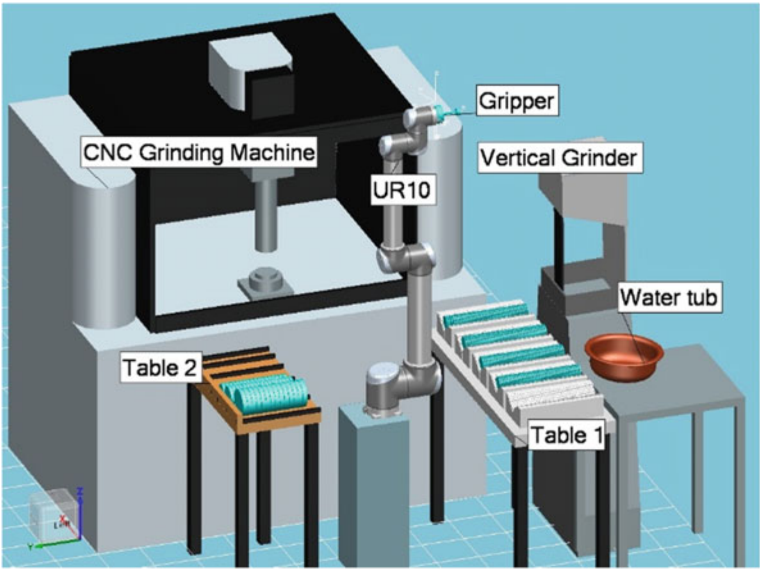


Fig. 2 Future work cell simulation image adapted from (Raza et al., 2021)

4.2 Safety

Early detection of potential hazards in a collaborative robot work cell leads to implementation design changes faster and in an economical manner (Huck et al., 2020). Huck et al., (2020) have proposed a method that uses a human model and Monte Carlo Tree Search algorithm to identify unsafe system states in a human–robot collaborative system. Consequently, it is possible to identify the system hazards and reduce them which leads to a safer system design.

A dynamic simulation makes it possible to obtain reliable measurements for ergonomic assessments. Maurice et al., (2019) have proposed an optimization-based method to animate a digital human model (DHM) and then simulated human–robot collaborative which allows quantifying the effect of kinematic, dynamic, and control parameters of the robot on the DHM posture and effort.

Raza et al., (2022) have discussed in their work about doing virtual safety assessment in the simulation environment before realizing an actual cobot work cell. They have described a simple framework based on the work of Ore et al., (2019) as shown in Fig. 3 to virtually audit the future cobot work cell in accordance with the requirements given in ISO/TS 15066:2016. They have concluded that virtual safety assessments of cobot work cells beforehand may lead to a safer design of cobot work cells.

4.3 Decision Making

Should we deploy a collaborative robot or not for a particular process? What will be new and different if we deploy a cobot solution? Lima et al., (2019) have suggested that simulation can answer this question and give important insights to the decision-maker. They have shown this by simulating a real production operation with and without a collaborative robot in the Tecnomatix process simulate. They have argued that studying both types of scenarios through simulation makes it possible to have a clear picture of the potential benefits of deploying a collaborative robot.

5 Discussion

Different ideas regarding cobot implementation have been discussed in the previous sections. Computer simulation can play an important role in designing and implementing an optimized cobot work cell. However, a general stepwise method for cobot implementation may help SMEs effectively go through the process. Based on the concepts discussed in the above sections, a generic five-step method is suggested for realizing a cobot solution in an SME.

Step 1(Deciding about deploying a Cobot): It is suggested that organizations should assess whether a cobot solution is needed. It is recommended that keep this

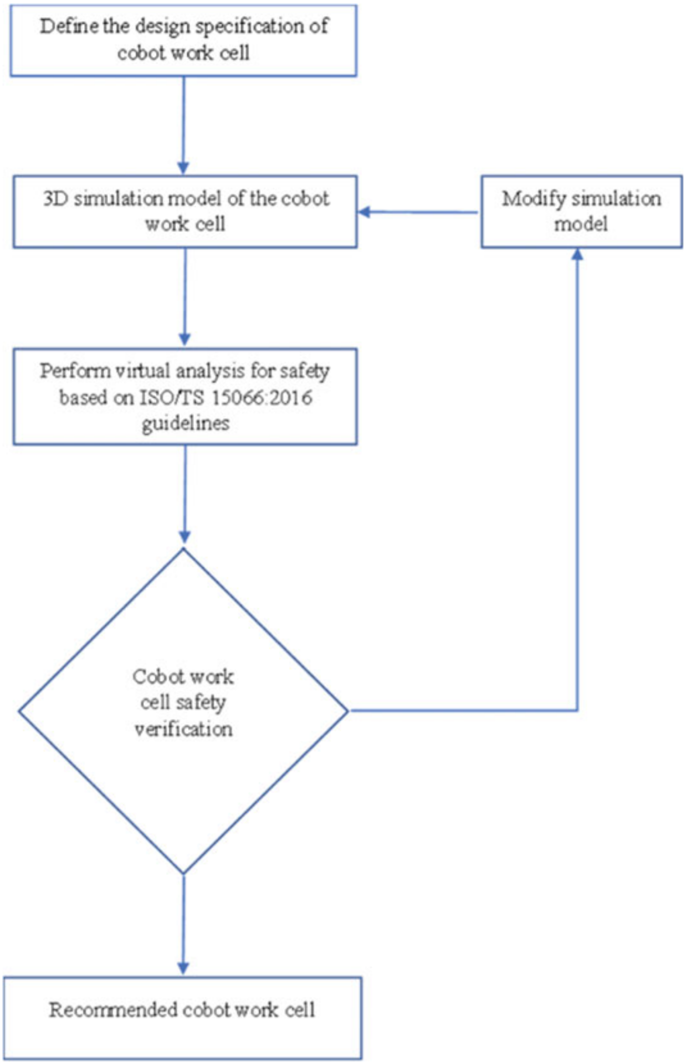


Fig. 3 Framework for virtual safety assessment of a cobot work cell based on ISO/TS 15066:2016 adapted from (Ore et al., 2019; Raza et al., 2022)

step simple and use some key qualitative measures to come to a go or no-go decision. A brainstorming amongst the relevant stakeholders might be a very good option for this purpose.

Step 2(Performing the gape analysis): Once it is decided that the organization should go for a cobot solution the organization should evaluate itself. This will help the organization to determine the required skills and competencies that should be strengthened or gained to achieve maximum benefits from the cobot solution.

Step 3: Preparing the business case. Before buying an actual cobot solution it is recommended to prepare a business case for implementing a cobot solution so that the economic benefits associated with the cobot solution are assessed.

Step 4: Virtual design of the collaborative robot work cell. Before implementing the final cobot solution it is recommended to design the solution in the virtual environment using simulation. It will help to implement an optimized and safe cobot solution.

Step 5: Implementing a cobot solution. Finally, the organization is ready to buy and install a new cobot solution.

6 Conclusion

Collaborative robots can offer significant opportunities to SMEs to deal with HMLV and to achieve high productivity and flexibility. In this paper, a generic five-step method is discussed that can help SMEs effectively implement a new cobot solution. This paper also presents some tools that can help SMEs in this journey, where especially computer simulation is an important tool that SMEs can benefit from to cope with cobot implementation challenges and to get maximum out of the collaborative robots' deployment.

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Intelligent Assistance Systems for Assembly Tasks

Marlon Antonin Lehmann

Abstract Intelligent Assistance Systems are a key technology for solving the problem of today's quickly changing product configurations and the corresponding production requirements focusing on human needs. A recent study among industrial German companies identifies higher productivity, process control, quality, and cost-effectiveness as the main potentials of assistance technologies by reducing the worker's cognitive load. Choosing the right combination of assistance technologies such as augmented reality, virtual reality, machine learning, and their functionalities like learning capabilities, situation awareness, and assembly activity recognition remain essential for their success. This chapter presents an assistance systems overview, focusing on assistance technologies, for application at production sites. Furthermore, an example of a gesture recognition-based assistance system is given, showing the benefits arising from today's advanced assistance technologies.

Keywords Assistance system · Gesture recognition · Production · Assembly

1 Introduction

As product life cycles get shorter, the manufacturing plants and the worker have to adapt at the same pace to the changing product portfolio. Therefore, the cognitive load increases. Assistance systems are meant to tackle the problem by guiding the workers through their daily working routine providing the required assembly information, such as involved tools, parts and joining specifications, to solve the current work task. To accomplish the assistance function the assistance systems have two major defining properties: They (1) provide work task support for humans throughout a human–machine interface and they are (2) computer-based (Steil & Wrede, 2019). The human–machine interface is used for both input and output of data, which means providing and sensing information in a haptic, visual or auditory way.

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While the definition of assistance systems includes other fields of applications such as driver assistance systems as well as applications in health and medicine, this chapter only refers to assistance systems used in production. Furthermore, only cognitive and no physical assistance systems are addressed. In this case, the most common applications of assistance systems are worker guidance and quality control (Bertram et al., 2020; Mueller et al., 2019). Whereas work instructions on a monitor with navigation buttons already match the assistance systems definition, today's assistance systems have been developed towards situation awareness and intelligence using the latest machine learning techniques (Gräßler et al., 2020; Klapper et al., 2020; Kästner et al., 2020; Sorostinean et al., 2021). Therefore, 17 assistance systems published in the years from 2014 to 2020 (see Table 1) were identified.

The assistance systems were selected by reviewing publications with relation to assistance and production in their title, e.g. assembly or manual repair. They all assist

Table 1 Published assistance systems for production from 2014 to 2020; (P)—company publication or product

Original title	Translated title	Year
ProMiMo (Rüther, 2014)	2013	2014
Plant@Hand (Aehnelt & Urban, 2015)	–	2015
motionEAP (Kosch et al., 2016)	–	2016
Manual working station of SmartFactoryKL (Quint et al., 2016)	–	2016
TNO (Bosch et al., 2017)	–	2017
Schlauer Klaus (OPTIMUM Datamangement Solutions, 2017) (P)	Smart Klaus	2017
Der Assistent (Ulixes Robotersysteme GmbH, 2017) (P)	The assistant	2017
cubu:S (Schnaithmann Maschinenbau GmbH, 2017) (P)	–	2017
APPsist (Ullrich et al., 2018)	–	2018
Assisted rework station (Müller et al., 2018b)	–	2018
Laserbasierte Montageassistenz (Müller et al., 2018a)	Laser-based assembly assistance	2018
MEHDIS (Woitag, 2019)	–	2019
Workbench with assistance system (Oestreich et al., 2019)	–	2019
Assembly assistance system (Nikolenko et al., 2019)	–	2019
Laser-Assistenzsystem (Müller-Polyzou et al., 2019)	Laser-assistance system	2019
Cognitive assistance system (Müller et al., 2019)	–	2019
ActiveAssist (Bosch Rexroth AG, 2020) (P)	–	2020
Monsiko (Jauch)	–	Na

in production tasks, mostly assembly. Worker guidance and therefore information display at the right time and in the right step in the work task is addressed in all the reviewed assistance systems, either by introducing information or domain models or by describing the technologies. The technologies are analyzed and discussed in the following section.

2 Assistance Technologies in Production

This section's goal is to identify the most used technologies in assistance systems. Based on the assistance system's defining properties the technologies are split into three categories:

1. information display technologies,
2. user input technologies and
3. technologies to calculate the system's responses.

Common ways to implement the *information display* are monitors, projectors or handheld devices such as tablets (see Fig. 1). There has not been a smartphone-based assistance system in the reviewed publications. Stationary assistance systems designed for a specific assembly station are equipped with monitors and projectors. Depending on the given assembly scenario, it is preferable to keep the hands free and therefore uses augmented reality glasses instead. One benefit of using augmented reality glasses is the information display at the right position in space e.g. directly on the assembly part. The glasses come with the drawbacks of higher programming effort in terms of 3D visualization, increased acquisition cost and seasickness when they are worn for too long. The mentioned *information display technologies* appear to be well known as state-of-the-art.

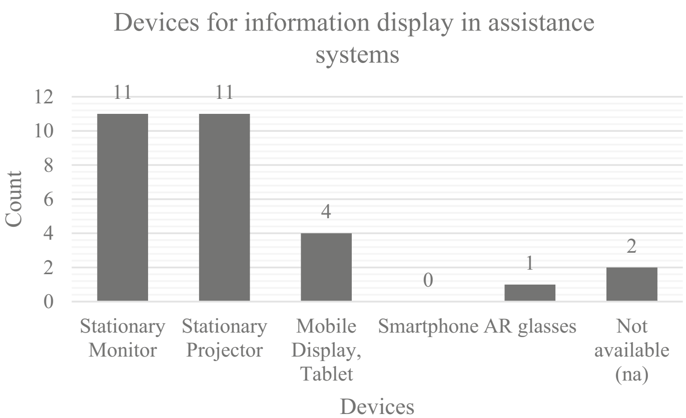

Fig. 1 Implemented information display technologies in the 17 reviewed assistance systems

User input technologies have been subject to the latest research especially together with the situation awareness of assistance systems. Keyboard and mouse, which are not implemented in any of the reviewed assistance systems, and touch displays are the most spread human–machine interfaces. All three keyboard, mouse and the touch display offer an intuitive interaction opportunity but are limited when gloves are worn during the assisted task. Furthermore, they require active user input, which does not provide value. Most assistance systems aim for automatic situation detection instead. Figure 2 shows the input technologies in the 17 reviewed assistance systems. Depth cameras and RGB cameras are often used for hand detection and object detection. Further, machine vision technologies as implemented in some augmented reality glasses are capable of recognizing predefined gestures for basic commands such as the selection of menu items. When hands are needed in the work task, such as in assembly, speech recognition is an option to interact with the assistance system. In addition to the user's intended input, intelligent assistance systems are able to continuously monitor and recognize user actions in order to automatically react to them e.g. when a torque gun is detected the required torque is displayed. The situation awareness of the assistance systems allows for the prediction of the next work step and therefore saves the interaction time, which is needed by the human to quit a work task and select the next step. To achieve situation awareness the assistance system needs contextual information about the work task, place, people and real-time perception of the state of the work task. The first three can be obtained through a user login at the workstation whereas state recognition is a more complex task.

One approach is to use computer vision together with machine learning or deep learning algorithms for object classification. Both tools and parts with respect to their assembly state can be detected. The information can be used to derive the current work state e.g. with probabilistic approaches like Hidden Markov Models. However, vision systems suffer from changing light conditions, the intersection of

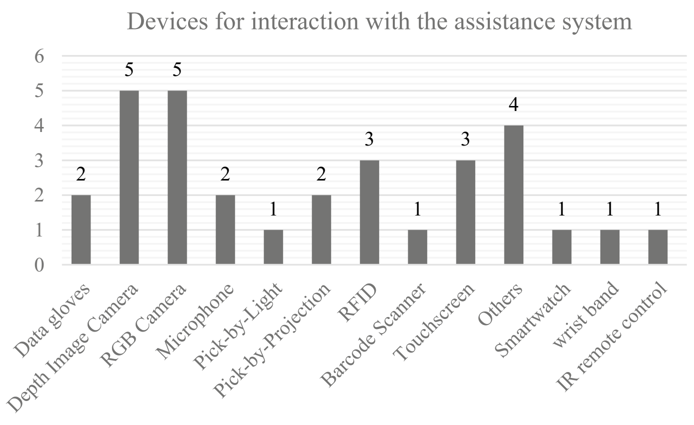

Fig. 2 Implemented interaction devices for user and information input in the 17 reviewed assistance systems

the line of sight and reflections on surfaces. A second approach is based on non-vision gesture recognition. Motion sensors like inertial measurement units or flex sensors measure hand and/or arm movements in 3d space. The sensors are integrated into wrist-/armbands, gloves or smartwatches. The accuracy of the devices does not rely on environmental light conditions but needs to be attached to the human body, where they are exposed to mechanical stress. Further, they are mostly battery-driven and therefore charging has to be included in the overall workflow.

The third category is the *technologies to calculate the system's responses*. It contains methods and algorithms, which take input data, such as buttons or videos for gesture recognition and generate actions (output) based on rules or knowledge. The introduced situation awareness is part of response technologies. Rasmussen's human behavior model describes all necessary functions for the systems response generation. It divides the responses into three levels regarding cognitive quality: skills, rules and knowledge. The skill level is a one-to-one mapping of sensor input (provided by user input technologies)—and in the case of the reviewed assistance systems—to an information output device. The rule level requires situation awareness to derive the current task to react to it. On the knowledge level, the system itself makes decisions on how to reach the task goals (planning). The first two layers are commonly implemented in today's systems. The modeling of the domain-specific knowledge and processes remains subject to research activities (Müller et al., 2019). Petri nets (Bertram et al., 2020) and business process model and notation (Ullrich et al., 2018) have been used to model assembly processes for implementation in assistance systems.

Manual modeling of work tasks is a time-consuming and costly process, requiring programming and specific domain experts to formalize the work tasks. The rapidly changing production settings and products prohibit such an inflexible system and therefore the application of assistance systems. One approach to tackle the problem is to implement self-learning functions into the assistance systems to learn work tasks from demonstration through a supervisor/expert.

3 Use Case: Glove Based Assembly Assistance System

In this section, an assistance system set up for automatic assembly process digitization with data gloves (Lehmann et al., 2022) will be described. The goal was to develop a mobile assistance system, that (1) provides work step information without adding further process time to the overall work process, (2) at the same time monitors the assembly quality, and (3) is capable of learning new processes by digitizing workflows. The novel approach is the situation awareness feature based on gesture recognition. It does not rely on cameras and therefore is independent of light conditions or the line of sight. Through gesture recognition, the assembly system is able to determine the current assembly step and provide the relevant assembly information to the worker.

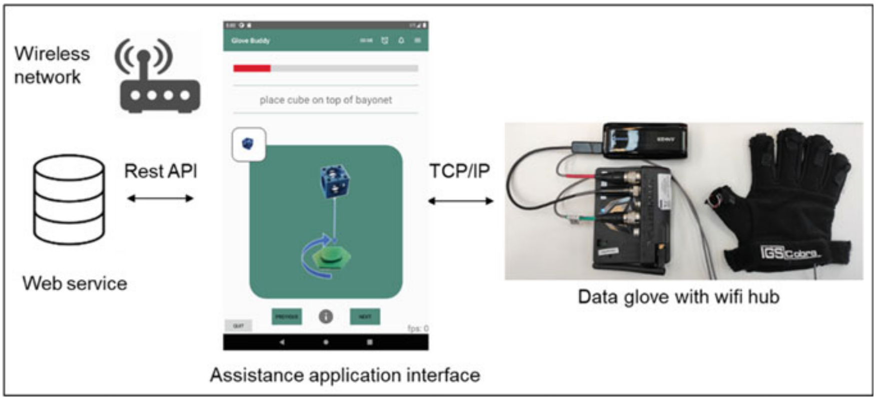

Fig. 3 Assistance system architecture

The assistance system is described in regard to the three technology categories. The setup consists of data gloves as the input device, a tablet for information output and a wirelessly connected web server for computationally expensive tasks and data storing (see Fig. 3). The assistance system recognizes gestures using acceleration and orientation data recorded by a pair of data gloves. The Naïve Bayes machine learning algorithm classifies assembly gestures. The single gestures are put into an order to estimate the assembly sequence for both digitizing the work task for the first time and second to monitor quality in production. The assembly sequences that are not fully performed are classified as failures.

The assistance system was evaluated by testing the recognition accuracy with the basic assembly operations *insertion* and *screwing* with a cordless drill, an Allen key and a spanner. Three assembly parts, a cube, cover and bayonet mount as seen in Fig. 4 were recognized by combining the situation awareness approach with the data glove input interface.

On the first hand the assistance system was able to recognize the assembly gestures and therefore determine the required assembly information, e.g. where to put a specific part or what action to perform next. Secondly, the high variety of grasping the same object in different ways led to failed recognitions. The gestures highly depend on individual habits. To solve the issue further assembly operations need to be recorded to enlarge the training dataset.

The assistance system's high potential is not yet fully available. Scenarios, where assistance systems can already be put to use with high benefits, are non-changing tasks with high cognitive load. Since humans learn a non-changing task over time, assistance systems have lately been used to speed up learning for beginners. As the assistance system's self-learning capability increases in the future, the field of application is likely to grow in the same way.

Fig. 4 Data glove as an assistance system input device for assembly recognition (left) and grasping of assembly part “cover” (right)

4 Conclusion

The increasing demand for individualized products cannot be tackled by the classical industrial automation approach alone, as they are not flexible enough. Assistance systems seem to be a well-suiting complement as they take advantage of the human’s flexibility by learning themselves. Still, the major drawback of today’s assistance system is the same inflexibility as it is for the fully automated production lines. Therefore, the learning ability is key for the successful implementation in the future. This article focused on presenting today assistance technologies and pointing out the importance of the learning aspect. The lately increased integration of machine learning-based sensor techniques, such as object detection and gesture recognition highly improves the learning ability for the assistance systems. For industrial applications, vision techniques with RGB or depth cameras combined with machine learning are the most suitable and stable solutions. As described, those are already available on the market. The development of assistance systems by large companies as Bosch Rexroth shows the importance.

In research, the trend goes towards a combination of vision systems and gesture recognition using gloves, wristbands or smartphones equipped with inertial measurement units to overcome the well know issues of camera systems with changing light conditions. Both the industrial development and the research community have been focusing on the machine learning approaches lately. The rapid development of those techniques offer the most promising approach for future assistance systems.

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IIoT and Smart Sensors in Human-Centered Manufacturing

Christian Borck, Randolf Schmitt, Ulrich Berger, and Christian Hentschel

Abstract Borck et al. evaluate the challenges and opportunities of Industrial Internet of Things (IIoT) and smart sensors in human-centered manufacturing. Particularly in small and medium-sized manufacturing with fewer machines and smart tools, it is significantly more difficult to automate processes and get the required information from the shop floor. Therefore, they give proven recommendations for the use of sensors based on a set of frequently occurring tasks in assembly, maintenance and logistics to achieve the support of smart data models in the context of Industry 4.0. âŁœIIoT and smart sensors in human-centered manufacturingâŁž concludes with concrete sample scenarios and describe the challenges and one solution using smart sensors and data models.

Keywords IIoT · Smart sensors · Human-centered manufacturing · Assembly · Industry 4.0 · Digital twin

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1 Introduction

IIoT is one of the key enabling technologies for industrial digitalization and smart factories. Connecting data from machines and tools within an IoT context can improve the efficiency and predictability of complex processes and thus save money. IoT can help to enable or simplify the implementation of complex analysis and controls of the production process such as predictive maintenance, production planning, stock taking or quality control.

In small and medium-sized manufacturing with fewer machines and smart tools, it is significantly more difficult to automate processes. Especially with the evolution to batch-size one production, it is more important to connect the manual and semi-manual assembly with a smart digital model (e.g. a Digital Twin—DT) to get more dynamic production pipelines with shorter feedback cycles. To operate the DT with consistent quality, it is important to obtain reliable data from production in an automated way. The use of IoT-networked sensor systems and computer vision systems based on them can make a major contribution to this.

Planning the integration of IoT requires an individual and overall view on the processes and the IT infrastructure of the specific SME. State-of-the-art concepts and model for Industry 4.0—sinks of experiences of many other enterprises in this domain—can help building a tightly meshed network between existing systems and the IoT to lower costs and efforts for integration. The Reference Architecture Model Industry 4.0 (RAMI 4.0) describes a way to transform a classical enterprise to a digital agile player while lowering barrier in the transformation process.

2 Background

In the course of the fourth industrial revolution (Industry 4.0), the strictly hierarchical structure of the factory defined by hardware is being dissolved and replaced by a network of flexible equipment and machines connected to the external world and the product. The network enables communication among all involved actors across the former hierarchical levels. This change is reflected in the RAMI 4.0 as can be seen in Fig. 1.

The model provides a uniform framework for the product life cycle, the business levels and the factory hierarchy and it illustrates their close interconnection in the smart factory (SF). The aim is to be able to make better and, in particular, faster decisions through networking and digitization. Valid, continuous data collection is indispensable for all goals targeted within the scope of SF, such as the Digital Twin (DT). The Internet of Things (IoT) or Industrial Internet of Things (IIoT) is an essential component for networking and acquiring information about all actors involved in the value creation process in the lowest layer (Alcácer & Cruz-Machado, 2019). Among other things, "things" can be connected to each other and to the outside world via the IoT, but not every actor present in the factory offers the appropriate interface for this. This may be due to the fact that it is an existing machine that was integrated into production long before the digitalization came into place or the machine respectively process does not allow for internal and automated feedback. This can also be the case, for example, with processes that are strongly characterized by manual work. In addition, due to a lack of standards, the acquisition of information from existing systems can be more time-consuming than the integration of modern, multimodal data acquisition based on external smart sensors (Uhlemann et al., 2017). The solution that is emerging is a combined system that supports the majority of the interfaces of the heterogeneous system landscape in the factory as well as external smart sensors. This enables the most comprehensive data collection possible in the SF, adapted to the respective process.

In order to understand the challenges and opportunities that the integration of IIoT with the addition of smart sensors offers, it is necessary to classify and explain the basic innovations in existing structures. In difference to the presented RAMI 4.0 structure, SMEs today mainly show strictly hierarchical structures similar to the levels in the automation pyramid. Compared to the RAMI 4.0 model, the automation pyramid generally has five levels in the functional hierarchy (DIN Deutsches Institut für Normung e. V, 2014, p. 17). These are extended in the new reference model by two additional ones: the product level and the networked world level. Figure 2 shows the extended pyramid with the common system representatives.

Level 0 includes the product in the hierarchy. Level 1, 2 and 3 include functions for monitoring, operating and controlling plants and production lines. The 4th and 5th levels include higher-level activities and information flow concerning the entire company (level 5) and the entire plant (level 4) respectively. They are responsible for production planning, among other things. The 6th level implements networking across company boundaries, e.g. with suppliers. The main difference between the levels is the time frames in which activities are carried out and the data basis on which they work. The higher up the pyramid the less up-to-date the underlying data and the larger the time frames. This should improve significantly due to the loosened hierarchy of levels 1 to 5 and the multidirectional communication of all actors. The structure and the established systems should not be dissolved or replaced in the course of advancing digitalization, only expanded and more strongly connected

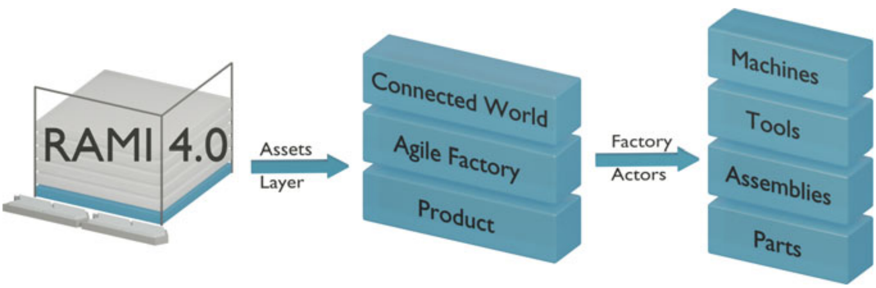

Fig. 1 Representation of the RAMI 4.0 asset layer with its actors (Plattform Industrie 4.0, 2021)

(Kleinemeier, 2014). This is intended to reduce the inconsistency of data that results from the lack of interfaces between the isolated solutions of the individual levels (Schöning & Dorchain, 2014). A number of key technologies have been identified for the evolution towards the smart factory (Alcácer & Cruz-Machado, 2019). One that is relevant for achieving the goals of reducing hierarchies and connecting the factory progressively is explained below—the Digital Twin (DT).

The DT is the digital representation of a real object or system. Depending on its use case, the DT can combine different models, methods and tools that are used to reflect the life of the corresponding real twin (Glaessgen & Stargel, 2012; VDI-Gesellschaft Produktion und Logistik, 2021). Generalized, the DT can be differentiated into three integration levels: the Digital Model without connection to reality, the Digital Shadow with a unidirectional data exchange from reality into the shadow and the actual Digital Twin with the characteristics of the shadow extended by the ability to control the reality (Kritzinger et al., 2018). This differentiation highlights the importance of networking the various actors with their environment and across levels in order to be able to provide appropriate data for the DT or to accept control commands. In order to make the challenge of creating and, in particular, permanently operating the DT for the smart factory more manageable, a subdivision of the DT based on the basic structure of the automation pyramid is being considered (Martinez et al., 2021). At the higher levels of the pyramid, an important step has already been made with ERP and PLM systems, but at the lower levels, there is still a large difference between

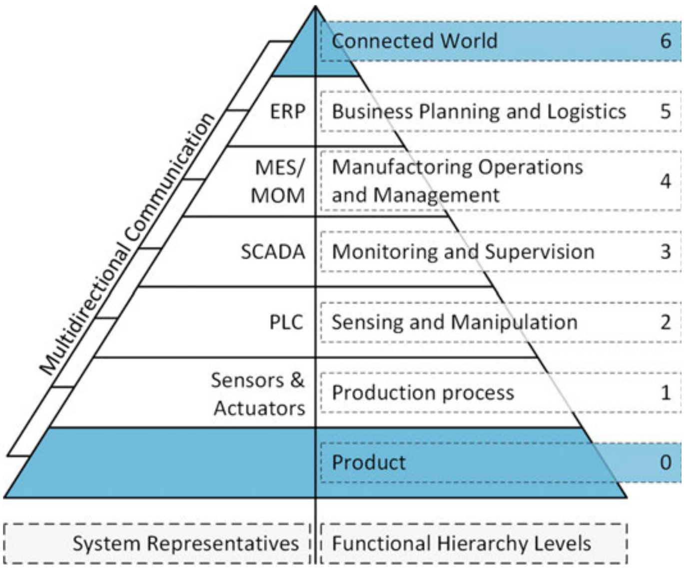

Fig. 2 The automation pyramid is extended by the Connected World and Product level, in line with RAMI 4.0 and extended to include communication across all levels. In addition, the common system representatives for each level are listed: Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Supervisory Control and Data Acquisition (SCADA), Programmable Logic Controller (PLC) and Sensors and Actuators

reality and its twin. The solution to these problems is to connect the existing systems via IIoT and integrate smart sensors to provide the necessary data (Butun, 2020).

IIoT uses sensors and actuators of the first and second level and provides interfaces for interoperability with the upper levels. This enables the upper level to operate in soft-real-time. With the collaboration of information technology (IT) and operational technology (OT), IIoT also enforces the collapse of the supervisor level 3, so it directly interacts with level 4 and therefore breaks the rules of the automation pyramid. It allows that the MES can explicitly or implicitly control/monitor a set of machines in real-time to be able to directly react to changing circumstances. Under the name IIoT-connected MES/MOM (Mantravadi et al., 2022), a system architecture is presented on how an IIoT platform following the automation pyramid rules can open up soft real-time sensing and control of machines as well as resource management for the MES/MOM.

In current human-centered processes, the number of things that could be connected and thus the density of the provided data is much smaller than in automated operations. The actors here are in particular humans and the assemblies and parts. As a result, there is a need for externally integrated data collection, especially for levels 1 and 2. This is where smart sensors come into play, which in addition to their original function, also offer the necessary interfaces to be integrated into IIoT networks.

3 Sensing the Shop Floor

The shop floor is the main driver of the value creation in the enterprise. Managing the activities in the shop floor in the context of Industry 4.0 requires binding sensors and actuators of the production environment to the upper layers of the automation pyramid to get soft-real-time interoperability. In human-centered manufacturing with fewer machines and automation human worker activities are in the focus of IIoT especially by using sensors.

3.1 Human Worker Activities

Humans can perform significantly more complex activities compared to machines. Defining standard operation procedures (SOPs) in an enterprise is an established method and often a requirement to describe step-wise instructions (tasks) for the workers for standardizing the routines. Thus efficiency and quality are increased while misunderstanding is reduced. Bøgh et al. (2012) has analyzed 566 industrial tasks for automation in the domains of:

- **Logistic** including transportation and part feeding,

- **Assistive** including machine tending, assembly, inspection and process execution and
- **Service** including maintenance, repair and overhaul (MRO) as well as cleaning.

They conclude that for logistic and assistive tasks only 13 basic skills (explained in Sect. 3.3) are required. This essentially reduces the complexity of building IIoT systems on a human-centered shop floor and gives a sub-set of references for including smart sensors.

3.2 Smart Sensors

Sensors exists to measure the energy quantity of objects or processes in the real world continuously or in discrete intervals. Energy itself comes into 6 basic forms, which are transformed by sensors into an electrical signal: mechanical, thermal, radiant, electrical, magnetic and chemical. Meijer (2008) is dividing this form into 9 parameter classes: mechanical for solids (33 parameters) and fluids (9), thermal (8), optical (8), acoustic (6), nuclear (6), magnetic & electrical (11), chemical (19), other significant (4). The list seems not to be complete (optical time of flight is missing) but is a good reference because of its background and size. For instance, typical mechanical parameters are force, pressure, position, orientation and torque while optical parameters are e.g. color images. In this book (Meijer, 2008) is also mentioned, that for example thousands of different pressure sensors are on the market.

Differentiating sensors with similar parameters also depend on different other factors like costs, certifications, availability, compatibility, vendor bindings and some technical characteristics on, how well the physical quantities are measured. Some important of these characteristics are (Dincer et al., 2019; Meijer, 2008):

- **Accuracy** describes how close the measured values are to the real world quantities.
- **Precision** is the statistical variations over a time range caused by a random error.
- **Range** of values, the sensor can guaranty its precision.
- **Reliability** is the ability to perform a defined task while keeping failures below or equal a defined rate.

Besides these criteria, there may be some other conditions that restrict sensors to be attached to things, e.g. on assemblies, parts and workers. For these use cases, sensors are used, that can measure the environment from outside in—so-called contactless sensors.

All of these factors are also influencing the smart sensors which are driving the world of IIoT. If a classical sensor gets combined with an analog-digital convert and a bus interface in one casing, a smart sensor is created (Meijer, 2008). Smart sensors are an essential part of Industry 4.0 and must be chosen depending on the use cases.

An essential difference between the sensor classes is their data output. In contrast, a temperature sensor sends sequences of numeric values, while a camera system serves a sequence of 2D images. This implies for imaging systems compared to simpler sensors a significantly higher data volume processing load and system complexity are to be expected. But it also allows acquiring more complex information from its environments such as for object detection and tracking. Also, imaging systems aren't yet really used in the context of IIoT. We wrote about that and a proof of concept as a solution in our recent work (Borck et al., 2022). Nevertheless, image sensors can also interact with classical IIoT data structure and standards using data converters and reduction.

Furthermore, one should additionally consider, that sensors can also measure additional information not purposed for specified use cases - privacy. The acquisition of personal data must follow the laws of specific countries. A proven way here is the anonymization of the captured data close to the sensor or in the smart sensor.

3.3 Smart Sensors for Human Skills

The choice of well-performing sensors and sensor combinations for specific use cases depends less on a generalized formula than on best practices of current state-of-the-art technologies, which can differ from case to case. In the previous two sections industrial human-centered use cases were divided into 13 skills and smart sensors into parameters, which now helps to recommend smart sensor classes for nearly every use case in the shop floor shown in Table 1. Thus, IIoT can be supporting the whole manual manufacturing process.

Moving and locating objects are two of the most frequent skills. The localization and tracking including the position and rotation (or pose for short) of such objects are often established by beacons or cameras for contact-based or contact-less use cases respectively. It must be considered, that optical sensors have problems in orientation tracking for point-symmetric objects. Also, beacons are better suited for wide-range tracking because of their mobility. Beacons can also track bulk goods contact-less by attaching them to containers. Locating hot spots or leakages can be a task of thermal, chemical/nuclear or acoustical sensors depending on emission.

Picking up objects requires prior localization. The picking process itself is characterized by applying a force to an object, so it is immovable relative to the picker and moving them afterward. This force can be measured with mechanical sensors, e.g. attached to data gloves or integrated into collaborative robots. Beacons or optical sensors can support verifying the picking process Placing or aligning objects into the correct target pose is commonly solved by either using mechanical sensors measuring distances or electrical contact sensors or by optical sensors detecting the pose.

Unload can be grouped into two content types: objects/fluids and energy. Detecting the absents of objects or fluids is mostly sensed by mechanical sensors (weight) or acoustically by measuring the signal response of the container. The reason behind the use of acoustical sensors is, that filled and empty containers sound different. Optical sensors can also support the detection depending on the visibility within the

Table 1 An overview of the 13 skills (Bøgh et al., 2012) and the possibilities of capturing these skills using different sensor parameters

LT	AT	Skill	Sensor parameter						Skill Description
			Mechanical	Electrical/ Magnetic	Optical	Acoustic	Thermal	Chemical/ Nuclear	
X		Move To	○	○	●				Change the location inside the factory
X	X	Locate	○		●		●		Find the pose (position and orientation) of an object
X	X	Pick up	●		○				Take and hold an object
X	X	Place	●	●	●				Move an object to the target pose
	X	Align	●	●	●				Adjust the object pose relative to another
X		Unload	●	●	○	●			Empty a container
	X	Check	●	●	●	●	●	●	Verifying or falsify of pre- or post-conditions of an object or process
	X	Open/Close	○	●					Move a separator (door) from open/closed to close/open position, so it is (im)passable
	X	Press	●	●					Apply mechanical force to a surface
	X	Release	●	●					Removing a force or constraint on an object
	X	Turn	●	●					Rotate an object by applying some torque
X		Shovel	●		○				Pick up a set of objects with a shovel

●—Primary Sensors
○—Secondary Sensors (Optional alternative/Addition/Less frequently used)
LT logistic tasks
AT assistive tasks

container. In the case of accumulators, electrical sensors are used to sense the output voltage.

Check covers a wide range of skills and hence sensors measuring specific verification or falsify parameters. For every parameter of the sensor stack in combination with corresponding thresholds, a check can be established (Meijer, 2008, p. 7).

Detecting open and close processes are mostly sensed by electrical contacts. In some cases, the detection can also be done by leakage localization mentioned above.

Sensing press or release an object is either be implemented by an electrical contact sensor in case of buttons or a mechanical sensor measuring the force. The process of turning an object results in two relevant indicators: the current angle or the torque. Both can be measured with mechanical sensors.

The detection of Shovel as a corner case is mainly split into two parts: detecting the load and tracking the movement of the shovel. The load can be measured mechanically using a mass or weight sensor or by object optically by object detection. The movement can be tracked similarly to the Move skill using optical sensors.

4 Example Scenarios: Issues and Solution

In this section, concrete sample scenarios will be used to highlight some opportunities of IIoT in human-centered manufacturing and describe the challenges and a solution using smart sensors and data models. It is assumed for these examples that tools for ERP, PLM and MES/MOM are already in use and talking to an IIoT platform.

4.1 Quality Control

Scenario: After some weeks of a product launch, many reclamations were registered. It turns out, that the product is frequently destroyed including injuries to employees when following the prescribed steps. The production has to be stopped and investigated. After weeks the error source was found in a supplier part, that is out of the specifications. Afterward, the production process was updated and can be continued. Until that, huge costs coursed by the production downtime and customer service are accumulated.

Challenge: Detecting production failures as early as possible to keep its costs low.

Solution: An IIoT-enabled camera system for quality control is attached to the workbench and sends continuously anonymous quality data of the parts and the assembly process itself to the PLM through the IIoT platform. The PLM builds a digital twin of the product and compares it with its shall-state.

4.2 Responsive Production

Scenario: The ERP signals, that a production line A should get a higher priority so another active production line B gets paused until A is finished, but the current products in B should be finished before. The ERP wants to see the current progress of B, but not to interrupt the workers.
Challenge 1: Soft-real-time information about the production progress on the shop floor must be sent to ERP.
Solution 1: Using tools with integrated PLC and interfaces to IIoT protocols like MQTT or UPC-UA can automatically signal instructions acknowledgments to data objects of the IIoT platform.
Challenge 2: Match changes of tools, materials, instructions with the shop floor.
Solution 2: A mobile platform with multiple attached IIoT-enabled sensors like depth cameras or Lidar driving autonomously or by a worker creates a digital twin of the production environment. Required tracking information about the known object in the environment is requested of the IIoT-platform. Located objects are reported to the PLM and MOM through the IIoT-platform.

4.3 Unsupervised Worker Training

Scenario: A trainee should incorporate on building the valve, but the trainer is currently ill and other workers should not be interrupted. The fitting instructions are difficult to read and contain many information gaps.
Challenge: Train a new worker in building the valve without any supervisor yet teaching tacit knowledge.
Solution: Capture motion data from a previously instructed worker while building the valve and stream it to the PLM to the product data of the valve. The worker can now be trained without a supervisor using videos or a Virtual Reality application generated from this motion data. The capture of the motion data is done by a Multi-Access Edge Computer (MEC) using a 3D tracking camera which captures hand, body and tooling poses as well as meta information for instructions. The MEC post-processes the motion data and sends its results to the IIoT platform where it can be delegated to the PLM.

5 Conclusion

It was shown how the use of IIoT and smart sensors can create the necessary data basis for the smart factory. In addition, it was shown that only a small set of mechanical, electrical/magnetic and optical smart sensors are required to get the most required information from a general-purpose workspace into the IIoT and thus support a digital twin. Optical sensors and beacons for localization and tracking as well as some mechanical for force, weight, torque, angle and some electrical sensors for contact detection. Only in some corner cases, other sensors such as acoustic or thermal are needed. This fact makes the integration of IIoT in human-centered manufacturing simpler, more affordable and interesting for SMEs.

It could also be shown, that for most tasks which sensor types are required. Hence, information gaps can be closed. The integration of smart sensors utilizing IIoT also helps the integration of the existing IT infrastructure of an enterprise and thus reducing monitoring and control delays between the shop floor and the upper departments.

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Paperless Production Demonstrator

Jumpstarting Digital Transformation

Dan Palade and Charles Møller

Abstract This chapter presents the paperless production concept as an integrated solution for smart production. The chapter provides an overview of the potential and challenges of going paperless through a paperless production factory vision. It is directed towards SMEs. Internal and external barriers and enablers are debated, the former pertaining to SME's practices and later pertaining to technologies. The paperless production demonstrator is introduced presenting the detailed framework and the methods used for the engagements. The procedure is to decompose, simplify, and explain digital technologies in a learning factory context. The demonstrator is structured to promote co-creation by balancing between top-down approach, driven by technology, and bottom-up approach, driven by industrial needs. The research aspect is examined, and a knowledge gap was identified pertaining to the use of a learning factory. We also contribute with guidelines for industrial practice for the digitalization projects, and the framework which is based on extensive collaboration with our industrial partners.

Keywords Paperless production · SME · Learning factory · Digitalization

1 Introduction

Paperless production is the industrial term used to describe the inception of digital transformation. Digital transformation is "a process that aims to improve (the industry) by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies" or put simply it is the profound change that takes place in industry with the use of digital technologies (Vial, 2019) which replaces and/or supplements paper. The underlying narrative of paperless production is that the use of paper is the bottleneck in the

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streamlining of the production, that however is not always true. Nonetheless, the use of paper denotes a culture that is set in the old ways and incapable of adapting to modern needs. It is also characterized by a specific relationship with technology: it treats technology as an overarching solution, rather than solution to a delineated problem.

Paper is often used to transit information between systems that are not connected or people, thus the use of paper diminishes the opportunities presented by emerging digital technologies. Digitization is the process of converting analog (from paper) data into its digital form. In contrast digitalization is the process of company transformation, embracing digital technologies and having the cultural paradigm shift of connectivity. The vision of a fully digitalized enterprise promises fully digitized processes, seamless data integration between information systems, and intelligent optimization of business processes. Paperless production is the beginning of this journey.

2 Paperless Production in SMEs

Paperless production encompasses bringing transparency to business processes from the business level to manufacturing level (Scholten, 2007) and streamlining the processes by implementing automation. It is especially attractive to Small and Medium Sized Enterprises (SMEs) as they usually lack technological competencies. SMEs are defined by European Union as enterprises with less than €50M and no more than 250 employees. SMEs account for more than 80% of industrial companies within European Union, so digitalizing SMEs is bound to have a major impact on the economy.

2.1 A Vision

Paperless production streamlines the data flow between four core business units/processes: *order management*; *warehouse management*; *planning and scheduling*; *operator management*. Here is a scenario where paperless production is presented (see Fig. 1 for a visual representation): Company A receives an order from one of its usual customers. From the order details, the Bill of Materials is derived. The availability of materials in the warehouse is checked. If they are not present, a purchase order is created, and based on historical data the arrival time is calculated. From the order details a Bill of Processes is derived, that shows the flow of materials through machines to become the end-product. This is fed to the planning and scheduling system, together with the desired finish date and automatically determines the details of the concrete machinery and working personnel based on availability and historical cycle times for each process. The output of this is the cost of resources as well as the time expectations, which then are approved by a manager and sent back to the customer with a quotation and expected finish date pending confirmation from the customer. When confirmation is received, the necessary materials are automatically procured, the order is planned into production, and the operator instructions are created.

The operator will then receive his instructions on a digital work device like a mobile phone, accept his task and proceed to the workstation. Once there he starts the instructions, which would prompt a background process of time collection, thus creating historical data about the real duration of each process for later calculations and better predictions. In case there is need to pick up materials from the warehouse, the operator would scan the material (that has a QR-code or RFID) with his phone before collection, thus automatically updating the warehouse management system. With this setup more analytics for improvement can be done to enable more intelligent production (self-learning).

The order plans are visualized in the planning and scheduling system, having different views based on the user who is logged in. A manager would have a bigger

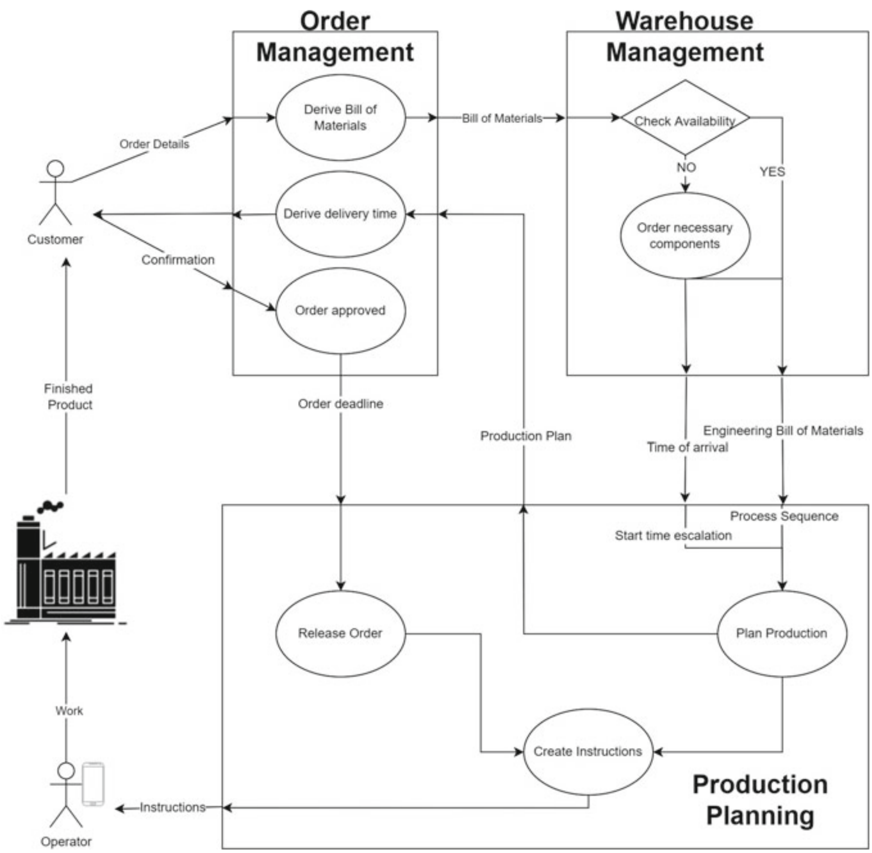

Fig. 1 Visualization of paperless production workflow

overview with a Gantt chart displaying the planned production based on order and on resources used. Each resource has efficiency calculation and visualization, ensuring a quick response in case of deviations. In an emergency, like a broken machine or sick employee, the manager could re-plan the production in the planning and scheduling system using drag and drop functionalities or ask the system to suggest a plan with minimal side-effects and inspect it. This scenario promises transparency in supervising an order as well as automatization of tasks.

2.2 Enablers and Barriers

The assumption is that technology is out there, and the problem arises in exploring what to use and how to use it while minimizing the turbulence in day-to-day activities in an enterprise. This refers to ambidexterity, the ability of a company to balance between exploration of digital technologies and exploitation of existing resources, also called bimodality in grey literature (Li et al., 2018).

There are internal and external enablers and barriers for digitalization. Internal enablers have to do with the status of SME of companies. The lack of a comprehensive information legacy system is one as it defines the digitalization project as Greenfield which is easier to conduct than Brownfield projects (Nowacki et al., 2021), since it is easier for SMEs to integrate new technologies compared to LEs, where long-term planning and implementation phase are expected (Becker & Schmid, 2020). Historically, Enterprise Systems (ES) like Enterprise Resource Planning (ERP) were designed to be rigid, and the customization for specific enterprise needs were delegated to vendors or consultancy companies. It made sense ante-Industry 4.0, as the manufacturing world was slower, and the ES systems were "build-to-last". Presently however, production needs to be flexible, and the ES should mirror that, so the cost to update an ERP according to ever changing needs with the help of vendors and consultants rose, which SMEs could not sustain. SMEs typically lack IT knowledge to enable digitization and funds to acquire the necessary knowledge. They are also reluctant to invest in explorative projects that do not guarantee success (Moeuf et al., 2018). We hypothesize, however, that SMEs are more comfortable with small explorative projects that allow knowledge acquisition and solution development within the enterprise. The missing link is a comprehensive strategy of conducting these small explorative projects and the knowledge about what technologies are most relevant, which we try to solve with paperless production demonstrator.

Another barrier to digitalization (paperless production) is the mentality to sustain such a project. Nominally the approach to such projects was the top-down technological approach, which is unreasonable for SMEs. As an alternative the demonstrators take a more personal approach, enabled by the existing technologies, but pulled by the company needs. The scope of the demonstrator is the *co-creation* of solution based on existing knowledge of the participants. The result of the demonstrator is several functioning prototypes that address the identified problems. In the rest of the section technologies that enable digitalization in SMEs, and which are used in the paperless production demonstrator are presented.

Cyber-Physical Systems are systems of collaborative computational entities that are connected to the physical world (Monostori et al., 2016). They can be generalized as: "Physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core".

(Rajkumar et al., 2010). It allows transfer of analog data through specific tools, manual input from workers to the IS. Development and implementation of CPS is difficult because the subject represents a wide range of system levels. To facilitate this process Lee et al. (2015) created an architecture framework for guiding the creation of a cyber-physical system, see Fig. 2, which was one of the inspirations for the structure of the paperless production demonstrator.

The identified technologies include but are not limited to barcodes, RFID tracking system, smart sensors, cloud.

Internet of Things (IoT) is the name for a concept where a collection of products, systems, sensors, everyday things, are connected through the internet and share data thus creating value. The IoT translated to manufacturing context is called Industrial Internet of Things (IIoT). The purpose of IIoT is to integrate operational technology (OT) with information technology (IT) thus connecting all the industrial assets with

Fig. 2 5C architecture for implementation of cyber-physical system, adapted from (Lee et al., 2015)

the ES. This leads to improved transparency of manufacturing processes, interoperability, visualization, and enables analytics (Sisinni et al., 2018). The smart sensors, data transmission protocols, IoT platforms, and connectivity gateways are enabling quick proliferation of IIoT and consequently enables Smart Production.

Big Data Analytics is the methodology that refers to high-velocity data capture, storage, and analysis. The methods used are not the ones applied to traditional databases, since the data is normally unstructured (Rajaraman, 2016).

Low code/no code programming languages are systems that allow computation of simple problems, and transformation of information without the knowledge of traditional programming language. It is normally highly graphical and intuitive. In manufacturing context, it is used with a focus on system integration and visualization of data.

We hypothesize that the understanding and use of the presented technologies in a structured and explorative manner, by taking into consideration the underlying enablers and barriers of the SMEs will empower the enterprises to transform digitally. Our response is the paperless production demonstrator which is presented further.

The rest of the chapter is structured in the following way: Sect. 3 presents how the paperless production demonstrator is conducted, Sect. 4 presents how research is derived from the engagements, Sect. 5 displays the findings resulting from the engagement, and Sect. 6 presents the conclusion.

3 Paperless Production Demonstrator

Paperless production demonstrator stage is part of the Innovation Factory North initiative that focuses on helping SMEs in their digitalization journey. It is divided into three sequential stages: (1) Awareness stage where the participants assess their digital maturity level, create a vision for their digital future, and construct a roadmap for achieving it; (2) Demonstrator stage where participants identify an immediate problem and co-create a solution; and (3) Anchoring stage where a change management strategy is developed. For more information about IFN process see Chap. 10.

In the paperless production demonstrator stage, the participating companies, together with the academia and the technology provider partners, are co-creating a solution for their identified problem, while in parallel being guided through various technology demonstrations, also called industrial demonstrators, that promote discussion and further co-creation. In parallel the participating companies cooperate on a student project, which creates synergy in collaboration with the paperless production demonstrator. The demonstrator stage is composed of five planned seminars. Table 1 presents the progression and the scope of the seminars, the technology demonstrations, and the workshops details.

The first *initial* seminar has the objective of introducing companies to the demonstrator stage and identifying a common problem. First a flash-lecture about the process is conducted, where the terms like MVP, prototyping, SCRUM, are presented.

Table 1 Overview of the paperless production demonstrator seminars

Theme	Presentations	Demonstrator	Workshop
Initial	Prototyping MVP SCRUM	Paper-based factory	Define the interests of the participants
Instrumented	Digital twin Industrial IoT Retrofitting equipment	Digital Twin of smart lab Home assistant Node-red	Product vision canvas
Interconnected	Digital operator instruction Decision support system Visualization and integration	Odoo ERP Integromat PowerApps ClickUp Andon board	Operations improvement with demonstrated technologies
Intelligent	Automated data workflow Machine learning Process mining	Google teachable machine Disco	Process optimization
Integrated	DevOps	Smart factory	Project success factors

Second, a workshop designed to map the interests of improvement (the common problem) of the participants is conducted. Third, a discussion takes place facilitated by the finding in the workshop. After the seminar, the facilitators have the task of deciding on which problem to be undertaken, and letting the participants know.

The second seminar is characterized by the term *instrumented*. It focuses on equipping something (usually a machinery) with measuring instruments that would enable the solving of the identified problem. First the concept of Digital Twin is explained by distinguishing between process visualization, digital shadow, and full-on digital twin. The first industrial demonstrator displays a digital shadow of the Smart Lab, a learning factory in our facility (more on Smart Lab in following section). Next, we introduce Industrial IoT as a concept for achieving an instrumented ecosystem and we demonstrate an open source IoT platform used for home automation, but which nonetheless can be deployed at an industrial site. The final part we talk about retrofitting equipment and present an industrial demonstrator where a vibration sensor is equipped on a ESP32 microcontroller and sends data through MQTT protocol to Node-RED, a low-code programming platform. In Node-Red the data is processed and displayed, creating a real-time monitoring device. The data is also saved in a database to create a historical perspective and enable analytics.

The third seminar is characterized by the term *interconnected*. It tackles the problem of silo mentality in informational systems. We establish transparency in the data workflow as the immediate need of SMEs. First the operator assistance concept is presented where we demonstrate digital operator instructions. The operator receives the tasks, uses a timer while the task is in progress, has the details about the task on a monitor and after the task is finished all the data about the process is saved for analytical purposes. Second, we discuss what is a decision support system and what is the bottleneck in the participating companies. Examples of those bottlenecks where: “lack of standardization in the process”; “lack of data about the process”; “lack of data about the workers”; “time consuming planning”, etc. The following technology demonstrator consist of several tools that bypass or help diminish those bottlenecks by visualizing data, streamlining workflows, and orchestrating actions e.g., ClickUp, Microsoft PowerApps, Integromat. Third we communicate the importance of integrating informational systems and enabling fast setup of connectivity. For this demonstrator we use a gateway from a partner caller SIA Connect, which allows effortless and quick conversion of most information transport protocols. As part of the demonstrator, we connect to the OPC-UA server in our Smart Lab and migrate the data about the ongoing orders and machine status to a Dashboard and PowerBI, thus creating simple visualization.

The fourth seminar is characterized by the term *intelligent*. We focus on showcasing simple analytics that could bring transparency into the business processes. First, we argue the importance of integrating the systems and having an end-to-end data flow. We demonstrate it by presenting a full automated order workflow that starts in the Odoo ERP system, is sent to a python-based program that controls the planning, which assigns the order to specific carrier the presence of which then triggers a certain machinery. This industrial demonstrator includes a step with a manual station where instructions are presented on the screen, and the operator’s input triggers the next process. The last step is updating the order in the ERP system which signals that it is ready to be shipped. Second, the concept of Big Data is presented and how the application of big data tools can result in more confident decision making, greater operational efficiency, and reduced risk. The demonstrator consists of displaying the Google teachable machine that trains on a set of images and can accurately identify clusters of meaning. The tool is open source, very intuitive and easy-to-use. It is a fitting example of how complex analytical processes in manufacturing are enabled by open-source tools proliferated in the community. Third we consider process mining as an example of process optimization tool. Other tools like machine learning are also presented but not discussed in depth. The demonstrator consists of a live demonstration of a process mining tool (Disco) using an event logger to understand the process in detail, check for deviations in the guidelines, identify the process bottleneck, and control the performance target.

The fifth seminar is the evaluation of the demonstrator stage where we demonstrate the combined *integrated* solution. It is structured in three parts, a presentation/lecture given by the facilitator about the process, the presentation about the co-created solution given by the participants, followed by a discussion about the conducted process, positives, and negatives.

4 Researching the Paperless Production Demonstrator

The IFN engagements are used as a source for gathering research data and testing hypotheses. The paperless production demonstrator looks at research in three dimensions mirroring the levels of abstraction of the IFN ecosystem. The paperless production demonstrator is the result of a staging process, which results in three parts, the *script*, that dictates the structure of each play, the *front-staging*, which dictates the content of the *play*, and the *back-staging*, which is the design and development of the *props* used in the play. Staging refers to the process of designing activities used in participatory design (Clausen et al., 2020). A *play* refers to a seminar. For more details about IFN and the staging process see Chap. 10.

Scripting refers to the action of writing the *script* for the upcoming engagements. The result of scripting on paperless production demonstrator is the plan for the five seminars, the themes presented there within, and the sequence. Internally we designed different demonstrators with the intention that they will supplement one another, and thus created a script for each. The first observation was that some themes are present in multiple demonstrators and mapping the themes in a common file resulted in a metro map on account of visual similarity. The metro map for paperless production is presented in Fig. 3. The observations from the conducted demonstrator engagements are used to refine the metro map to bring more clarity to future participants.

The front-staging refers to planning concrete seminars, including the presentations, the industrial demonstrators, and the facilitated workshops. The focus is on maximizing discussion points related to how the technologies can be used at the participant's company, and the co-creation of the solution.

The back-staging refers to developing the props that are used in the paperless production demonstrator engagement. A prop is a tool used in a participatory design activity. An important prop we have at our institution is the Smart Production Laboratory, also called The Smart Lab, see Fig. 4 It is used to enable research on smart factories. The Smart Lab acts as a learning factory (Abele et al., 2019) but it also stretches the definition of a learning factory since it is designed to support *co-creation* in collaborative projects between researchers, enterprises, and students. A learning

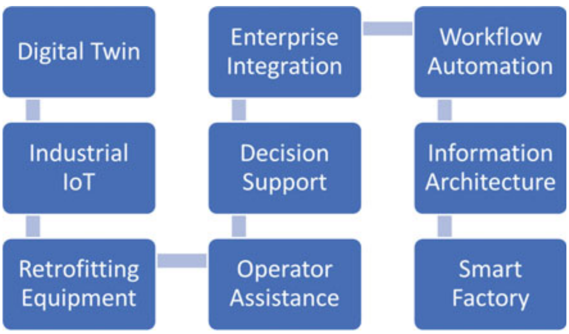

Fig. 3 Metro map of the paperless production demonstrator

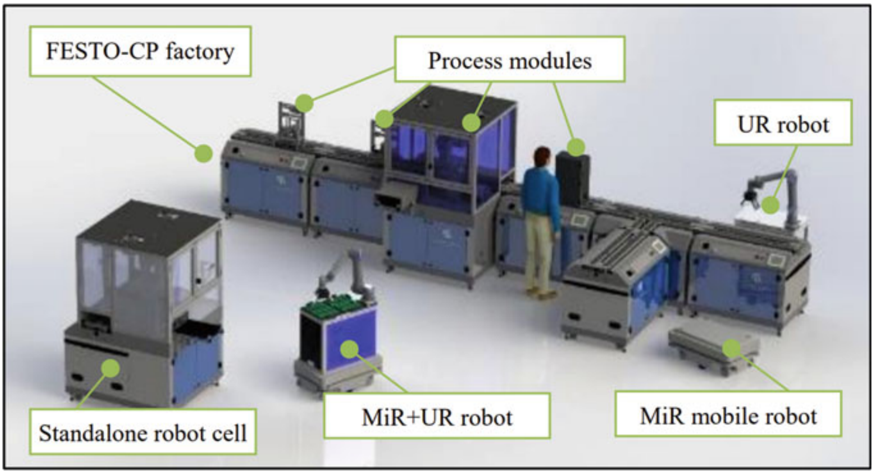

Fig. 4 Overview of smart production laboratory (Nardello et al., 2017)

factory is a realistic representation of a production environment that is used for education, training, and research. The observations in paperless production demonstrator enable a better understanding of the industrial needs which drives the improvement of the Smart Lab and contributes to the research on Learning Factories.

The Smart Lab is comprised of several standard FESTO-CP-factory transportation modules (conveyor belts), process modules like parts dispenser, drilling module, and assembly module, as well as dedicated integrated robots (KUKA) and mobile robot platforms (MiR). From a data perspective, everything is IP enabled. Each module has one PLC controlling the sensors and actuators, equipped with OPC-UA servers. It is controlled using a proprietary solution from FESTO (MES 4) that came with the procurement of the line, and incorporates a couple of ERP specific jurisdictions, like order creation and bill of materials.

Odoo is a platform for developing and integrating IS. It is a semi open-source system with pre-programmed functionalities from ERP, CRM, SCM, and other IS. It was developed specifically for SMEs, being easily customizable and flexible. The functionalities are grouped in modules and there are possibilities to create complete custom modules, as well as websites, configurators, tools for visualization, and others. We use it to demonstrate how seemingly difficult to implement services can be enabled with little effort and how integration between data sources can bring more value than the sum of its parts.

Co-creation is a form of collaborative innovation that enables information to be shared rather than kept for oneself. It is the scope and result of the IFN demonstrators. The seminars are the optimal medium for observing what facilitates and what hinders co-creation, which allows us to design better methods for co-creation like workshops and questions to empower discussions, which contributes to the research on co-creation.

During the demonstrator stage we are witnesses to digital transformation and the observation of the complete process allows us to discover trends that facilitate the creation of frameworks, technological maturity maps, and critical success factors, that are later tested in similar environments using Design Science Research approach.

5 Discussion

Initially, we did two runs of the demonstrator with themes related to paperless production (data-driven decision making). From those we refined the scope to make it more general and marketable to prospect participants. Afterwards, we had two runs of the paperless production demonstrator with six participating companies and one technology provider in total. During these runs we made observations that allowed us to improve the methods used in the engagement.

We observed that industrial demonstrators, being a visual tool, would empower participants to deliberate how the showcased technology could be used at their facility. However, they would be reluctant to share their ideas right away for two reasons: there is a general barrier in discussion for the first to speak, and their ideas are not clear and structured thus hard to present. We decided to overcome both by bringing more structure into the discussion and thus creating workshops after industrial demonstrators. The role of the workshop is to guide the participants through an activity and thus facilitate the discussion. We identified two requirements for the design of the workshop for this purpose: (1) the facilitating questions should be as clear as possible and should guide to a clear answer (bad: "How would you use this technology in your company?"; better: "What business process can be optimized using this technology?"); (2) the questions should be complementary to force the compounding of details in the answer of the participants.

We also observed that the presentation of industrial demonstrator should cater to the knowledge of the participants. This means that technical details should be minimized, and instead focus put into functionalities from the user perspective.

The needs of the companies differed, but there were some patterns observed. The visualization technologies got more interest than more complicated technologies, like big data, which was also suggested by the academic literature (Culot et al., 2020), and more easily implementable technologies like smart sensors got more traction than the ones that require more expertise like ES. We used this knowledge to simplify the knowledge and expertise that was presented, so it would compound on already existing knowledge.

The discussion during the demonstrator runs enabled the further development of the maturity assessment model used in the awareness stage of the IFN project, that would fit SMEs better than the one used prior (Colli et al., 2019).

We observed that unless given a specific task the participants would shy away from taking initiative with regards to solution development. To counteract this phenomenon, we decided to start the seminars by giving ten minutes to each participant to share what he has been doing since the last seminar. This forced the participants to be more proactive but did not fully accomplish the task, so we decided to also add homework in between seminars, the results of which they would present at the seminar. This proved sufficient to instill a responsibility towards the solution creation.

At the end of one demonstrator run, an interview was conducted with the participants to enquire about the process, but also to identify critical success factors for implementing digital technologies and thus enabling digital transformation. The interview consists of two parts, one structured with the use of Likert scale to bring even more transparency about the participating company, the second a semi structured. The compounding gathered information allows us to be more critical about the findings. For example, in a company with a long-standing culture based on information sharing, also called free culture, the participants did not identify it as one of the critical success factors, compared to a company that recently implemented this thinking into their culture. Interestingly, a company that does not have a free culture also did not identify it as one of the critical success factors although it was suggested by the demonstrator facilitators how important it is.

The user involvement in the development process was identified as a crucial factor from the participants, which is also advocated by the literature (Ghobakhloo & Iranmanesh, 2021), although we observed that all companies were reluctant to invite users to the seminars. However, this reluctance was not seen in the student projects with the participants, which took place parallel with the paperless production demonstrator. One of the reasons may be that companies are accustomed to the process of having student projects and the methods involved, while not being accustomed to the IFN methodology enough. While they understand the importance of user involvement in the process, they do not understand or do not trust the process enough. The next dilemma that we need to resolve is how to gain the trust of the participants so they would bring a user from the production into the seminar.

Another finding refers to the progression of the project. SMEs prefer smaller and faster steps like the SCRUM methodology, that yields direct results, to a waterfall approach. The reason is their reluctance to invest in big projects because they lack knowledge to guarantee the success of such projects as well as funds to invest. However, they endorse the investment in smaller explorative projects.

Overall, the proposed framework, summarized in the Metro Map (Fig. 2) and Table 1 supplemented by the engagement method was deemed successful in enabling digital transformation by the participating companies.

6 Conclusion

In this chapter we have presented the paperless production demonstrator as part of the Innovation Factory North. We present the concept of paperless production as the first step in digital transformation journey using a vision of a fully integrated paperless factory. We argued that SMEs have ingrained barriers that diminish their potential to digitalize, and that a structured development approach based on co-creation and small incremental explorative studies will enable and accelerate digital transformation in SMEs. Our conceptual approach is the paperless production demonstrator framework and the methods applied for the engagements. From these we derive some guidelines for co-creation for industrial purposes: (1) divide the digitalization project into small digestible parts that compound; (2) focus on problem solving rather than being driven by technology; (3) involve the user as early as possible, from the design phase; (4) consider the solution in the context, not as an isolated technical solution.

The paperless production demonstrator was the result of a systematic staging process, which contributes to academic knowledge related to Learning Factory. Abele et al. (2015) identified five scenarios of use for a learning factory, we present a sixth which is solution development through co-creation with industrial partners. Future research is needed in this domain.

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The Journey from Direct and Indirect Additive Manufacturing of Individual Parts to Virtual Warehousing of the Parts Portfolio: Lessons for Industrial Manufacturers

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Abstract The advent of the virtual warehouse (VW) supported by additive manufacturing (AM) represents a significant opportunity for reconfiguring modern supply chain, which can provide leverage for quick response, resilience, global reach and sustainable capabilities for small and large companies alike. In this article, we outline the benefits and challenges in adoption of VW, identify the factors, which need to be considered for adoption of VW and provide a preliminary framework for its adoption considering the different stages of the product lifecycle. Our findings suggest that though the benefits of VW can be high at the later stages of the product lifecycle, it is prudent that companies consider that at the product design stage as the cost of adopting it in the earlier stages are one-time and relatively lower compared to those adopting it for products in late lifecycle stages. VW also opens up opportunities for small and medium enterprises (SME) suppliers to be integrated into the digital supply chain of its customers.

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1 Introduction

Many large industrial product manufacturers or Original Equipment Manufacturers (OEMs) rely on small and medium enterprises (SMEs) to supply them with critical spare parts. As these SME suppliers may not be able to produce the parts when needed within the desired lead-time or may even stop producing those parts, OEMs are forced to keep inventory of those parts, needed by their customers to satisfy contractual obligations of service. Despite high inventory carrying costs, they face challenges in meeting demand due to deteriorating quality of the stored parts, difficulty in forecasting, and in delivering the parts to the customers on time. Additive manufacturing (AM) can help address the above challenges by facilitating on-demand production of the spare parts. Many manufacturers have attempted to adopt AM for spare parts production by choosing individual parts. Those attempts have been successful in improving availability of the spare parts and in reducing inventory costs and led to better quality, if coupled with redesigning the part for AM. Nevertheless, multiple challenges exist in choosing the appropriate parts, which can be printed. Such challenges include lack of availability of 3D files, lack of availability of design and supply chain data in easily usable format etc. The most important limitation is the variability in quality of parts that can be produced with AM. For spare parts manufacturing, one can try to replace an original component with something that has to be as close a match as possible, and many legacy components will have been made using injection moulding (IM). Components manufactured with AM will differ on surface quality (in most cases), material type (in most cases) and on material quality (in all cases where the original product was not produced using AM). Components manufactured with Freeform Injection moulding (FIM) will match on material type (in most cases), and on material quality (in most cases). In addition, surfaces or features critical to quality may be made with metal inserts.

Unless the part portfolio is digitised at the design stage, the companies will continue to face challenges in adopting on-demand production using AM. Design and production configuration changes can be expensive and time-consuming when using traditional subtractive manufacturing processes. AM allows freedom of redesign. Manufacturing a revised design involves modifying the CAD data, exporting a new programming file and manufacturing the part using AM. There may be very substantial additional costs for part verification. If you are replacing an injection-moulded part with an AM part, you need to verify that the AM part is as good as the injection-moulded part for the situation of usage. This may require extensive testing in specialized environments. For FIM, the same base materials and manufacturing process are used. This lowers the risk of failure.

A virtual warehouse (VW) of parts can be a key enabler for on-demand production. A VW is collection of digitized components that can be produced on-demand according to the requirements applicable to the component without the need to keep the parts in inventory. By replacing physical inventory, virtual warehouses can send 3D files to the closest 3D printer. Thus, if a machine part breaks and needs to be replaced, there is no need to have a warehouse to store these slow-moving parts as they can be produced using AM on demand. In a broader sense, VW can be considered as a state of real-time global visibility for logistic assets such as inventory and vehicles. It relies on information technologies and real-time decision algorithms to provide operating efficiencies and global inventory visibility (Fung et al., 2005).

Industrial manufacturers are also facing increasing customer demand for variety and customization, which adds complexity in managing the part portfolio and serviceability over the product life cycle (PLC). Failure to digitise the part portfolio at the design change adds significant cost later on in terms of redesign, assessing suitability for AM etc. Individual customer preferences and the PLC are important aspects to consider in practice to rapidly develop and manufacture customized products (Lacroix et al., 2021). Develops models to generate insights on technology-switching strategies addressing individual customer preferences in terms of ideal buying times and product variants across the PLC. VW can be used not only for the parts with proprietary designs by the OEMs but also for the parts, which the OEMs rely on SME suppliers. The digital design and VW will allow the SME suppliers to also be integrated in the VW so that those parts can be produced on-demand without the need to keep inventory. Any need for customisation can also be quickly addressed.

But there is limited research on the approach that industrial manufacturers can adopt to implement VW so that on-demand production can be well integrated within the company's processes and incorporated at design stage and not explored only when significant challenges are faced in spare parts delivery. Hence, the objectives of this research are as follows:

(1) To identify the benefits and challenges in adoption of VW supported by AM technologies
(2) To develop a framework for adoption of VW for industrial product manufacturers with particular focus on SME manufacturers.

2 Literature Review

2.1 Advantages of Direct and Indirect Printing

As a manufacturing technology, AM can be effective in reducing inventories (Durach et al., 2017; Ghadge et al., 2018; Holmström et al., 2010) because parts can be produced when needed within a short lead time. Also, AM has been shown to reduce lead-time (Oettmeier & Hofmann, 2016; Muir & Haddud, 2017), as orders are generated by sharing digital files (Oettmeier & Hofmann, 2016) offering instant global reach. Similarly, AM can also help in reducing supply risk for spare parts, where low demand parts can be printed if a supplier for a traditionally manufactured part is not able to deliver in such low quantities (Knofius et al., 2016). AM can also enable mass customization (Shukla et al., 2018) and generally assist new product testing and introduction. Though AM may allow localized production and lighter-weight parts, it is generally unsuited for larger-scale production as it offers limited economies of scale compared to conventional manufacturing technologies. This also means that the primary barrier for using AM for after-market and spare parts manufacturing is the quality/quantity of parts that may be produced with AM vs. the quality/quantity of parts that may be produced with conventional manufacturing e.g., IM. This lack of scalability substantially reduces the potential impact of AM to reduce the consumption of materials, since most successful AM applications in general manufacturing are very low volume.

IM is a mainstay in global manufacturing. However, injection moulders find the implementation of new manufacturing models and new materials to be complicated by high tooling costs and high run-in costs.

In terms of potentials towards early and late stages of the product life cycle AM offers strong potentials. Even today, with simulations and prototypes supporting product development processes many products fail when introduced to the market or collects dust in the warehouse due to over production. It is tempting to conclude that the new product introductions (NPI) and end-of-life (EoL) models are ripe for an overhaul. One of the critical flaws in the NPI model is that we cannot conduct real-life tests with prototypes. We need real products, and to produce these means investing in production tooling. Production tooling often means injection mould tooling, and injection mould tooling comes with high initial investments, minimum order quantities and other unpleasant side effects. Because of the high tooling investments and minimum order quantities, manufacturers will tend to overproduce, which makes product failures painful. Especially from an environmental point of view, since products that fail will often generate a lot of waste. First, materials, energy and money are invested in producing a quantity of products. Then, these products have to be discarded without having ever been used.

Soft tooling and FIM have the potential to address the shortcomings of both AM and IM, reducing manufacturing costs for mould inserts of any complexity, which can then be used for producing low volume injection moulded parts. FIM and Soft tooling combines the short lead-times, low start-up costs and design freedom of AM with the versatility and scalability of IM (Sharifi et al., 2021a). The key objectives are to allow manufacturers to bring products to the market faster, cheaper and with lower risk, and to maintain the relevance of these products through easy customization and adaptations once they have been launched (Sharifi et al., 2021b). It should, however, be mentioned that printed soft tooling cannot fully address the shortcomings of AM and IM as it does not cover all injection mouldable materials and also suffers from design limitations whereas FIM to a large extend support these elements (Sharifi et al., 2021a).

Manufacturers will have to perform extensive part-by-part verifications when implementing AM for manufacturing of spare parts that were originally produced with IM. With FIM, the verification is substantially less intensive, as the base material and manufacturing process is the same as traditional IM. If a company wants to launch a product based on injection-moulded components, it can produce a limited quantity of launch-grade injection-moulded samples without having to invest in injection mould tooling. It can also support gradual scale-ups as it is compatible with conventional IM, and printed inserts may be combined with metal tool elements in a gradual transition from prototyping to production. Accordingly, minimum order quantities are replaced with an on-demand based model that is extremely advantageous in the early stages of a PLC.

2.2 Selecting Individual Parts for Direct and Indirect Printing

Many industrial manufacturers, willing to explore AM face a major challenge in selecting the appropriate parts, which can be produced using AM. It is an imperative that a systematic approach be followed to facilitate the selection of parts that are suitable for AM by considering both technical and supply chain aspects (Lindemann et al., 2015).

Different spare parts classification criteria need to be considered while taking into account the specific application context before finalizing the most appropriate method for selecting spare parts most suitable for AM (Frandsen et al., 2020). Although a large body of literature exists on spare parts classification, there is limited literature on selection of spare parts that are suitable for AM and even less for FIM.

There is a need to identify the appropriate technical and supply chain related factors, which can be used to classify and identify the spare parts that are suitable for AM. More importantly, there is a need to develop suitable approaches that can help a company to analyse their large portfolio of spare parts (often several hundred thousand), and determine the most suitable parts, which can be produced by AM. Without such an approach, companies face challenges in adopting AM for spare parts manufacturing (Chaudhuri et al., 2021). Some recent research, which addressed this problem and offers methodologies for assessment and selection, include (Chaudhuri et al., 2021; Knofius et al., 2016; Sharifi et al., 2021b).

2.3 Building the Virtual Warehousing of Complex Part Portfolio

A key challenge remains that digital representations of components do not exist or lack important details. Using a CT scanner, parts can be analysed to capture the geometric aspects of a part in combination with the mechanical properties originally assigned. This data is then translated into a CAD model, which is converted into the digital file used with a 3D printer. This will enable companies to use virtual warehousing to generate and store digital files of their legacy parts. Through a joint industry project, with participating companies throughout the entire AM value chain, (Kandukuri & Moe, 2021) proposed an assurance framework for virtual warehousing. The above framework answers questions related to whether digital drawings are available when needed, whether the parts can be made 'first time' when needed, whether the parts can be made at the same quality in different locations and which requirements to be put in place for on-demand manufacturing.

2.4 Gaps from the Literature

The review showed that there is limited literature on how manufacturers can move beyond selecting and producing a few parts using direct or indirect AM to digitizing their part portfolio and adopting virtual warehousing. Having worked with multiple manufacturers in their journeys to adopt AM and FIM, we believe it is the logical next step beyond replacing conventional manufacturing with digital manufacturing to changing the overall configuration of the order-to-delivery system. This also provides opportunities for SMEs to overcome constraints related to lack of resources and funds to be part of the digital supply chains of their customers.

3 Benefits and Challenges of Virtual Warehousing

3.1 Benefits of VW

Consolidation of slow-moving and excess inventory can free-up warehouse space. In addition, there will be time savings related to avoiding checking and rationalizing of cycle and safety stock. Moreover, stock-out costs can be avoided as parts can be manufactured on demand. Hereby the VW also offers a response to supply chain uncertainties and fluctuations. Building resilience into supply chains has become an important strategic objective (Asmussen et al., 2018; Fiksel et al., 2015), combining dynamic flexibility—i.e., building robustness (e.g., strategic stock) and ability to respond to given circumstances by having integrated supply chain systems, and structural flexibility—i.e., the ability to reconfigure the supply chain according to environmental circumstances. The VW builds the foundations for both dynamic and structural flexibility and its benefits should, therefore, not only be accounted for through operational performance by should be seen as a strategic mechanism enabling responses in the face of disruptions and risk.

A VW of part designs that can be printed on demand, without the associated costs of offshore production, storage, and multi-stage distribution, can decrease the level of inventory and waste dramatically. Furthermore, parts are manufactured closer to where they are needed, resulting in a reduction of inbound logistics, limited storage and hence a lower environmental footprint.

3.2 Technical Challenges

3.2.1 Data Availability and Quality

A manufacturer may decide to produce a few spare parts using AM as part of pilot projects, but they will need a systematic approach to identify spare parts, which can be produced by AM. Such an exercise is a data intensive process and will require design data, available in 3D files and supply chain data, collated from enterprise resource planning (ERP) systems. Many companies lack 3D files for a large number of parts and hence design data is not available in easily accessible form. Creating a combined database of the part portfolio consisting of both design and supply chain data is a time-consuming process. Once this database is created and the first set of feasible part candidates are identified, produced, and certified for use, the companies may decide to move those parts into a VW.

Due to the lack of data, other companies may decide to follow a completely expert-driven approach to identify such spare parts. This is, however, a cumbersome exercise involving many employees and over many years, which many organisations may not be able to afford.

3.2.2 Suitable Digital Tools for Automated Virtual Warehousing

Digital tools involve creation of digital design files for the parts with detailed specification, materials as well as real-time supply chain data of the parts. Thus, it should be able to integrate the data from existing product lifecycle management (PLM) and ERP systems. It should enable customer ordering and assign customer orders to suppliers or manufacturing facilities for manufacturing and delivery to customers.

3.2.3 Need to Verify Performance of Replacement Parts

The performance of the parts produced by AM needs to be verified and for most industries, those have to be certified to be used in final products. This can be a time consuming and complex process, which involves certifying the individual processes and the equipment. Use of indirect AM technologies alleviate the above problem as the finished part is produced using the well-tested IM manufacturing technology.

3.3 Organizational Barriers

3.3.1 Lack of Integration Plan

Most organisations have not thought beyond producing individual parts by AM. Isolated substitution of one manufacturing technology with another will rarely create a long-term positive impact on the business unless the supply chain configuration is changed.

Analogous to the substitution of an experienced and seasoned footballer with a younger footballer with more energy, the one-to-one substitution seldom changes the game, unless a new team configuration is created to achieve the end objectives, utilising the skills and energy of the player, coming on as a substitute. Hence, there is an opportunity to rethink the entire order-to-delivery process using VW with minimum physical inventory as possible and by utilising, direct and indirect AM across the PLC. There is lack of such strategic thinking in organisations while utilising AM.

3.3.2 Reluctance to Scrap Existing Inventory

Most organisations also have sizeable volume of spare parts inventory. Those can amount to multiple years of stock possibly accumulated as a result of last-time purchases. Transitioning to a VW will imply scrapping some of those inventories. Creating such a warehouse will involve one-time investment though recurring cost of maintaining the inventory will be minimal or even zero. This requires the senior leadership team of the organisation to have the conviction to make the transition to VW.

3.3.3 Culture and Mind-Sets

Organizations with traditional hierarchical structure may have more difficulties to adopt new technologies. Several layers of decision-making create impediments for adoption of new technologies (Boyer et al., 1996). Moreover, multiple functions are involved in management of spare parts such as sourcing and after-sales service while responsibility of digitising spare part designs will lie with research and development (R&D). Rarely, the above functions are aligned in terms of their objectives, key performance indicators and their priorities. These create further challenges in virtual warehousing of the part portfolio.

4 Digitising Production of Parts to Virtual Warehousing: A Case Study

Shell, the British-Dutch multinational oil and gas company, is leveraging spare parts 3D printing to create a virtual digital warehouse. Shell's in-house AM capability started in 2011 with a metal laser-printing machine to fabricate unique testing equipment for laboratory experiments at the Shell Technology Centre Amsterdam (STCA). Today, Shell has about 15 polymer, ceramic, and metal printers located at its technology centres in Amsterdam and Bangalore.

Within Shell, the focus for AM is on spare parts, novel designs, and visualisation objects. Although Shell has the capability to manufacture spare parts itself, it considers the following options for sourcing of 3D printed components:

- collaborate with an original equipment manufacturer (OEM) qualified to supply 3D printed components
- when an OEM is not available, and in compliance with intellectual property (IP) laws, Shell can reverse engineer the part and have a commercial supplier print it from a 3D model
- in emergency cases and when IP is not an issue, Shell will print spare parts in-house.

However, Shell's AM strategy is not to manufacture parts itself. Rather, it aims to develop a digital warehouse, which stocks all the information required to print components whenever they are needed, in partnership between Shell's technical authority, OEMs and local partners. A digital warehouse enabled by local eco-systems would provide real lead-time reduction, and responsible use of resources. The recent success is driving Shell's commitment towards developing digital warehouses in the energy industry. To date Shell has installed over fifty 3D printed spare parts in the operating assets, both produced in-house as well as sourced from different manufacturers (Manufactur3D, 2021).

Many other companies have recognized the potential AM and its digital nature brings to solve the challenge of efficient and cost-effective manufacturing and supply of spare parts. These include Saudi Aramco, ConocoPhillips, Vallourec, Petrolvalves, Valland, IMI CCI, Voestalpine, JFE Steel Corporation, Hiptec, Guaranteed, Ramlab, Norsk Titanium, Immensa Technology Labs, Additive Industries, Addilan, 3YOURMIND, XDM 3D Printing and Viaccess-Orca. Together with DNV these companies have formed a consortium and are working on a joint industry project to create a quality assurance framework for how distributed and on-demand printing of spare parts should be carried out to ensure the ultimate goal; that the end user gets the right part, with the right properties within the right time (Moe, 2021).

5 Framework for Adoption of Virtual Warehousing

Digitizing the components and production is a prerequisite for transformation from conventional warehousing to digital warehousing. There are different internal and external factors (Fig. 1) influencing the digitization process and successful implementation of VW.

Similar to adoption of any new technology (Hall & Khan, 2003), the decision to invest in implementation of VW must be linked to a new business model and overall strategy of the manufacturing company and value creation potentials (Colli & Waehrens, 2022), and particularly the service and spare parts strategy. From an organizational point-of-view, size, structure, culture, social capability of employees and top management supports/commitments are key factors to be considered for successful adoption of VW. It may be assumed that the larger organizations can adopt VW easier due to the availability of funds to cover the costs of implementation, but operational and supply chain factors are usually much more challenging in the big organization. The supply chain factors, which need to be considered, are the customer lead-time requirements, minimum order quantity, existing levels of inventory and supply risks. High supply risks coupled with high minimum ordering quantities and low customer lead-time requirements are positive indications to shift to VW. But high existing inventory levels is usually a deterrent as companies are reluctant to scrap that inventory even if those may be unusable when needed. Hence, the management needs to take bold decisions and consider a long-term strategic perspective considering the entire lifecycle.

External factors are equally important to be considered for successful adoption of VW. From technology perspective, maturity, benefits and drawbacks of new manufacturing technologies that enable the companies to manufacture the parts on-demand

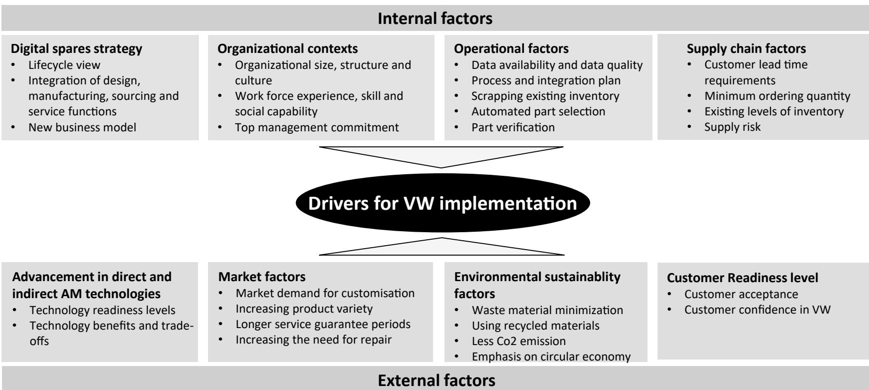

Fig. 1 High-level framework for adoption of virtual warehousing

should be taken into consideration. Customer readiness level, market and environmental factors are also some of the key external factors that influence the VW adoption process (Fig. 1). For example, market demand for customisation, increasing product variety along with extended service guarantees are market factors, which will prompt the manufacturers to rethink their existing practices. The emphasis on environmental sustainability to reduce material consumption, CO_2 emissions and adoption of circular economy should also encourage companies to redesign products, digitise design and adopt VW. At the same time, customers also need to be convinced of the benefits of VW and their confidence in terms of on-demand delivery will dictate to the extent the industrial manufacturers can adopt VW.

Each company will have to assess the relative importance and the interrelationships of the above factors, which will be dependent on the environmental contingencies (e.g. companies working in dynamic environments are likely to benefit from quick response capabilities and will be prone to invest in resilience building capabilities), and the specific resource configuration of the company (e.g., companies with high technological maturity are prone to have strong integration of systems and acceptance, supplying the basis for adoption of VW). At the same time, companies must assess the different objectives across the lifecycle of the product, the supply risk and the cost and benefits of implementing VW to decide on design options, manufacturing technology choices and the order-to-delivery strategies to implement VW.

As it can be seen in Fig. 2, the benefits of VW are much higher in the last phase of the PLC. However, it should be noticed that the cost of VW implementation will be also much higher if a manufacturing company decides to adopt VW only for the parts in the last stage of PLC (e.g., spare parts manufacturing). The reason is lack of digitized components. The process of part digitization is time consuming and complicated, especially for the companies with large part portfolio. Therefore, the process of component and production digitization should start in the design stage.

6 Conclusions and Future Directions

Many industrial manufacturers have explored use of AM for production of individual parts, but lack a long-term, comprehensive strategy to digitise their part portfolios. Thus, such adoptions become one-off activities and fail to provide the benefits, it promises. Moreover, multiple challenges in adoption of AM still exists. In this article, we describe how combination of direct and indirect AM technologies like FIM and creation of virtual warehouses for portfolio of across different stages of the product lifecycle can provide such benefits. We have identified factors for adoption of VW and have provided a preliminary framework to aid its adoption.

There is need of in-depth studies involving carefully chosen sample of small and large manufacturers in developing the business potential of adoption of VW using direct and indirect AM and to design suitable interventions to overcome obstacles faced in implementation of VW. Such a study can provide a generalizable framework

Sales volume / *Factors*	Introduction into market	Growth in market Acceptance	Maturity of market, sales level off	Decline as market become saturated
Dominant operations performance objectives	• Flexibility • Quality	• Speed • Dependability • Quality	• Cost • Dependability	Cost
Supply Risk	Medium	Low	Medium/High	Highest
Cost of implementing virtual warehouse	Low	Medium	High	Highest
Benefits of virtual warehouse	Low	Low/Medium	High	Highest
Design	• Digital Design • Design for AM • Design for recyclability	Continuous product upgrade to suit specific customer needs	• Continuous product upgrade to suit specific customer needs	
Manufacturing process technologies	• AM • Conventional	• AM • FIM • Conventional	• FIM • Conventional	• AM • FIM
Spare parts order-to-delivery		• Assemble to Order • Make to Stock	• Assemble to Order • On-demand	On-demand

Fig. 2 Objectives and operational choices for adoption of VW during different stages of PLC

enabling decisions related to the evaluation of which companies and which kind of part portfolios that will have a best fit with VW and create the maximum benefits. Other studies can assess the impact such implementations on overall economic, environmental and social sustainability performance of companies. Investigating adoption of VW will create more localised and resilient supply networks can be another interesting research direction.

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A Modular Engineering Pipeline for Mixed Reality Environments

Jacob Böhnke, Paul Derno, and Christian Hentschel

Abstract Böhnke et al. discuss a set of challenges of digitalisation in industrial environments, especially for Small- and Medium-sized Enterprises (SME), and present a customisable and Modular Engineering Pipeline (MEP) for Mixed Reality (MR). MR can help to better understand industrial three-dimensional (3D) data through spatial visualisation, but also to optimise processes, increase efficiency and therefore lower costs by digitising former analog processes. The entire value chain can benefit from the productive use of MR, e.g. in production and assembly for virtual trainings of assembly sequences and production simulation or in engineering for Immersive Analytics (IA) such as Virtual and Rapid Prototyping. The contribution concludes with a variety of example implementations that the MEP is used in productively.

Keywords MR · VR · AR · Rapid prototyping · Collaboration · Worker training · Scientific visualisation · Immersive analytics

1 Introduction

Engineering and production expierence a drift in the direction of circular economy and towards batch size one due to customer and governmental requirements. This leads to several side effects, such as non-applicability of existing processes, as these are designed for high-quantity production and disposal of the products after their ser-

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vice life. Business model innovation is needed to adapt to those changing boundary conditions. Sustainable circular economy with highly customised production close to batch size one, means more effort in terms of Maintenance, Repair and Overhaul (MRO), as employees have to master a wider range of MRO scenarios. By using Mixed Reality such scenarios can be developed, trained and refreshed with reasonable effort. MR training scenarios can be automatically derived from conventional assembly or maintenance instructions.

Another possibility of generating such trainings is by tracking a skilled employee while executing an assembly and converting this data into a repeatable training session. This method allows to convey the implicit knowledge of the employee about the process, that is not included in the instructions, to other colleagues. The latter method bears the chance of process optimisation (e.g. Six-Sigma) via implicit knowledge in manufacturing, but especially for manual assembly.

Virtual and Rapid Prototyping help speed up engineering and development and minimise errors at the same time. Especially in the context of industrial digitisation the amount, size and complexity of data in research and development (R & D) has drastically increased (Pajarola, 2012). This is mainly a result from growing computing perfomance, that has been outperforming Moore's Law (Moore, 2006) for the past decades (Koomey, 2010) and is continuing to grow further in a "Post-Moore Era" (Vetter et al., 2017). So the tendence of bigger and more complex data will not be plateauing soon, if ever. This huge and constantly growing pile of information is almost impossible to process close to realtime. This development leads to tasks being split into smaller and more refined sequences, requiring more interdisciplinary cooperation and information transfer, e.g. in the form of data visualisation. Due to its ability to represent complex, spatial data in a comprehensible way and across locations, MR is excellently suited for this task. MR is a hybrid of VR and Augmented Reality (AR) according to the reality-virtuality spectrum of Milgram et al. (1994, 1995) and does neither solely take place in the physical nor in the virtual world. In MR physical and virtual objects coexist and interact in real time, allowing the creation of completely new visualisations. According to a study performed by (Millais et al., 2018) usage of VR in data analytics also benefits deeper and more precise findings in the data and a higher level of satisfaction and success for the user, when exploring data through VR. Several other research supports those theses based on human vision and perception (Moloney et al., 2018; Bach et al., 2018; Donalek et al., 2014).

The majority of data generated by Computer Aided Engineering (CAE) today is 3D (e.g. Computer Aided Design (CAD), Computational Fluid Dynamics (CFD), Finite Element Method (FEM)), but analysis and post-processing of this data is mainly performed on two-dimensional (non-immersive) user interfaces (e.g. Desktop), although respective MR hard- and software is available on the market. This contradiction leads to a lower information yield from the data despite what could be possible. According to (Donalek et al., 2014) it is beneficial to visualise as much dimensions as possible in order to have a higher chance of finding additional information, such as correlations, patterns or outliers, in the data.

MR can not only help to better understand and comprehend complex 3D data, but also to translate real-world challenges to the virtual world in order to find solutions

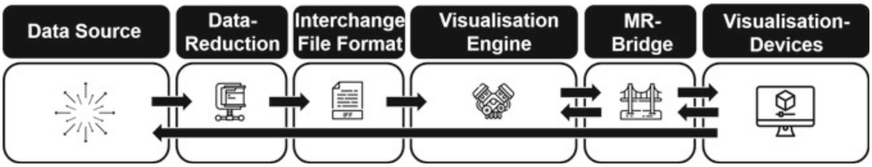

Fig. 1 Modular mixed reality visualisation pipeline

in a more effective and robust manner. Another promising field of application for MR is the training of personnel, be it in the medical or the technical field.

Off-the-shelf MR software solutions are costly and therefore do not find much application in the SME area. However, since the problems and opportunities of digitisation affect most enterprises, from big players to SMEs, this contribution presents a cost-effective, modular and highly customisable engineering pipeline to interactively visualise industrial 3D data, collaborate and do virtual trainings in MR.

This contribution is subdivided as follows. Section 2 discusses the functioning of the modular engineering pipeline and briefly discusses the main challenges. Section 3 explains a realisation of the pipeline for the use case of immersive and interactive post-processing of unsteady simulation data, like CFD. Section 4 gives additional examples for the usage of the modular engineering pipeline in different fields. Section 5 concludes this contribution by evaluating the opportunities and possibilities enabled through the Modular Engineering Pipeline.

2 Modular Engineering Pipeline

The following section illustrates the modular and customisable engineering pipeline for collaborative visualisation of industrial 3D data in MR without using costly commercial visualisation software. Figure 1 shows the basic structure of the engineering pipeline, whose modularity lies within its loosely coupled sub-modules, that can be exchanged easily depending on the desired use case or whenever a more powerful solution for a specific use case arises.[1]

The visualisation pipeline allows to immerse into data from a Data Source. Data from various sources can be processed. Be it stationary geometrical data from CAD or unsteady simulation data from CFD, FEM or a process simulation. Basically all representations or physical simulations from a digital shadow or twin (DT) can be integrated.

The data goes through several pre-processing steps before being visualised and is prepared for MR in the Data-Reduction pre-processing step. The underlying meshes and textures of the 3D data are reduced or decimated using mesh manipulation algorithms. Because of increasing computing power (Moore, 2006; Koomey, 2010; Vetter

[1] Icons made by Freepik from www.flaticon.com.

et al., 2017) finer temporal and spatial resolution (discretisation) of data is possible, resulting in huge and complex data sets (Pajarola, 2012). The data is becoming more difficult to handle for 2D, but especially for MR post-processing, leading to a drop in visualisation performance. Whereas in the MR context, ensuring the visualisation performance leads to the reduction of so-called cybersickness. Poor visualisation performance translates into low frame rates and asynchronous behavior of the virtual scene and the users' input. If the physical movements of the user no longer correlate to the virtual movement, VR sickness or cybersickness occurs (Rebenitsch & Owen, 2016). After pre-processing, the data is transferred to the Visualisation Engine via an Interchange File Format (IFF) and imported to the virtual scene. With several different modules for the visualisation engine various use cases are covered. Virtual training purposes for example require an additional module, that allows to (manually or automatically) set up a sequence of assembly or maintenance steps. Tracking and recording a skilled employee, as mentioned before (see Sect. 1), is dependent on yet another module capable of processing this respective input and converting it into a sequence. The Visualisation Engine takes over the rendering on the various Visualisation Devices via an MR-Bridge. This module is mostly supplied by the manufacturer of the respective Visualisation Device. In exceptional cases, this module can also be obtained elsewhere. An example for such an exceptional case is the use of a Cave Automatic Virtual Environment (CAVE) as Visualisation Device, since they are not very widespread and mostly unique. Due to the flexibility of the Visualisation Engine, different MR Visualisation Devices can be operated. Common HMD for VR (e.g. Oculus Quest/Rift, Windows Mixed Reality headsets) and AR (e.g. Microsoft HoloLens1/2, Tablets), such as aforementioned CAVEs are supported by the Visualisation Engine.

A client-server connection allows to have several Visualisation Devices simultaneously participate the same virtual scene and work on the same data set. The Visualisation Engine uses the tracking data of the Visualisation Devices via the MR-Bridge to locate the users in the virtual scene. Other user inputs, such as commands on the Graphical User Interface (GUI), are also processed via this channel. The interaction with the data can be adapted from case to case and has to be specifically implemented for the Visualisation Devices used.

A closed loop, that allows manipulation of the Data Source from the virtual scene, secures a seamless and fully immersive workflow, so that there is no need to leave the virtual scene during an MR session.

3 Demonstrator for the Modular Engineering Pipeline

In accordance with the previously discussed engineering pipeline (see Sect. 2), a modular process was set up as a demonstrator. It allows for immersive and interactive post-processing of both, steady and unsteady simulation data in MR on different

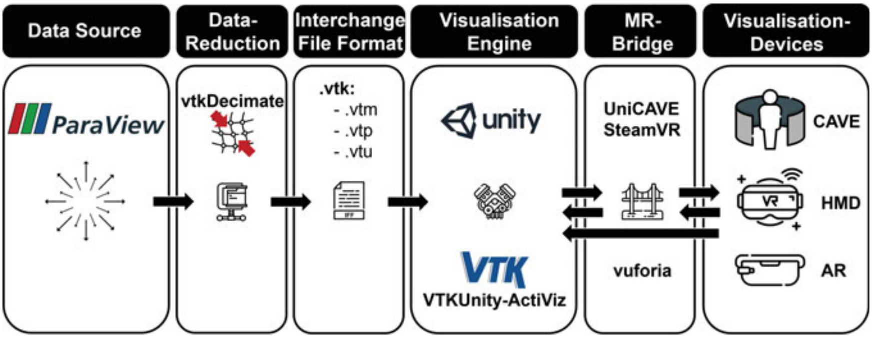

Fig. 2 Software modules within a modular mixed reality visualisation pipeline

Visualisation Devices (see Fig. 2). It can therefore be assigned to the field of Scientific Visualisation (SciVis) or more accurate to the field of Immersive Analytics.[2]

3.1 MEP for Immersive Analytics

The process uses the widespread simulation post-processing tool ParaView as Data Source. ParaView is capable of reading, interpreting and post-processing numerical simulations of various types and IFFs and is based on the Visualization ToolKit (VTK). The VTK features a range of filters for the post-processing of simulations such as other data (e.g. point clouds). To ensure good visualisation performance one of those filters, the "vtkDecimate"-filter, is used for Data-Reduction. An adaptive edge collapse algorithm (Schroeder et al., 1992) is used to reduce the number of triangles in the meshes of the simulation data. Those meshes can be reduced either before export or at runtime in the Visualisation Engine, whereby Data-Reduction in advance of export is recommended to keep input-output-times brief. Reduced simulation data and underlying geometry can be exported from ParaView in efficient, VTK-native IFFs (VTM, VTP, VTU).

Using a game engine for visualisation has turned out to be a cost-effective and flexible solution compared to other visualisation software. Therefore and because of the availability of source code from a similar project (D'Eri, 2017) (at the time of implementing the pipeline) Unity® has been implemented as the Visualisation Engine in this pipeline. In order to process the data from the Data Source a plug-in has been integrated as a module of the engineering pipeline, that renders a VTK-scene

[2] Icons made by Freepik from www.flaticon.com Logo of the Visualization Toolkit (VTK), Steve Jordan (Kitware, Inc.)., Logo of ParaView, Sandia National Laboratory, Los Alamos National Laboratory, Kitware Inc. Unity® Logo, Unity Technologies ApS.

into the Unity® rendering pipeline.[3] This plug-in has been developed by KitWare Inc., whom also maintain the VTK and ParaView, as they recognised increasing demand for an integration of the VTK within Unity® for SciVis. The plug-in executes a VTK-instance parallel to Unity®, that allows to use the vast majority of VTK-readers, -filters and -writers from inside Unity®. The before mentioned closed loop back to the Data Source is not needed anymore, since the "VTKUnity-ActiViz" plug-in is capable of manipulating the data in the same extent as the Data Source. Based on this functionality two workflows were developed:

(i) Visualisation of prepared post-processings.
(ii) Interactive post-processing of raw simulation volume data.

Several software is then used to bridge the gap in between the virtual scene (Visualisation Engine) and MR (Visualisation Devices):

- SteamVR supports a large number of HMDs including the Oculus series and all Windows Mixed Reality HMDs.
- Remote rendering[4] is realised through the Oculus Quest HMD and Virtual Desktop.
- AR devices, such as the Microsoft HoloLens2, are covered by vuforia and the Mixed Reality Tool Kit (MRTK). The latter also supports remote rendering to the Microsoft HoloLens2.
- Rendering into CAVEs is enabled through UniCAVE (Tredinnick et al., 2017).

The unsteady data can then be explored and interacted immersively.

3.2 Discussion of the Demonstrator

The demonstrator for immersive and interactive post-processing of unsteady simulation data described above makes it possible to dive into and better understand relationships in the data. This is realised by an uninterrupted, immersive workflow that leads to a stronger focus on the data.

The main challenge for this use case is the management of the large amounts of data that are generated in the context of numerical simulations and increasing computing power. The optimisation of the visualisation data is currently based on arbitrary mesh reduction mechanisms. In order to improve the visual quality of the reduced meshes and thus enable further reduction, the reduction of the data should be parameter-oriented. Thus, a further step is to develop and implement a reduction mechanism based on a Machine Learning (ML) or Artificial Intelligence (AI) approach.

However, the immersive and interactive post-processing of simulation data in MR is a promising approach that, with some effort and optimisation, could significantly increase the information yield when data mining.

[3] KitWare, 'Rendering VTK into Unity', https://blog.kitware.com/rendering-vtk-into-unity/, 02/23/2022.

[4] Wirelessly rendering the virtual scene from the workstation onto the HMD.

4 Application Examples Within the Modular Engineering Pipeline

The following section briefly presents more examples for the MEP to demonstrate its flexibility in terms of use cases and applications. The pipeline combines aspects of Engineering and Immersive Analytics, Production and Assembly such as Virtual Collaboration. Thus creating an uncompromised and fully immersive workflow.

4.1 Production Planning and Control (PPC)

The engineering pipeline is used for aspects of PPC, such as layout planning, visualisation of layout changes or process simulation with an respective backend. An example application has been implemented that allows for visualisation and interaction of a periodically updated production layout. Within this application it is possible to switch between different time stamps of the production digital shadow and move through it at original scale. It is intended to extend this application to interact with DTs as well, which will then allow manipulation and correction of processes directly from the engineering pipeline.

4.2 Immersive Training and Process Optimisation

Coming from the PPC example, the application of manual assembly in production cannot be neglected. With the addition of the externally provided module “Innoactive” to the engineering pipeline, manual assembly processes can be digitised or developed and afterwards be used for process optimisation or training purposes. A process was set up that automatically translates assembly or maintenance instructions into virtual assembly sequences via Natural Language Processing (NLP). The process allows for execution of trainings and assembly simulations for (new) parts on the Digital Mock-Up (DMU) instead of the physical product, thus saving a great amount of time, space and effort.

4.3 Virtual Collaboration

Motivated by the pandemic and the resulting decentralised way of working, the engineering pipeline also includes a virtual collaboration module. Hereby it should not matter which Visualisation Devices are used, possible are for example: CAVEs, AR- or VR-HMDs or tablets. Since development data contains very sensitive information, it is important to ensure a secure communication channel. The data must be distributed to all Visualisation Devices ensuring that all participants in the collaborative session have access to identical information. To ensure seamless communication, all model changes must be synchronised for all users.

The virtual collaboration module can be used with all other modulers and is currently in a demonstrator state.

5 Conclusion

Broad application possibilities for the modular engineering pipeline arise across many use cases for SMEs from engineering via production to assembly. The pipeline offers several advantages opposed to other solutions, since it is based on a game engine as visualisation software. Most importantly the very flexible working method, due to the open architecture of the underlying framework, opens many possibilities. The large community and professional support, which is not mandatory, help with urgent questions and solutions. The community even helps with free, high quality tutorials and template projects, that make the game engines easy to use even for users with little programming experience. Common CAE IFFs (e.g. OBJ, FBX, ...) are supported by readers or importers. If an IFF is not natively supported, there are plug-ins or so called assets for this purpose in most cases (e.g. JT, VTK). Another benefit is that common MR visualisation devices are natively supported. Even rendering into CAVEs and multi display setups is possible with a respective asset for Unity® and by native support in Unreal Engine. Since the Unreal Engine and Unity® share many features visualisation concepts and ideas can be translated in between the game engines with moderate effort. Last but not least the reasonable pricing is a great benefit for using game engines.

These benefits and the resulting opportunities of the pipeline were reinforced with several practical examples beforehand (see Sect. 4). There are several ways of implementing such a pipeline for a custom task in an SME. Hiring a game studio or software developer is a possibility, but as employees know the processes and tasks best it is recommendable to have them participate in the development. If an employee is at hand who enjoys programming and trying things out, the aforementioned advantages make it possible to create your own custom application with a modest amount of time and effort. If such an employee has limited time resources, it is also an option to contact a university or research institution to initiate a joint research and development project in which your needs and wishes can be addressed in detail.

All in all the Modular Engineering Pipeline can be described as a digitisation tool that is almost infinitely flexible in terms of use cases.

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Predictive Analytics Applications for Small and Medium-Sized Enterprises (SMEs)—A Mini Survey and Real-World Use Cases

Simon Bøgh, Daniel S. Hain, Emil Blixt Hansen, Simon Buus Jensen, Torben Tvedebrink, and Roman Jurowetzki

Abstract Predictive analytics is becoming more mature and is gaining traction in smart manufacturing around the world. Over the past decade, predictive analytics has hence reached a plateau of productivity while techniques and tools became more robust and accessible. Small- and medium-sized enterprises have to seize these new opportunities in order to optimize and embed analytics in high-value business scenarios and improve their competitiveness. However, getting started with predictive modeling can seem like an insurmountable feat for SMEs, why inspiration and pointers to real-world applications can be valuable. In this paper, we first introduce current trends in predictive analytics followed by a mini survey showcasing interesting real-world use cases in SMEs. Finally, we present common algorithms and models, followed by two recent real-world applications in Danish SMEs.

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Keywords Predictive analytics · Predictive modelling · Small- and medium-sized enterprises · Applications · Use cases

1 Introduction

Data analytics and business intelligence are two areas of major interest to manufacturing companies around the world. In the era of Industry 4.0 and Smart Production there are commonly four data analytics levels known from Gartner's *analytics ascendancy model*:

- Descriptive analytics—what happened?
- Diagnostic analytics—why did it happen?
- Predictive analytics—what will happen?
- Prescriptive analytics—what should I do?

The definitions and levels of data analytics continue to evolve as new methods, tools and more compute power become available. In the future, we will see techniques going beyond prescriptive analytics—*Cognitive Analytics*—leaving the decision-making and actions to artificial intelligence (AI) systems that will ultimately enhance or replace human reasoning needs (The Differences Between Descriptive, 2021).

The popularity of predictive analytics has for some years now been quite high, with prescriptive analytics starting to gain traction, see Fig. 1. Gartner's *Hype Cycle for Data Science and Machine Learning 2021* shows predictive analytics reaching the plateau of productivity within the next 0–2 years (Choudhary, 2021). Gartner's *Hype Cycle for Analytics and Business Intelligence 2021* shows prescriptive analytics reaching the trough of disillusionment, and will still take 2–5 years before reaching the plateau of productivity (Kronz & Krensky, 2021).

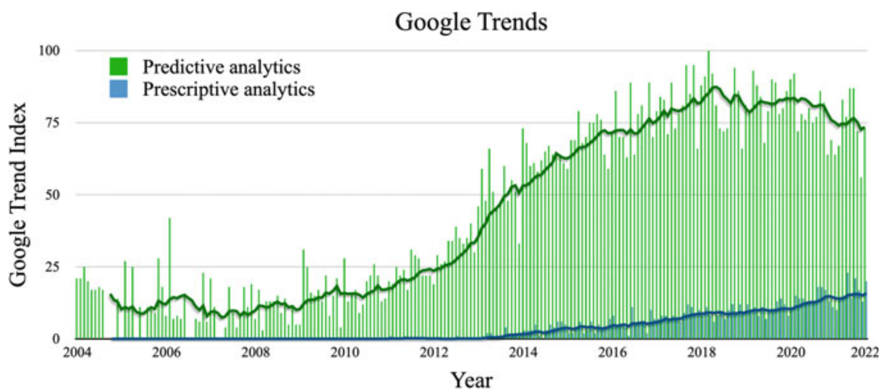

Fig. 1 The Google trend index for predictive analytics and prescriptive analytics in the period 2004–2021 (Trend, 2021)

One of the significant trends identified, which SMEs have to keep an eye out for, is the pivot from traditional AI that relies on big data to a category of analytics that uses smaller and more varied dataset (Sallam et al., 2021). It fits well in the agile nature of SMEs, which may be more dynamic, acting fast, and having less access to big data and infrastructure. Overall, these trends indicate it is an opportune time for SMEs to invest in predictive analytics technologies in their manufacturing as the technologies are becoming mature.

In this work, we focus on predictive analytics methodologies and applications targeted towards small and medium-sized enterprises (SMEs). We survey relevant use cases and techniques, and report recent real-world implementations in SMEs. The goal is to highlight the techniques and opportunities for SMEs that lie within the predictive analytics domain. With increasingly easier access to large amounts of data, industrial manufacturing companies are seeing new opportunities to identify trends and predict outcomes in their productions and daily business. Predictions become relevant as they bring valuable insight into the daily operations in the company, whether it is in business decision-making, uncovering hidden patterns and their relationships to visualize and explore data (Babu & Sastry, 2014), forecasting health indicators (Guo et al., 2017, 2018) or predicting remaining useful life (RUL) of machinery (Lei et al., 2016, 2018; Si et al., 2011; Tian, 2012).

Prior work has shown it is increasingly important that SMEs have easy access to AI technologies and learn to make them operational. Hansen and Bøgh (2021) present a comprehensive survey and investigation of how widespread AI and IoT technologies are among manufacturing SMEs. They discuss current limitations and opportunities towards *facilitating* predictive analytics for SMEs, which is anchored in AI and IoT technologies and enablers. It is evident from the survey that SMEs need to be on the forefront of the new industrial revolution to stay competitive, and for starters should focus on scenarios such as machine-wise predictive analytics. Machine-wise predictive analytics implementation is cheaper than going for a full scale integration in a complete manufacturing line. Machine-wise predictive analytics can be achieved by deploying smart IoT devices that could be connected to a single machine or process, hence reducing the cost of adoption (Hansen & Bøgh, 2021). Thus, SMEs should initially pursue such implementations, to keep cost down and ease implementation effort.

The remainder of the paper is organized as follows. In Sect. 2 the methodology used for a systematic review is outlined, and its result is shown. In Sect. 3 predictive analytics methods such as models and algorithms are presented. Finally, in Sect. 4 we report on real-world use cases from the authors' own empirical studies with partner companies, wrapping up in Sect. 5 with discussion and conclusions drawn on the current state along with future work for the topic.

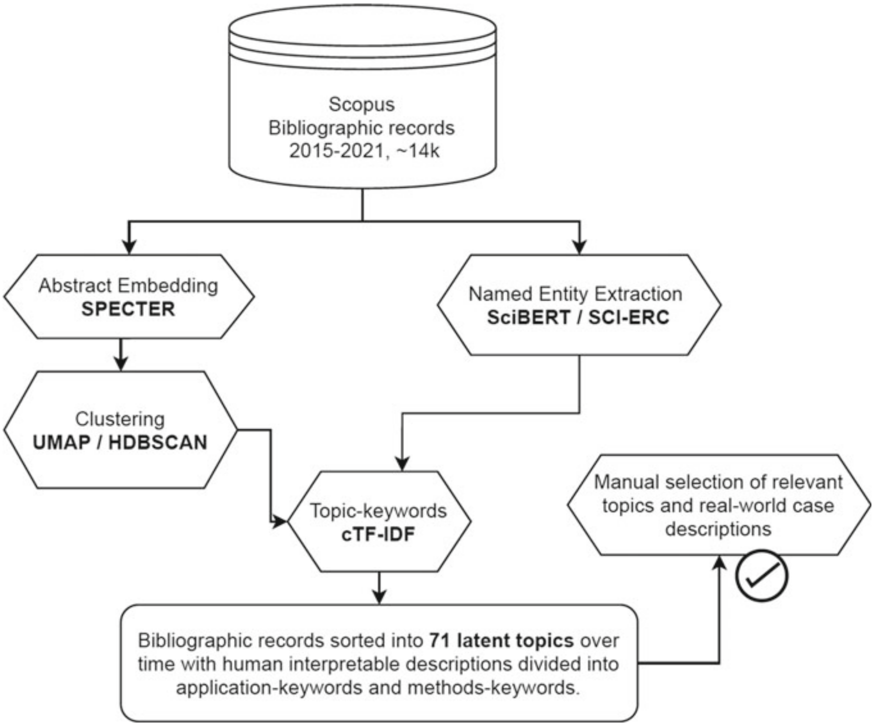

Fig. 2 Literature survey methodology pipeline

2 Mini Literature Survey

In this section we describe our data-driven literature survey approach taken. Given the nature of predictive analytics and its application potentials in various fields, relevant cases can be spread over different industries and technologies. The aim of this survey is to identify relevant areas of application and provide specific examples where predictive analytics techniques are applied in real-world use cases. Given the scope and emergent nature of potential application we opted for this data-driven approach to make sure to not oversee relevant areas og usage. We rely on a combination of techniques from Natural Language Processing (NLP)—a sub-field of AI and related to predictive analytics—to support the identification of relevant papers in the growing field. We designed a pipeline Fig. 2 that combines a novel approach in topic modeling on a large bibliographic dataset with manual selection of use cases within relevant themes.

We collected a bibliographic dataset from Scopus using a broad search-string with the aim to include different types of predictive analytics techniques applied to various real-world industry settings in SMEs. Here we used a (long) search string that recombines an array of synonyms and key-phrases (e.g. SME, predictive analytics, Machine Learning, case study, real-world application) to capture real-world applications of machine learning and AI in SMEs.

Search results were limited to English publications and the subject areas of engineering, chemical engineering, environmental science, energy and material science. We extracted the permitted maximum of 2000 records per year sorted by decreasing *relevance* resulting in 13.923 complete records including their abstracts. This approach introduces some bias due to under-representation of latter years, given that the overall number of publications returned by the search was constantly over 2000 per year and growing throughout the selected period.

An approach building on BERTopic (Grootendorst, 2020) topic modeling was used to identify latent themes in the collected research literature. First, we embed the extracted abstracts using SPECTER (Cohan et al., 2020), a state of the art transformer model for document-level embedding model for scientific text. We then use a combination of UMAP (Becht et al., 2019) and HDBSCAN (McInnes et al., 2017) to cluster documents. Discounting for unclustered records and those put into a "catch-all-cluster" we end up with 10824 documents distributed across 71 clusters, with an average size of 152 and a maximum of 827. The minimum size has been set to be 50 as a hyper parameter during clustering.

To create insightful cluster-descriptors we use keywords generated trough Named Entity Extraction (NER). Here we utilize a SCIBERT transformer model retrained to perform NER using the SCIERC dataset (Luan et al., 2018). The algorithm identifies and extracts "scientific keywords" sorted into the categories *task, method* and *other scientific terminology* from the abstracts. This is a development from simple statistical methods for keyword extraction such as word/n-gram frequencies or algorithms like RAKE (Rose et al., 2010). Finally we weight these keywords by importance for the respective cluster with simple TF-IDF. Figure 3 depicts how extracted NER-keywords of two types are used to describe an identified topic.

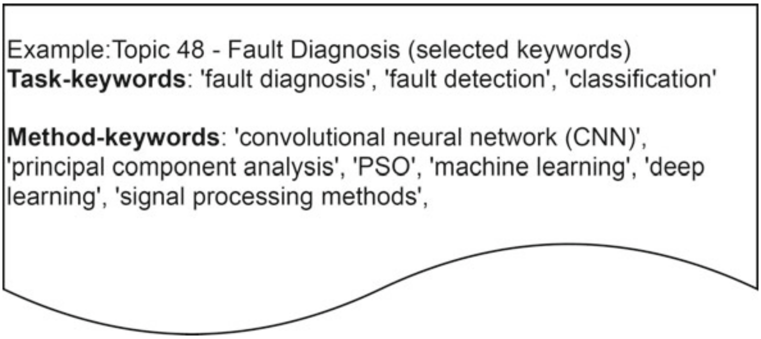

Fig. 3 Example of keywords describing an identified topic

2.1 Survey Results

Through this process and following our focus and broader definition on *predictive analytics in manufacturing SMEs* we were able to identify a number of topics with papers showcasing various industrial applications. In Table 1 select applications, their goals and algorithms applied are shown. Through the literature survey and subsequent manual selection process a trend emerged for general applications and goals. These are briefly explained in the following followed by common data and algorithms found.

Applications and goals Applications were commonly categorized as *predictive maintenance* (tool failure, reduce downtime, demand for maintenance, anomaly detection), *process and manufacturing execution optimization* (additive manufacturing, reduce energy consumption, process planning, manufacturing planning, lean manufacturing), *improve quality* (product and process quality), and *demand forecasting* (sales).

Data and algorithms A wide range of algorithms are utilized throughout the different applications. In recent years deep learning models are dominating predictive modeling research. Many applications entail time series data hence long short-term memory networks (LSTMs) and deep auto-encoders are often used. Time series data may also be processed with Convolutional Neural Networks (CNNs) by first preprocessing the time series data into image data. Combination of the different models (ensembles) has also proved very efficient in applications with multivariate data. In simpler applications with less data, algorithms such as random forest, XGBoost and gradient boosting, or even simple multilayer perceptrons (MLP) perform well.

3 Predictive Analytics Methodologies

In the following we detail, as an extension to the survey in the previous section, different types of common predictive analytics approaches, their models, and algorithms. Predictive modeling is a type of supervised machine learning that uses historical data to predict outcomes of interest, either on existing data where they are not known yet, or on future data. The data is usually collected from real-world events. It follows the logic that a specific algorithm is used to create a function that maps data to an observed outcome of interest. The goal is usually to use this function to predict cases where the outcome is not known yet.

3.1 Models and Algorithms

Over the last decade, a vast amount of machine learning algorithms have been developed to solve a large host of different prediction problems, depending on the charac-

Table 1 Overview of select predictive analytics applications in manufacturing

	Application	Data/Parameters/ Features	Goal	AI method
Munirathinam and Ramadoss (2016)	Wafer fabrication process	591 attributes (590 sensors, 1x pass/fail) (McCann & Johnston, 2008)	Predict equipment faults during fabrication process, Maintain high process yields	Decision tree, Naïve Bayes, Logistic regression, k-nearest neighbor
Feng and Wang (2003)	Finish turning	Work-piece hardness (material), feed, cutter nose radius, spindle speed and depth of cut	Surface roughness prediction in finish turning	Nonlinear regression analysis, Neural Networks
Morariu et al. (2020)	Robot pick and place for assembly	Time series energy data measured from robot	Anomaly detection in manufacturing energy consumption. Re-assign resources (for batch cost optimization)	LSTM
Steiner et al. (2016)	Wood-composite manufacturing process	237 predictor variables (fiber moisture, line speed, fiber temperature, press pressure etc.), 2 response variables	Real-time predictive models for strength properties of manufactured particleboard	Maximum-likelihood, Markov Chain Monte Carlo (MCMC), Partial least squares regression (PLSR)
Cica et al. (2020)	Turning operations of carbon steel	Machining parameters of cutting speed, depth of cut and feed rate	Predict machining force, cutting power and cutting pressure in the turning of AISI 1045	Polynomial regression (PR), Support vector regression (SVR), Gaussian process regression (GPR)
Zhang et al. (2019b)	TFT-LCD production	Process data (public dataset, 8029 features)	Forecast product quality	R-SVM (Random SVM)
Ghosh (2018)	Predictive maintenance for production line	Data from IoT sensors in real-time	Detect signals for potential failures. Prevent production stops	Random Forest, XGBoost, Gradient Boosting, AdaBoost, Multilayer Perceptron (MLP) Regressor, Support Vector Regression (SVR)
Hollingsworth et al. (2018)	Energy consumption	Energy consumption data from roughly 30 power meters providing power to business and residential areas (kWh, kVARh, V2h)	Forecast energy demand and anomaly detection	ARIMA, LSTM
Essien and Giannett (2020)	Metal packaging	525,600 observations of minute-wise machine speed (strokes/min)	Machine speed prediction to dynamically adjust production processes, optimize throughput, minimize energy consumption	Convolutional LSTM encoder-decoder (ConvLSTM auto-encoder)
Zhang et al. (2020)	Human-robot collaborative assembly	Raw observation of human poses	Robot motion trajectory prediction for safe HRC	RNN

teristics of the input data (e.g. tabular, text, sequences, images), and the type outcome that has to be predicted (e.g. numerical, categorical).

Broadly, we distinguish between regression problems with the aim of predicting a numerical outcome (e.g. production, output, failure rate, sales numbers) and classification problems with the aim of predicting a categorical outcome (e.g. machine breaks down or not, customer buys product or not).

Linear models: In *linear regression* models, the outcome is predicted as a simple linear combination of the input features multiplied by a coefficient. This simple functional form eases the interpretation and explanation of model results, yet limits its ability to predict outcomes created by more complex processes. Since linear models are among the simplest possibilities to model multivariate relationships between features and outcomes, they tend to have higher bias (in case the true underlying relationship is not linear) and low variance.

While outcome predicted is supposed to be a continuous numerical value, adaptations for different types of outcomes (e.g. *logistic regression* for binary categorical outcomes) exist. Furthermore, model variants geared towards predictions on high-dimensional and noisy data are available. Penalized models shrink noisy feature coefficients, which typically increases bias and reduces variance. In popular applications, this penalty can be linear (LASSO, Tibshirani, 1996), exponential (RIDGE, Hoerl & Kennard, 1970), or a combination of both (Elastic Net, Zou & Hastie, 2005). All penalized models can be used for regularization, while in some (e.g. LASSO), coefficients can be set to zero, which results in feature selection.

Tree-based models: The rich class of *classification and regression trees* is characterized by a flexible functional form able to fit complex relationships between features and outcomes, yet is can be illustrated in an accessible way. They appear to show their benefits over traditional regression approaches mostly in settings where we have a large sample size (Perlich et al., 2003), and where the underlying relationships are mostly non-linear and dominated by interactions between the features (Friedman & Popescu, 2008). The general idea behind this approach is to step-wise identify feature explaining the highest variance of outcomes. This can be done in various ways, but in principle you aim to at every step use some criterion to identify the most influential feature x of the model (e.g., the lowest p value), and then another criterion (e.g., lowest χ^2 value) to determine a cutoff value of this feature. Then, the sample is split according to this cutoff. This is repeated for every subsample, leading to a tree-like decision structure, which eventually ends at a terminal node (a *leaf*) associated with a certain class or value. The resulting tree-like decision structure can be used to illustrate and replicate the model's decision structure in an accessible manner.

To increase the performance and robustness of tree-based models, several variations and extensions based on ensemble techniques have been developed, where predictions are not based one one but several tree models jointly. A popular extension is the *random forest* (Ho, 1995), which aims at reducing overfitting by introducing randomness via bagging and bootstrapping. The idea here is to create an ensemble of classification trees, which all are trained on separated subsamples of the data, and restricted to random subsets of features they can access for prediction. The final model prediction is formed by a "majority vote" of all trees.

As an alternative, the use of gradient boosting can also improve the performance and robustness of tree-based models. Here, an ensemble of shallow trees is trained iterative, where each iteration uses the error residuals of the previous model to fit the next model. The final prediction is a weighted sum of all of the tree predictions. The most popular boosted tree algorithm is the highly efficient implementation of *eXtreme Gradient Boosting* (XGBoost, Chen & Guestrin, 2016).

(Deep) Artificial Neural Network-based models: A promising class of algorithms that throughout recent years has found applications across most fields and industries are neural networks. While early ideas about artificial neural networks (ANNs) were already developed in the 1950s and 60s (McCulloch & Pitts, 1943; Rosenblatt, 1958), it took several decades for this type of biology-inspired models to see a renaissance in the recent few years. This can be attributed to three reasons: (i) New training techniques, (ii) the availability of large training datasets, and (iii) hardware development, here particularly the ability to train neural networks highly distributed on graphical processing units (GPUs) (LeCun et al., 2015).

Neural Networks are designed to approximate any nonlinear function and thereby theoretically produce near-optimal predictions to every well-defined problem. The more data points, the more accurate the approximation, and thus, the more accurately the resulting training network can predict the results. Neural network architectures are highly flexible too, and depending on how many layers and neurons are used, what happens within the layers, and how they are connected, they can be adjusted to various data types and prediction problems.

For prediction problems where a high spatial interaction between the features can be expected (e.g. visual data, where the meaning of single pixels is always dependent on its environment), convolutional neural networks (CNNs) are often applied. Here, hidden layers are included, which perform convolutions, meaning each neuron only processes data only for its receptive field. CNNs are mainly used in computer vision for tasks such as image classification (e.g., Krizhevsky et al., 2012), but have also applications in financial time series analysis and natural language processing (NLP).

If the features and/or outcomes are sequential of nature, recurrent neural networks (RNN) structures are often used. Here, recurrent layers are added, where the neurons maintain a memory of former states, and thereby include past information in current predictions. As an extension, long short-term memory networks (LSTMs) (Hochreiter & Schmidhuber, 1997), include further mechanisms to explicitly remember or forget certain former states. They are commonly applied for predictions based on sequential data, such as time series (e.g. financial forecasting) or natural language.

In recent years, embedding techniques gained popularity for representation, analysis, and prediction based on sequential data. First applied in the field of NLP, word embedding models (Mikolov et al., 2013) create high-dimensional vector representations of words (so called embeddings) based on the context a certain word tends to appear in, thereby retaining information about its meaning. Similar approaches have been applied to embed whole documents (e.g., Le & Mikolov, 2014), and nonlanguage data such as time series and gene sequences. Most recently, transformer models exploiting attention mechanisms (Vaswani et al., 2017) trained on massive amounts of data (e.g. BERT, Devlin et al., 2018) achieve current stat-of-the-art performance in a variety of text classification but also other tasks related to sequential and more recently computer vision problems (Dosovitskiy et al., 2020).

Autoencoder architectures (Hinton & Salakhutdinov, 2006) that force the network to learn to reproduce inputs by encoding them into lower dimensionality and then decoding back can be used to spot anomalies while training the model only on available "normal observations".

Other traditional model types: A variety of other approaches to model the relationship between features and outcomes exist. Besides the ones presented here in more detail, other popular strategies are instance-based approaches that predict outcomes based on other observed instances (e.g., k-nearest neighbor as well as support vector machine algorithms, Altman, 1992), and Bayesian approaches (e.g., Bayesian networks, Pearl, 1985).

4 Real-World Industrial Case Stories

In the following section we present two real-world use cases from Danish industry. The use cases are joint work between Danish universities and industrial partners.

Case 1: Anomaly detection in fuel cell production

Application: In this case, the enterprise seeks to optimize a time consuming quality control process of fuel cell electrode plates. In short, fuel cell electrode plates are used as conductors in methanol fuel cells (see example in Fig. 4). The quality control has previously happened through a very time consuming manual inspection, where an X-ray image is captured of each fuel cell electrode and the X-ray image is inspected by a domain expert. The quality control process is optimized and automated by training and deploying a deep neural network (DNN) to perform the quality control of the fuel cell electrodes, thereby freeing up the time spent by the domain experts.

Data and algorithm: In order to train a DNN which can perform anomaly detection, the enterprise collected approximately 800 X-ray images of fuel cell electrodes and labeled them as being normal or abnormal. The enterprise utilized CVAT[1] for annotating the X-ray images and it required ∼30 man-hours of work for a domain-expert to annotate the entire dataset. Approximately 20% of the samples were labeled as abnormal and 80% were labeled as normal, meaning the dataset was imbalanced. A dataset of size 800 can be considered to be a very small dataset when utilizing a DNN, which typically requires thousands of data samples. As an attempt to overcome this problem, a CNN pre-trained on ImageNet (Russakovsky et al., 2014), is utilized as the backbone in the DNN. Additional data augmentation is applied to further increase the size of the dataset as explained later.

[1] Computer Vision Annotation Tool (CVAT): https://cvat.org/.

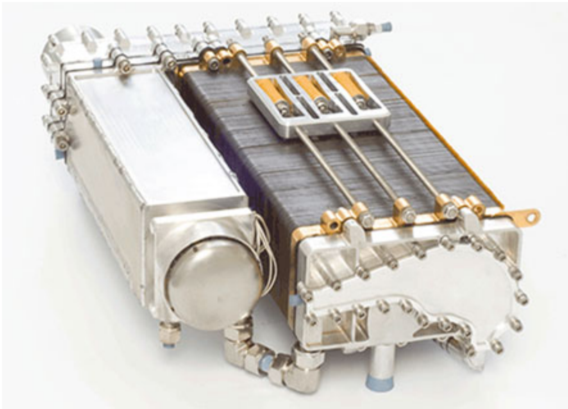

Fig. 4 A fuel cell system with a stack of fuel cell electrodes

The DNN consists of a pre-trained ResNet (He et al., 2015) CNN, implemented in Python's deep learning framework, PyTorch (Paszke et al., 2019). The CNN is extended with two fully connected layers of size 512 and 256 and finally with a softmax layer of size 2, to get an output for each class, normal and abnormal. Essentially, turning the anomaly detection problem into a binary classification problem. The DNN model is trained on a Nvidia GeForce GTX 1080 GPU for 50 epochs, while using data augmentation techniques during training e.g., random horizontal/vertical flips, thereby synthetically quadrupling the ∼800 image samples into ∼3200 samples.

Results: During evaluation of the anomaly detector, a balanced accuracy of 85.18% is achieved. The system is evaluated using the balanced accuracy metric as it weights correct and incorrect classifications of normal and abnormal samples equally important, despite the dataset's class imbalance of ∼80% normal/∼20% abnormal samples. The anomaly detector is deployed as a REST API microservice on a local server, equipped with a GPU, at the enterprise.

Challenges and barriers: A challenge which appear when annotating samples for a binary or multi-class classification problem, is the fact that an annotator has to make a decision on which class a sample belong to. In this case, whether a fuel cell electrode is normal or abnormal. We found that making this decision, for some fuel cell electrodes, is not always a trivial task. While one expert might label the sample as normal another expert might label the same sample as abnormal. There are various ways to overcome this problem, such as e.g., distributing the annotation task to a number of people and let the annotation voted for by most people represent the ground truth annotation of the sample.

Another challenge is the availability of large-scale annotated datasets. In this case, the dataset consisted of only 800 X-ray images which, for the purpose of training a deep learning model, is a very small dataset. This challenge can sometimes be overcome be using e.g., transfer learning, where a neural network model has been pre-trained on a related open-source large-scale dataset.

Future research: In order to improve the accuracy and robustness of the anomaly detector model, one thing to consider for future research could be to use more extensive data augmentation. Data augmentation is the technique of augmenting samples in ones dataset by applying various transformation on to the samples. Thereby creating slightly modified copies of already existing samples and synthetically increasing the size and variance of the original data set. Besides from randomly flipping the images horizontally and vertically, it could also be beneficial to randomly modify the contrast and brightness of the image and apply random rotations of a few degrees.

Case 2: Data-driven R&D

Application: In this case a manufacturer wants to improve and optimize laundry detergent recipes. The aim is to reduce the time-to-product by using performance data on existing product recipes, in order to guide the product developers in the design phase. Laundry detergents consists of several types of ingredients, where synergies and anti-synergies between the ingredients complicates the design of new products. Hence, the domain insight and know-how represents a substantial value in the development of new products. The business model of the manufacturer also includes a particular interest in being able to rank the recipes in relation to each other. That is, even inaccurate prediction of the absolute performance of a recipe is a valuable outcome as long as the relative ranking of the recipes' performance holds.

In order to compare the performance of the detergents, standard stain patches are used to measure the detergent's efficiency in removing fourteen types of stains found in typical households, e.g. ketchup, grass, coffee, chocolate and red wine. The measurements was made using a Mach5 Colorimeter-Spectrometer, which measures the reflective index for each of the fourteen stain patches. The reflective indexes ranges (theoretically) between 0 and 100, where the higher the value the more successful the detergent is in removing the stain. For practical purposes the values typically ranges in the interval from 50 to 80, where fruit juice typically is in the lower range (i.e. harder to remove) and ketchup is in the higher end (i.e. easier to remove). For comparing recipe performance the average reflective indexes across the fourteen stain types are used. Due to the difference in standard deviations of the reflective index across the stain types, it may, however, be more optimal to model each of the stain types separately prior to forming the average index.

Data and algorithm: The data consisted of performance measurements (reflective indexes on each stain type), the composition of the recipe and other variables such as hardness of the water, washing temperature and dosage. Furthermore, each active ingredient (excluding colorants and perfumes) belongs to a larger group of ingredients (e.g. anionic, non-ionic and enzymes), where it is expected that the ingredients will interact within and between these groups, which will affect the overall performance of the recipe. Typically the enzymes have a specific property enabling them to remove targeted stain types, e.g. hamburger grease. In addition, unit prices on each ingredient was provided in order to focus on prize optimization rather than increased washing performance. There was close to 400 unique recipes (identified by their composition of active ingredients), where each recipe was tested at least once. In total there were around 900 performance tests, since some recipes was tested multiple times (e.g. as technical replicate, or with a difference in dosage or temperature), while others was just tested once.

After the removal of non-active ingredients (colorants and perfumes), some 120 active ingredients was used in different quantities in the various recipes. Few ingredients were only used once (i.e. singleton ingredients used in a single recipe at a single quantity), whereas as others were used in close to all recipes (e.g. lime-free water). These imbalances in ingredient usage (specifically the presence of singleton ingredients) and lack of consistent recipe repetitions in the performance data showed to be a particular challenge in the modeling selection phase and parameter estimation. In particular, the singleton ingredients prohibited the use of standard k-fold cross-validation procedures, since $k-1$ of the folds did not include the singleton ingredient. Hence, the direct effect of these rare (i.e. singletons, doubletons and tripletons) was hard to assess, and their interaction effect with other ingredients was statistically impossible to quantify. This is an example of the difference between an human-centered incremental product improvement process and a data-driven model-based approach to the same task. Assessment of the uncertainties are instrumental in the modeling phase, which calls for more systematic collection of data and conduction of experiments or tests.

One of the aims of the analysis was to make suggestions for recipes with improved performance or comparable performance at a cheaper price. Furthermore, priority was given to interpretable and explainable methods and models as this would ease the fusion of data-driven recipe generation and human-centered processes. In order to model the recipes' performance the following methods was considered and implemented: Reluctant Interaction Modeling (RIM) using LASSO (Yu et al., 2021), Support Vector Regression (SVR) (Vapnik, 1995), Regression-Enhanced Random Forest (RERF) (Zhang et al., 2019a) and Neural Network Regression (NNR).

Results: The technical replicates (recipes tested under the same settings) showed that the intrinsic variability of the data was around ± 2 points on the average reflective index. Hence, this indicated a lower bound on the expected accuracy of the predictions. Furthermore, small perturbations on the recipes (i.e. small adjustments to the ingredient composition) resulted in rather larger changes in the recipe performance. Hence, this indicated a very non-smooth surface of the response variable as a function of the explanatory variables. Thus, not surprisingly did this result in SVR performing better than the linear driven RIM and RERF but also NNR. In particular, SVR showed the best concordance in the observed and predicted ranking of the recipes' performance scores.

Challenges and barriers: In the transition from serving as a historical record of product development, the data entered the iterative data model process, where registration errors, inconsistencies and erroneous labeling suddenly had a different impact. This resulted in an increased attention to data discipline and quality, which a new focus area of the manufacturer and calls for changes to the way data is stored, collected and curated.

Future research: In order to improve on the models accuracy, it may be necessary to scale the amount of data substantially. The results of a simple k-nearest regression indicated a very non-smooth relationship between the recipe's score and composition, where small changes to the compositions resulted in several points difference in the score. One solution could be to perform a more systematic testing in some recipes' neighborhoods, to assess if this non-smooth behavior was due to a volatile surface or was caused by measurement and logging errors. This is a single example on the change in the mindset needed in order to change the product development from knowledge-based to data-driven. However, a closer collaboration between modeling specialists and the domain experts is also essential for a smooth transition to a more data-oriented business model. By including the knowledge of the domain experts in specification of the model structure (e.g. prior knowledge of synergies and anti-synergies between specific ingredients or groups of ingredients), less data is needed to learn the structure from data. This latter concept is an other argument for choosing interpretable models.

5 Conclusion

It is evident that as predictive analytics is progressively becoming more mature, it starts to gain traction in smart manufacturing around the world. This leaves new opportunities for small- and medium-sized enterprises to explore these technologies and implement predictive modeling in order to optimize and embed analytics in high-value business scenarios.

In this work we conduct a mini survey to showcase a diverse overview of predictive analytics example applications in a wide range of manufacturing industries, their goals, data, and methods applied. From here we present relevant and common algorithms and models utilized in predictive modeling, which provides a starting point for SMEs to investigate techniques for their own use cases. Finally, we showcase two recent real-world use cases in Danish SMEs, where predictive analytics has been successfully incorporated. Overall, SMEs need to prepare for this exciting future that for sure will affect all industries. A place to start is with the machine learning basics, gather the right talents, frame a problem (business and technical), gather data, explore the data, explore different models, and finally launch, monitor and maintain the system.

For companies planning to engage with predictive modeling applications, literature as well as the presented cases illustrate the benefits of initial internal capacity building in proof-of-concept projects. Such projects optimally target "low hanging fruits", meaning they mainly use existing data and infrastructure, are technically not too demanding, yet have the potential to create tangible added value to the company. Here, the application of predictive models to internal processes and services appears often to be a more natural starting point than the creation of AI-embedded products. The main reason is that internal processes such as production, maintenance, logistics, or sales are well understood within the company, under its direct control, and typically have already accumulated a data foundation. For instance, almost every company maintains an ERP and/or CRM system, which can provide customer and sales data. This naturally suggests the creation of a recommender system. Such a system uses product, customer, and sales data to ease the product selection process for customers or product recommendations by sales personnel.

In the end, SMEs need to develop an AI strategy starting with (1) how to leverage AI to create an advantage in the given industry, (2) design a strategy that aligns with the "virtuous cycle of AI" (collect data, build AI model, create better product, collect more data, improve model, and so on), (3) create a strategy for data collection and sharing inside and outside the organization, and 4) build a team to support AI activities and broad training in the organization.

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SMEs and the Sustainability Challenge: Digital Shadow Enabling Smart Decision Making

Søren Løkke and Ole Madsen

Abstract In this chapter, we discuss the challenges SMEs are facing when working with sustainability. Two main issues are addressed. Firstly, making proper sustainability decisions requires expertise rarely possessed by SMEs. As presented in the chapter, there are many assessment tools available, but these are difficult to use for non-experts and often based on inconsequent value choices. Therefore, it is recommended that companies instead partly focus on knowing the physical flows of material and energy related to company activities, and partly seek understanding of how these interact with the surrounding systems. Secondly, sustainability is often assessed in the design phase only, often based on incomplete and overall global sustainability evaluations. This is partly because companies often lack information on important indirect impact elements, as well as specific details about the actual production which mostly is based on manual data-collection. To overcome these two challenges, the chapter presents a vision for a double digital shadow which integrates the production and the sustainability dimensions into one. One element of the digital shadow focuses on the production, applying concepts from Industry 4.0/Smart production, to obtain data about the actual state of the production. A second element focuses on sustainability aspects of the production using novel semi-automated, but often highly aggregated, environmental sustainability data models (e.g., EXIOBASE). In the chapter, the background and state-of-art is expounded, the double digital shadow presented, and important work on, and practical steps to, the integration of production and sustainability is outlined.

Keywords LCA · Circular economy · Data driven production · Digital twin · Smart production · i5.0

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1 Introduction

It is widely acknowledged that it is challenging for SMEs to work with sustainability, and that the current radical change towards a circular economy increases this challenge. In this regard, we divide SMEs into two groups facing two different challenges. Firstly, enterprises that aims for market niches based on ‘green business models’, and secondly ‘normal’ companies that produces goods to the market and who increasingly are being met by requirements for documentation of sustainability related KPIs, as well of improvements in sustainability performance (Das et al., 2022). These two groups have the problem in common that the assessment of sustainability requires expertise rarely possessed by SMEs, which clearly reflects that sustainability is not the core business. Vice-versa, sustainability is mostly regarded an opportunity in the first group and an additional task in the second group. The tools applied to assess sustainability are based on a wide variety of methodologies, and the EU Commission has counted close to 500 green claim approaches, where-of about the half are used in the EU. The most serious of these approaches are based on life cycle assessment, but may still be based on different methodological assumptions that eventually lead to greenwashing-like situations, e.g., by claiming improved sustainability performance by utilizing low-carbon-intensive but supply-constrained materials, or by defining biased system boundaries. The chapter discuss this, using experiences from working with Danish and European enterprises, and recommends a uniform approach that can improve the decision support framework for improved industrial sustainability performance seen from a global perspective.

A second challenge is the reconciliation of production and sustainability. Sustainability is often assessed in the design phase (e.g. through a Life Cycle Assessment). However, current sustainability assessment systems and approaches tend to be an ‘add-on’ to the management decision system, and provide only incomplete and overall global sustainability evaluation because they lack important indirect impact elements, especially related to land use, as well as specific details about the actual production and production inputs often mainly based on manual data-collection.

The last part of the chapter presents an overall approach for how to integrate the two dimensions (the production and the sustainability dimension) into one. Here we will apply concepts from Industry 4.0/Smart production, which is characterized by the application of data driven approaches. This opens up for new possibilities to overcome a number of the challenges presented above. As part of the research, we have outlined the structure of a generic digital twin which integrates both dimensions. In the paper, the background for this work and state-of-art is expounded, the generic digital twin presented, and important work on, and practical steps to, the integration of production and sustainability is outlined.

2 The Sustainability Challenge

How companies work with the sustainability challenge has been investigated. Das et al. (2022) examined 68 predominantly European companies to identify how they worked with environmental impacts in relation to circular business models. They found that the most common approach to measure performance of new models was rules of thumb, followed by life cycle assessment (LCA) or LCA-based tools followed by a spread of different approaches ranging from carbon foot printing, carbon calculators and mass flow analysis to various less meaningful approaches (ibid, p. 280). Furthermore, the barriers are reported to be lack of data, uncertainty of ex-ante assessments of product-production, time and money resources etc. These findings imply that the assessments are done with a wide range of different modelling assumptions and henceforth challenges with respect to the level of comparability. On the one hand the methodological differences between LCA and carbon footprints is just a question of reported impact categories (Weidema et al., 2008), and on the other hand different methods, even though commonly being LCAs and referring to the ISO standard, may give quite different answers (Weidema, 2019; Weidema et al., 2020).

It seems that companies, and particular SMEs, often has limited understanding of the use phase of the products they produce (see e.g. Harris et al., 2021; Das et al., 2022), which also is the general observation of the authors. Furthermore, even though industrial symbiosis continues to grow in potential, there continues to be a need for further improving the understanding of how best to assess and address minimization of environmental impacts (Harris et al., 2021).

On top of these challenges, there is a profound need for transparency of the data used in assessment of performance, and this need will increase dramatically when methods applied becomes more detailed and closer to reality. The current state of the art does not accommodate this, but promising approaches are under development (Hansen et al., 2020), and these are consistent with the approach recommended in this chapter.

Below in we have outlined the different core sites where key decisions influencing sustainability performance (see Fig. 1). To the left we have activities that especially in the case of SMEs most often will take place outside the company, i.e. design of fundamental or novel technologies that lays the foundation of the product- and or production technology. The next four sites include from design of product and production, the ongoing operation on the shop-floor to management strategic decision. This is followed by the last 'site', which involves a multitude of stakeholders including the suppliers, distributers supply-chain and downstream users.

At these sites, different questions related to sustainability and environmental performance will arise. Today, the predominantly request for performance evaluations are to be found when developing new/novel technology designs and in relation to user requirements. When developing novel technology with EU funding i.e. in the Horizon programs where there is a strong SME-focus, these questions are default, and more important. When seeking investments, finding employees, selling products, the external stakeholders (costumers and downstream users, future employees, investors)

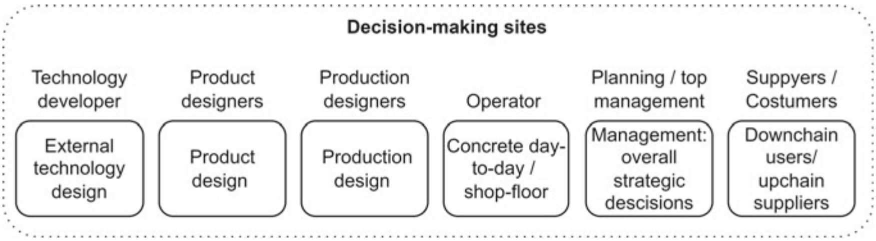

Fig. 1 Instances and sites of decision-making relevant for sustainability-performance related to the production ecosystem (production, supply chains and downstream users). The relationship between production related decision-sites and the lifecycle impacts is described afterwards. This figure is the upper component of the full system model for integrating sustainability into smart production, which we develop later in the chapter (Fig. 4)

are increasingly requiring life cycle performance documentation, often combined with the requirements in the Science Based Targets Initiative (SBTi), commitment to the Carbon Disclosure Project (CDP), use of environmental product declaration schemes (EPD). Often SMEs are not prepared for working in these dimensions, which is why the Danish Industry Association has initiated ambitious programs preparing SME companies to the climate competition they increasingly find themselves in.[1]

The experience is—as Kermit noted it: It is not easy being green! Many companies are uncertain how to begin exploring and documenting environmental performance. Often the capacity of working with sustainability has positive implications on digital competencies as well as the cost level—the cheapest material and the cheapest electricity is the ones you do not use! As an example, the Danish company Danfoss supplying mechanical and electronic solutions to heating, RE-systems and more, are currently—in 2022—running 200 projects improving company environmental performance with an average payback time of 2.8 years[2]!

To make this simpler, let us think of a company producing a simple range of products i.e., pans. The company uses aluminum and electricity as the primary production inputs, and the questions such a company are likely to ask includes the following.

Where do the emissions related to our products come from? Which materials should we chose? Where should it be sourced from? How will my product perform in different end-use contexts? How will my products perform in the end-of-life phase (EoL)? Should we prioritize recycled materials? Should we do what we can to increase recyclability and repairability of the products? Which requirements should

[1] 'Climate ready SME' assisting SME companies creating organizational carbon footprints, and to understand the climate impacts of company decisions: https://www.danskindustri.dk/klimaklarSMV/, with participation from DI, Axcelfuture, Global Compact Network Denmark, Aalborg University and Viegand Maagøe. This project was concluded in 2022 and has been extended with 'Climate Ready production company', running until 2026, and including all 12.500 Danish production industries.

[2] Example presented by the Danfoss-CEO at the closing conference of the 'Climate ready SME' project (https://www.danskindustri.dk/klimaklarSMV/).

we give to our suppliers? And most importantly: where do we best contribute most to the global decrease of harmful emissions and impacts?

Recycled materials are important but will often not significantly improve product sustainability performance: for example, if you use recycled aluminum, you will use a resource that is 'constrained', which means that an increased demand will be matched by increased production where this is not constrained (which happens to be Chinese aluminum production.[3] Still, it is a possibility to save materials from being lost, but this will typically either only be something that will be a transient situation or what economists would term a 'market failure': the normal state with a well-functioning circular economy will not be that materials are 'saved' but rather that they become integrate parts of the economy alongside virgin materials. Alternatively, if the material is overpriced compared to 'virgin' alternatives, then this may reflect that the material in fact is 'saved' from being lost. The recycled materials challenge can also be understood in the context of circular economy: in a fully developed circular economy there is no important difference between recycled and virgin materials, and using recycled materials is just a normal situation where market mechanisms secure an optimal use of the materials (recycled aluminum is typically suitable for casting but not for extrusion). Basically, the impact in this situation is that the company rather than focusing on reducing its impact by utilizing recycled aluminum, it should focus its efforts on reducing the need for aluminum, either by reducing aluminum inputs or by extending lifetime, repairability etc.

This example shows how the intuitive answers to central questions not always are the relevant answer, if the aim is reducing the use of resources and impacting on the environment. Getting this right, needs both the relevant data and the right modelling principles. In the following, we elaborate how these questions can be dealt with.

3 Measuring Sustainability—What Meets the SME?

Sustainability and environment are rarely the core business of a company. We will therefore dwell a bit on how the performance are being measured, and what approaches meets the SME wanting to engage with the transition to sustainable production. Our core message is that the company needs to invest the resources necessary to understand how the production and the products are connected to emissions, not only from the activities onsite, heat and electricity purchased, but also from materials and services purchased, and from downstream use and end of life. This is essentially what are being assessed in a life cycle assessment, where the aim is to assess inputs and outputs from the full lifecycle of the product. As illustrated in Fig. 2, the main phases start with extraction to production, through the use-phase to

[3] The absolute dominance on global aluminum production resides with China both in terms of absolute increase in production capacity and in relative proportion of total production capacity, which mean that increased demand for aluminum is answered by production increase in China (https://international-aluminium.org/statistics/primary-aluminium-production/).

the end-of-life of the products produced, and the implication of the circular economy is in the figure added as black arrows indicating reuse and recycling.

We acknowledge that seen from a company, this is somehow abstract, as the Manufacturing box represents all manufacturing activities in the global economy. A more concrete representation of a production will involve many types of manufacturing including purchase of heat and electricity, materials, semi-manufacture and services. Any production will therefore draw on activities coming from all five activities, including inputs from other manufacturing companies.

The unit of measurement at company level will be either the full company activities i.e., per year, or per specific product or service also in a measurable unit (in LCA-terminology this is called the functional unit or FU and all activities, inputs, co-products, and emissions are related to the FU).

A number of approaches addressing this is available. When looking to the assessment of company specific activities, the Science Based Target initiative (SBTi) initiated by the World Resource Institute together with Climate Disclosure Project (CDP), WWF and the UN Global Compact in 2018, is probably today some of the most influential initiatives. The initiatives target best-practices in emissions, methods and guidance to companies to set science-based targets aiming for the 1.5 °C UN-target. SBTi uses the Greenhouse Gas Protocol (GHG-P) as basis for calculations, but several approaches can be added to the SBTi and the GHG-P.

The most important systems in the EU are the European Product and Organization Environmental Footprint (PEF/OEF), and the International Environmental Product Declaration (EPD), that further require definition of specific product category rules and Product Environmental Footprint Category Rules (PCR and PEFCR respectively) which are guidelines on how to apply life cycle assessment on specific product-groups or activity types. These are rules for consistently producing environmental footprint analysis of specific products within a specific product category. These systems have been established to resolve challenges in the overall ISO framework, but has resulted

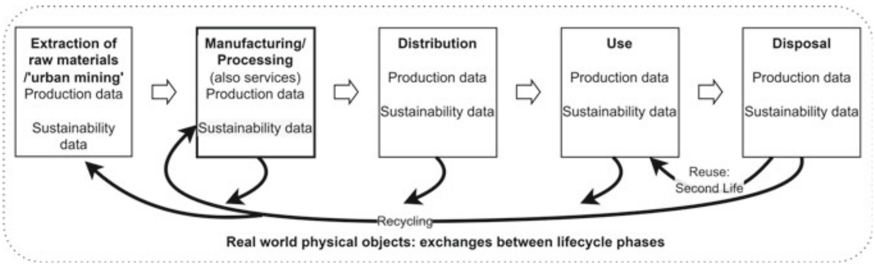

Fig. 2 Main phases which any activity 'activates'. Often, analogues to this figure is depicted as a circle, and the black arrows is identical to the 'closing the loop' arrows in illustrations of the circular economy. Without the black arrows the figure represents the linear economy, and with the increasing strength of the black arrows, the figure represents the circular economy. This figure is the lower component of the full system model for integrating sustainability into smart production, which we develop later in the chapter (Fig. 4)

in specific new challenges, as e.g. the PEF system may not conform with the internationally agreed on principles for LCA (ISO 14040/44), and even partly contradicting these (Bach et al., 2018). Furthermore, the EPD system has resulted in a proliferation of PCRs which are defined in a bottom-up consensus process, which, due to the negotiation processes involving stakeholders with different power and vested interests, has led to inconsistency and incomparability between PCRs (Wilfart et al., 2021). Furthermore, a high number of national and NGO-driven methods, including BPX 30-323 for France, and specific GHG-oriented methods as the before mentioned GHG-protocol and the British PAS 2050 exists, and these standalone guidelines has various degrees of comparability with the previous ones.

A central issue related to most of these approaches, is that they are based on normative modelling, also called attributional modelling, which is less relevant when performing decision support related to changing the supply to the market as consequence of changes in production. Instead, we recommend a consequential approach applied, which especially becomes important when the economy increasingly becomes circular (EC-JRC, 2010, 70; Weidema et al., 2018; Schrijvers et al., 2021; Geyer et al., 2017; Zink et al., 2016). The goal is to support companies with the ability to act in trade-off situations and avoiding suboptimization and seeking solutions that supports *system-wide sustainability* and which *avoids* counterproductive blame-games and *competition for constrained resources*. Examples of the latter (to avoid) are purchase of green electricity where the purchase is not accompanied with explicit additionality, or where the greenness of the production is pursued by using recycled aluminum without securing additional recycling of aluminum.

However, the SME should not get frustrated by the method discussions, because the issues under discussion are not related to the accounting of activities but rather to the methods for how to account for the related emissions (Weidema et al., 2019). This means that the company basically should work with collecting data with a robust strategy, which is collecting relevant and traceable raw data on exchanges and emission (Ghose et al., 2021; Hansen et al., 2020), instead of collecting calculated emission-data, e.g. EPD based carbon footprints. Basically, SME companies need to put efforts into building inventory of data needed for environmental assessment in a method neutral structure, which then can be recalculated into method-specific lifecycle-inventories (LCIs) and according to the relevant standards (International Organization for Standardization [ISO] 2006a, b; 2.-0 LCA consultants 2022).

Important obstacles for SMEs pursuing the sustainability agenda can be summarized to (1) sustainability data is often translated into assessments that depend highly on external experts, (2) Assessments are often detached from everyday practice in the company, as the transformation from physical data to impact assessment, e.g. carbon footprint, is strongly method depended, (3) decision support is often experienced as less relevant at many decision sites in- and outside the company, and does therefore not significantly influence decision making.

In other words, what is needed is that the company take back the data and enable partly improved data management enabling lower cost for carrying out assessments, partly improved accessibility to navigate the sustainability dimension in a production reality that will change with an increasing pace.

In 'old days', when focus was on mass production and mass customization, the time-lag and relatively high costs related to doing a sustainability assessment leading to a sustainability-optimized design which then should be put into production could be acceptable. But two different conditions have changed. Firstly, the urgency of improving environmental performance of products, including their production and use, has increased dramatically with the increasing urgency of the climate change problem (IPCC, 2022), and recognition of the sustainability challenge represented by the UN sustainable development goals (United Nations and The General Assembly 2015; Scheyvens et al., 2016).

Secondly, smart production, Industry 4.0 or the next generation Industry 5.0, are likely to imply that the boundaries between design, production-design and production will become more blurred. IoT will create the basis for this, partly by internally connecting the information flows in production, partly by connecting information from both supply chain, use chain and end of life processing.

This is a *projected* future, which is not yet here, or at least not yet relevant in full scale for most small and medium sized enterprises. The challenge, therefore, is how to prepare for this situation (assuming it will arise), and not least how to harness the information flows to best accommodate, not only improved productivity, but also improved environmental performance, and in this way contribute to how smart production will be enacted.

4 Vision for a Digital Double Shadow

The challenges in sustainable and smart production can be conceptualized largely in the same terms. Smart production is about integration both with respect to production parameters as well as sustainability parameters, and digital twins and shadows hold a great potential for enabling and operationalizing this integration. In relation to production, Kritzinger et al. (2018) has coined this as the difference between (1) *digital models* being digital representations of reality but with manual connections between reality and model, (2) *digital shadows* where the model is feed with real-life data (automatic data flow), and finally (3) *digital twins*, where the advanced models with automatic data input, automatically feed data back to the production-system. In other words, to have a digital twin it is not enough to have a digital model, it is required to have two-way interaction between production-reality and the model, and importantly, that the model can change with changing production reality. This situation is fully mirrored when it comes to sustainability modelling using LCA (which today almost solely is environmental impact modelling): Today, data flows in sustainability modelling and LCA are mostly manual! A typical system representation in LCA—a life cycle model, which in the professional jargon is the Life Cycle Inventory (LCI) is a digital model of the environmental performance of the production-reality. This is depicted in Fig. 3, upper part, where the digital model is connected with the production reality by manual data flows, i.e., experts interviewing production controllers and collecting and selecting relevant data inputs.

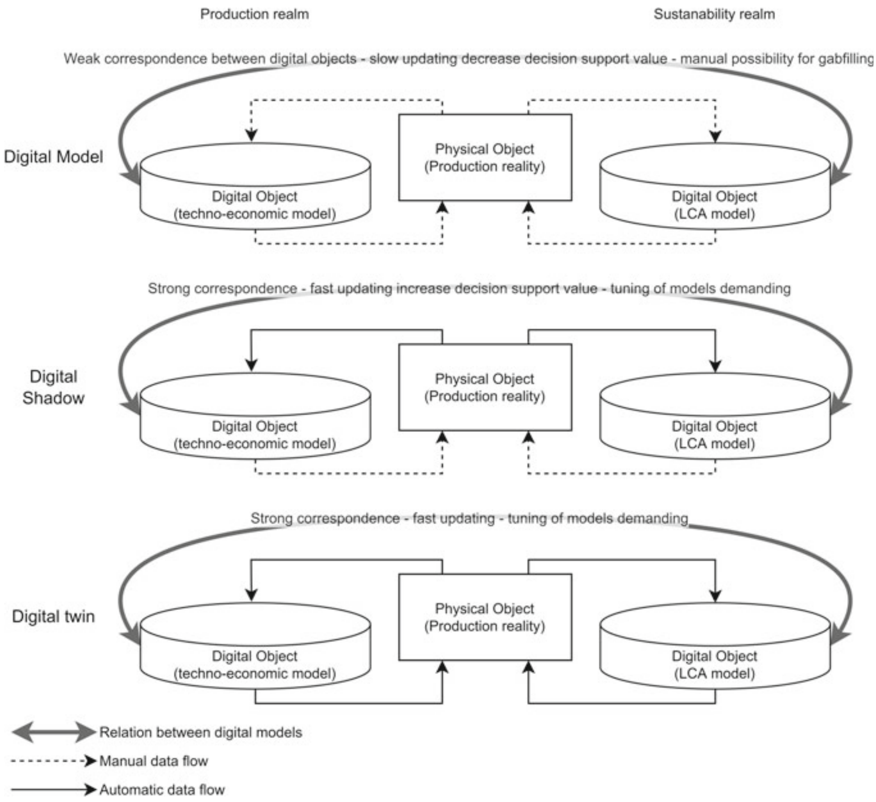

Fig. 3 Topology for digital models of the production reality, conceptualized as twin-digital representations of the production reality. To the left is the representation as Kritzinger et al. (2018) sketch it focusing on the manufacturing reality, and to the right the representation focusing on sustainability aspects of the production reality. The twin-approach is pragmatic and based on actual modelling practice, but the twin structure may be merged into a single digital representation

Smart production and Industry 4.0 are often being articulated as an enabler for sustainable development in enterprises (see i.e. Carvajal et al., 2019; Dagerman et al., 2015; Baumann, 2017; Niehoff & Beier, 2018; Pfeiffer, 2017; Kagermann et al., 2013). However, in general, the connection between smart production and sustainability has until this point seemed to be strongest in the toasts and speeches, which also is a central improvement point in what has been coined Industry 5.0 (European Commission et al., 2021). In line with this, we here present a conceptual model for how the similarities between the techno economic ‘production’ digital twin, and the emerging approaches for life-cycle assessment leaves a good space for creating linkages, as life cycle modelling can be viewed as just another digital model of the production reality. In the terminology of Kritzinger et al. (2018), current LCA digital representations are models, i.e. the top right corner of Fig. 3, but as with the digital production models, or techno-economic models as we call them here, the precision and relevance of the models is 'just' a question of how fine-meshed data collection we can make for foreground system modelling.

The challenges with the current 'manual' LCA-models outlined in the previous section is that the prevalent 'digital-LCA-models' conflates the representation of impacts with the input data, as the entities reported typically is the 'carbon footprint' per unit of input, instead of the physical flows per unit of input which is needed for proper analysis (WRI & WBCSD, 2013, 22) and this leads to a modelling which is not robust with respect to modelling assumptions. Stepping further down in the figure, the possibility for separating modelling assumptions from data collection increases, and henceforth does the robustness of the modelling, as different modelling assumptions answering different questions can be calculated in different layers.

The challenge we face is therefore a combination of one the one hand a need to take the right decisions, and on the other hand imperfect knowledge. Following the Kritzinger terminology the data representation can be done using digital model, digital shadows, or digital twins. We recommend aiming for digital shadows, not only because it is less ambitious and therefore more realistic, but also because we believe it to be a more relevant solution. The main challenge, in our eyes, is not to automate decision making but to gain relevant decision-support, enabling making the right decisions. One might say that sustainability is too important to leave with algorithms—on the contrary—sustainability requires consciousness, and it is therefore digital shadows that efficiently collects the relevant data and provides an open platform for interpretation, which is needed.

With respect to the digital sustainability representation of the production reality the focus of the company needs to be at two different levels. The first is to collect data which is relevant (Ghose et al., 2021), the second is to understand the impact potentials of the company, its production related decisions, and its products. As we have pointed out above, the data collection must be separate from the calculations of impacts, as these calculations will differ depending on the analytical questions asked, and even more importantly, the management of the company comes in control of the data that are used for the sustainability assessment in a form which is robust when encountering changing norms for how to do the assessments, and where the decisionmakers becomes educated in how decisions influence system sustainability performance. This may be improved understanding of impacts related to biomass (e.g. biodiversity, indirect landuse change), changes in how waste-based inputs should be counted, due to changing systems for recycling, or how constrained resource inputs should be modelled.

The latter is important, as this includes system aspects that lies outside of the normal production supply chain focus, as the aluminum example above show.

This way of organizing the sustainability related data with a focus on physical data describing the systems resembles the way 'normal' production models function, so by incorporating the sustainability modelling framework into the framework already known by production people we ease sustainability becoming a decision parameter at par with techno-economic decision parameters: sustainability KPI's are best be communicated in a way that production people are trained in understanding.

The sustainable digital double shadow is our effort in turning this generally shared vision of sustainability into a concrete action-oriented and operational reality. The model conceptualizes how to bring sustainability into the shop floor, the boardroom, the designer desk, and the consumer's mind. The double digital twin is a tool to connect tools for production monitoring and optimization of both economic and sustainable nature. Ultimately, all of this should become one digital twin, but our proposal and recommendation are to focus on creating an extra twin for enhancing sustainability to the digital twin, and we call it the sustainability twin (see Fig. 4).

To the left hand we have the traditional inputs to models, shadows and twins, basically leading to decision support. To the right we have the sustainability twin,

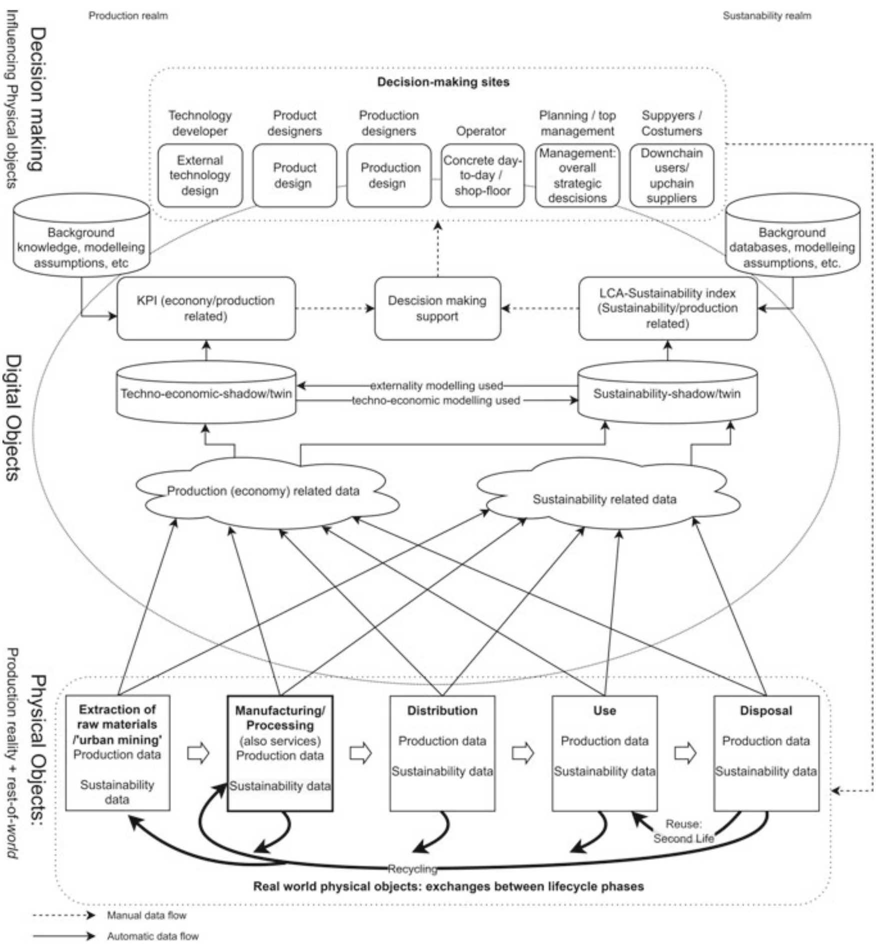

Fig. 4 The production/sustainable digital shadow. Dataflows marked are with arrows. When dataflows are manual, we speak of digital models instead of digital twins. When feedback from models we talk about digital shadows

which in principle are feed with the same data type of data as the production twin. The real-world data feed is illustrated at the bottom, and the types of flows that typically get most attention today is those related to manufacturing (onsite and purchased) and transportation.

Outermost to the left and to the right, background data for both twins are market databases, background data, modelling assumptions etc. necessary to interpret the collected data. To the sustainability side this type of data is beginning to be available in semi-automated but highly aggregated form, i.e., with the EXIOBASE data that are open access (Tukker et al. 2014; Stadler et al., 2018; NTNU et al., 2015; Merciai & Schmidt, 2018), and which has informed the projects run by the Danish Industry federation mentioned above. One of the advantages of the data is that impacts can linked both to physical entities, as well as to monetary entities, and that specific data are available for 43 countries and regions covering the global economy. EXIOBASE reflects real life global economy data, but in the current form these data are still expressions of manual data flows. However, it is in the pipeline to create versions of the data which are continuously updated (AAU, 2021), enabling increasingly accurate performance evaluations. Furthermore, this type of database enables the creation of qualified estimates of impacts based on economic data, as well as on physical data.

The collection of data at company level will in a foreseeable future be interlinked as distributed ledger technology will enable automated transfer of data without hampering production secrets. The current focus is on registering i.e., plastic qualities and traceability (Brøns et al., 2021; Licht et al., 2019), but these approaches will become normal for all exchanges in economy, as the sustainability challenge calls for three types of information following all products; price-, quality- and sustainability-data. This process is already going: Digital product passports is an important aspect of the European Sustainable Products Initiative (SPI) under the European Green Deal (European). This mean that the need for pursuing capacity building within sustainability data management will increase. In the proposal, the digital product passport will electronically share product-related information amongst supply chain businesses, authorities, and consumers.

An import aspect of these new regulations is that the company building capacity to control own data, and to request relevant data from the supply chain, will be surrounded by companies forced into similar considerations, which mean the demand for relevant data will be eased. Even more importantly, the companies building this capacity before the regulatory pressure arises will have a competitive advantage, as the data approach we here suggest will be robust regarding specific requirements that may defined either by specific customers or in future regulations such as the Sustainable Product Initiative.

5 Conclusion

For the SME a key question will be to work with sustainable system-understanding, and for this purpose aiming at building relatively simple models supporting the increasing pressure for taking relevant sustainability decisions. It is important that these models focus on physical exchanges, which is the prerequisite for making relevant impact modelling answering to the specific questions that arise in the different sites for decision making. The most important question is how changes in production influences impacts in a global context which includes induced production, but other perspectives may also be needed due to customer requirements, i.e., impact modelling in accordance with some of the specific method frameworks mentioned above. The important point here is, that the company must focus on collecting data in a form which is method neutral, and then—together with domain experts—develop an understanding and consciousness of how the company activities are connected to emissions and the sustainability challenge in general. When this is in place, then the next steps can be increased manual and automatic data collection from production and suppliers, where use of distributed ledger technology, digital product passports and like platforms can come to play an important role.

Using the vision for the sustainable shadow connecting data from reality, the company should start with simple data-collection and -deployment, aiming at becoming interlinking these data in models to support the company in making decisions furthering sustainability and thereby competitiveness.

Working along these tracks will have transformative power for the understanding of the relation production and sustainability and will be a key competitive parameter.

As future work we plan to make a prototype implementation of the proposed double digital shadow in the AAU Smart lab (Madsen & Møller, 2017), which will be important for the dissemination and mutual learning processes across the sustainability and production domains, as well as across production practice and production research.

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Part 4
Technologies

Introduction to Part 4

Technologies for Smart Production

Casper Schou

Abstract This part of the book addresses the technology aspect of Smart Production. In particular, we focus on the new digital technologies serving as enablers for transforming ordinary factories into smart factories. The part is composed of 10 chapters. This first chapter serves as a general introduction of smart factories, the role of technology in the smart factory and a set of key technologies for realizing smart factories for SMEs. The remaining nine chapters each introduce a specific technology chosen due to their high relevance to smart production in SMEs in general. These chapters will provide a short and concise overview of the respective technologies, discuss the implications specifically for SMEs and provide exemplification of the deployment.

Keywords Industry 4.0 · Smart production · Smart factory

1 Introduction

Over the past decades, we have seen a steep increase in consumer demand for product innovation. Innovation that pushes companies to shorten product lifecycles, releasing new generations more often, and offering ever greater product variance and customization options. Coping with the increasing product innovation pace is in itself challenging, but manufacturing companies also need to address the strain this puts on their manufacturing operations. Consequently, innovation in manufacturing paradigms, platforms and equipment has seen an increase as well, striving towards more dynamic and changeable structures on all levels of manufacturing as well as extensive digitalization of all assets and processes. As a result, we are now seeing a push of a new range of technologies promising the fulfillment of the visions behind Industry 4.0 (Dalmarco et al., 2019; Kipper et al., 2020).

Although the challenge of addressing the increased demand for product innovation is directly related to the value proposition, companies are today also faced with other challenges; in particular, the challenge of addressing both political and societal

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agendas (Deloitte, 2020). If the challenges are seen as the motivators for industry to move towards smart production, the new digital technology-toolbox contains the enablers needed to succeed in this transformation. Thus, technology innovation and adoption are among the central turning points of smart production.

2 Smart Factory

The heart of any production company's operations is the factory. Here, materials and parts are enriched and processed to form the product offerings to the market. It is also here, the increased product innovation pace and the impact of the challenges outlined above truly manifest themselves as challenging the current best practice. In finding new practices, the factory is also where new technologies and digitalization are anticipated to have the largest impact, effectively transforming factories to *smart factories*.

A smart factory is thus an extension of the traditional factory with extensive digitalization allowing data-driven operation. However, a recent definition of the smart factory (Schou et al., 2022) states, that a truly smart factory must also address requirements and agendas of the society in which it operates. Schou et al. (2022) defines the smart factory as:

> *A factory which by interconnecting its assets into a digital ecosystem, uses information to adapt, run and optimize its operations according to actual business conditions, thereby generating and appropriating business value while reflecting societal requirements.*

2.1 Sustainable and Socially Responsible

Companies are becoming more and more aware and focused on societal values and responsibilities as highlighted in a recent report from Deloitte (2020). However, the societal requirements will differ depending on the country and society in which the factory operates. In some societies, the outmost societal requirement might be to fight poverty and hunger, whereas in other countries it might be environmental sustainability.

Accentuating the context around the smart factory is also highlighted in the recent advent of the Industry 5.0 paradigm (Breque et al., 2021), which puts both sustainability and human wellbeing at its center; both of which are considered societal requirements.

2.2 Interconnected and Data-Driven

In literature, there are several other definitions of a smart factory, e.g. (Chen et al., 2017; Deloitte, 2017; Radziwon et al., 2014; Sjödin et al., 2018; Wang et al., 2016), most of which link the smart factory to specific technologies, frameworks, or manufacturing systems. We do not necessarily disagree with all of these; however, it is apparent that such definitions quickly become obsolete as technologies are replaced by newer ones. Thus, rather than pointing at specific technologies, the definition by Schou et al. (2022) specifies the capabilities the smart factory must obtain from deploying novel, digital technologies. Here, the central capability is the ability to govern its operations based on information created by contextualizing large amount of data from across the factory. This data is acquired by interconnecting the factory assets into a digital ecosystem. Assets can be everything from machines, to humans, to IT processes and systems, and thus it spans both horizontally and vertically in the factory. As such, a smart factory is a data-driven factory composed of many digitally interconnected assets.

2.3 Resilient

Given the increasing dynamic nature of the product market and the surrounding society as explained in Sect. 1, a smart factory needs to be resilient to the changing business conditions under which it operates (Schou et al., 2022). In can become so, by (1) responding in due time to changes in the demand, supply, legislation, and other operating conditions; (2) utilizing data to predict equipment health and process quality; and (3) using adaptable equipment to seamlessly changeover to new variants and quickly scale up and down in capacity.

2.4 Beyond Profit Value-Creation

The traditional factory creates value by processing materials and parts into products, and thus enabling the company to generate a profit. However, a truly smart factory can also extend this purely profit-focused value creation, by either purely or simultaneously generating other types of value for the company. It could be in the form of a *learning factory*, which serves to generate learnings, experience, and knowledge (Grøn et al., 2020); or as a *pilot factory* which serves as a sandbox for testing new technology, products, and methods (Hennig et al., 2019).

3 Technology

Although the *definition* of a smart factory (Schou et al., 2022) is independent of specific technologies, the implementation of a smart factory cannot be. For its embodiment, a smart factory needs technology, and new, digital technologies are the necessary enablers to achieve the capabilities and values outlined in Sect. 2.

3.1 Industry 4.0 Technology Stack

Since the dawn of the fourth industrial revolution (Kagermann et al., 2013), both industrial consultants and academic scholars have offered their take on which specific technologies are the essential enablers for Industry 4.0 (Bortolini et al., 2017; Craveiro et al., 2019; Ghobakhloo & Iranmanesh, 2021; Kipper et al., 2020; Sikandar et al., 2021). Boston Consulting Group (BCG) proposed in 2015 one of the best-known illustrations on industry 4.0 technologies (Russmann et al., 2015). The illustration points out nine technologies as being central to Industry 4.0, see Fig. 1.

Over the years, many others have proposed similar pictures of the key technologies in Industry 4.0 (Bortolini et al., 2017; Kipper et al., 2020; Sikandar et al., 2021).

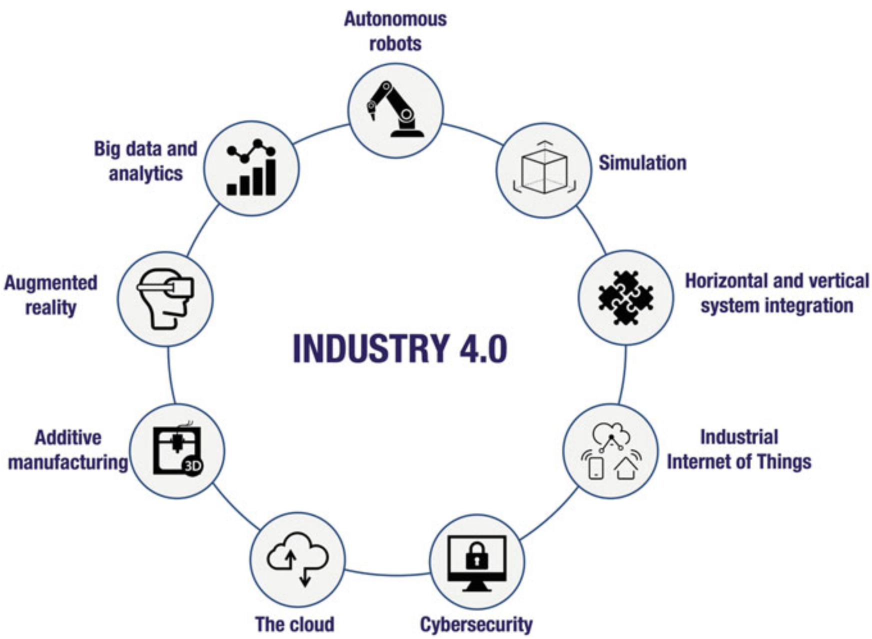

Fig. 1 Nine key technologies proposed by Boston Consulting Group as the main technological pillars of industry 4.0. Reproduced from (Russmann et al., 2015)

However, most are still closely aligned with the proposal from BCG shown in Fig. 1, emphasizing these as still being the key technologies of Industry 4.0.

3.2 Technology Innovation

Technologies tend to have a lifecycle; they are invented, matured, exploited, and later succeeded by newer technologies (Kim, 2003). Therefore, a static picture like Fig. 1 does not adequately capture the true technology potential of Industry 4.0. With the dawn of Industry 4.0, we have seen a large increase in innovation of manufacturing technology, resulting in a stream of new technologies labelled as *smart* or *industry 4.0 ready*. A stream that continuous today, and thus constantly brings new technological innovations and opportunities. An overview of upcoming, current, and mature technologies is presented by Gartner in their annually updated *Gartner Hype Cycle on emerging technologies* (Gartner, 2021). The Hype Cycle offers some insight into the maturity and readiness level of individual technologies, and thus constitutes a great tool for companies to both stay updated on emerging technologies and navigate the hype around new technologies.

3.3 Smart Factory Technologies for SMEs

By aligning the smart factory vision presented in Sect. 2, with the key Industry 4.0 technologies presented in Sect. 3.1 and the continuous flow of new technology discussed in Sect. 3.2, we have chosen nine key technologies that we deem central to the transformation of factories into smart factories in SMEs. The nine technologies and their relations are visualized in Fig. 2.

Given that SMEs tend to lack behind large companies in the digital transformation (Zeitschel et al., 2022), it is no surprise that the technologies suggested for the smart factory transformation for SMEs in Fig. 2 correspond well with the technologies proposed for Industry 4.0 by BCG in 2015. Although newer technologies have been introduced since, and more are on the horizon, the nine technologies in Fig. 2 are still today central and well-proven in the smart factory transformation.

Following the smart factory definition by (Schou et al., 2022), these nine technologies constitute a toolbox of *current* technologies that can embody the envisioned digital ecosystem and interconnect assets of the factory. For this purpose, Fig. 2 also visualizes how the nine technologies can form a new IT/OT architecture compared to the traditional automation pyramid. As shown in Fig. 2, some technologies provide the infrastructure necessary for the interconnection of assets, some enable the data flow, analysis, and management, and others exploit the available data, information and knowledge from the ecosystem. In brief, the nine technologies are:

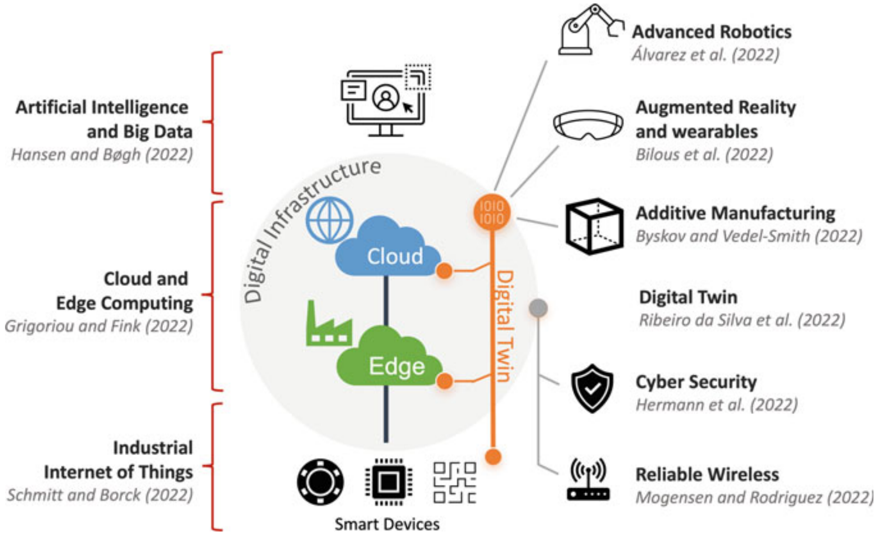

Fig. 2 Nine key technologies for the smart factory transformation in SMEs. The figure visualizes how the nine technologies fit into a smart factory IT/OT architecture. The references on the figure link the technologies to the following chapters in this part of the book

Industrial Internet of Things: Schmitt and Borck (2022) present industrial internet of things as the fundament of the asset interconnection in a smart factory and the data exchange of individual assets. This is achieved through Industrial Internet of Things promoting extensive connectivity of devices using smart devices (sensors, actuators, and controllers), new data exchange protocols and new cloud-based data-collection platforms.

Edge and Cloud Computing: Given the data exchange of individual assets, a digital ecosystem can be realized by integrating the data in a central platform. As discussed in Grigoriou and Fink (2022), using an edge and cloud-based platform, further promotes the integration between remote sites. Cloud computing also allows companies to draw on software tools and capabilities as a service, introducing new IT business models and architectures.

Artificial Intelligence and Big Data: With comprehensive data available in the digital ecosystem from across the company's assets, Hansen and Bøgh (2022) discuss how big data and artificial intelligence (AI) tools can be used to derive patterns and insight from the data. Thus, extracting information and eventually knowledge from the raw data. Such information and insight allow the company to adapt and optimize its operations and processes.

Reliable Wireless: The increasing need for more flexible and reusable production resources gives rise to more mobile and frequently changing systems; for instance, autonomous mobile robots and ad-hoc deployable production resources. Mogensen and Rodriguez (2022) argues that such systems benefit from a highly robust and fast wireless communication infrastructure beyond the capabilities of current Wi-Fi solutions.

Cyber Security: The extensive connectivity of assets, the switch to cloud computing architectures, and the increased use of wireless communication comes with the prerequisite of an inherent secure digital infrastructure. However, as discussed in Hermann et al. (2022), the ever-increasing cyber thread to companies' digital values means cyber security cannot be an aftermath, but must be an integrated part of smart factory solutions.

Digital Twin: Ribeiro da Silva et al. (2022) explains how the abundance of data available coupled with the analysis tools to extract insight and knowledge enables the creation of an accurate digital twin. Such digital twin allows the company to verify hypothesis and assess planned changes virtually. Thus, a digital twins will become an integrated part of the digital toolbox a smart factory uses to adapt its operations.

Additive Manufacturing: The resilience of a smart factory also comes from the application of flexible assets and processes. One example of such process-technology is additive manufacturing. Byskov and Vedel-Smith (2022) describe how additive manufacturing makes it possible to go directly from digital design to physical product. Apart from the inherent manufacturing flexibility, it also yields new freedom in product design and sourcing.

Augmented Reality and Wearables: The extensive digitalization of the shop floor is not contained to the automated processes. As production tasks grow increasingly more dynamic, the need to support the human workers grows too. Bilous et al. (2022) explain how introducing wearable technology for the operators and augmenting their workspace using augmented reality, digital support can be provided directly in-situ, and valuable data can be collected to represent the manual processes in the digital ecosystem.

Advanced Robotics: Álvarez et al. (2022) discuss how robots are among the key shop floor assets of the smart factory, given their versatile nature. However, as traditional industrial robots are intended for a fixed life in terms of hardware and programming, more advanced robotics solutions are needed. Solutions that are more autonomous and collaborative, allowing robots to operate in the dynamic environment of the human worker, and thus adapt to a greater task diversity over its lifetime.

4 Concluding Remarks

Growing market dynamics push companies to increase their product innovation to remain competitive. Meanwhile, political, and social agendas are also playing an increasing role to companies' operation and value proposition. Seen from an operation perspective, the manufacturing operations must become resilient to the frequently changing boundary conditions. This leads companies to pursue smart factories, which utilize new digital technologies and extensive data collection to continuously adapt and optimize. However, the solution space of new technologies is vast and continuously growing. In this chapter, we have suggested nine well-established technologies that together constitute a toolbox for the successful transformation of a factory to a smart factory for SMEs. The next nine chapters of this book (the rest of this Part) provide a catalogue of these technologies, including: a short introduction, implications for SMEs, and one or more examples of deployment.

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Industrial Internet of Things (IIoT)

Randolf Schmitt and Christian Borck

Abstract Schmitt et al. provide a brief overview of the key technology for Industry 4.0, the Industrial Internet of Things (IIoT). For this purpose, the paper first examines how this technology has developed, what its essential components are and what challenges still need to be overcome. The work particularly presents the specific requirements, challenges and opportunities for SMEs. " Industrial Internet of Things (IIoT)" concludes with an example about the integration of IIoT in a model factory.

Keywords Industrial IoT · SME · Industry 4.0 · Digital transformation

1 Introduction To IIoT

The Industrial Internet of Things (IIoT) is a variation of the Internet of Things (IoT), which was first named as such by Kevin Ashton in 1999 (Ashton, 2009). There is still no uniform definition for IoT today, but it could be generally defined as follows:

> An open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data and resources, reacting and acting in face of situations and changes in the environment. (Madakam et al., 2015)

The idea of connecting different objects and the internet is not new, there were already first implementations at the beginning of the 1990s. In recent years, the technology has been increasingly used in both the private and industrial sectors. Driven by advances in development in the area of connectivity, almost every object can now

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be connected cost-effectively (Rose et al., 2015). The basic functions and principles are identical for IoT and IIoT, only higher requirements are placed on industrial use, for example in the areas of accuracy and robustness (Butun, 2020). The IIoT can then be explicitly defined as follows:

> A system comprising networked smart objects, cyber-physical assets, associated generic information technologies and optional cloud or edge computing platforms, which enable real-time, intelligent, and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment, so as to optimize overall production value. This value may include; improving product or service delivery, boosting productivity, reducing labor costs, reducing energy consumption, and reducing the build-to-order cycle. (Boyes et al., 2018)

1.1 Technical Overview

IIoT is fundamentally divided into three layers (Zhang, 2011) as shown in Fig. 1: Perception Layer, Network Layer and Application Layer. The Perception Layer is where the data or information from production is collected. The main actors of the layer are sensors and short-distance transmission technologies. The Network Layer integrates the heterogeneous communications from the Perception Layer as well as other networks, including the Internet, and thus provides a link between the various sources of information to collect, process and transport information about the different objects. The Application Layer forms the interface between the user and the IIoT, the various applications use the data of the underlying structure and offer different solutions depending on the use case, e.g. to support decision-making.

1.2 IIoT—Key-Technology for Industry 4.0

We are in the predicted fourth industrial revolution (Industry 4.0). An important component of this is the smart factory (SF). The SF should be able to make decisions independently, recognize problems at an early stage, optimize and configure itself (Mittal et al., 2018). There is no one-size-fits-all solution for achieving the goals that have been set; each company must draw up a strategy for itself. This step is also already the first in the roadmap to the smart factory (Sufian et al., 2019). Next comes connectivity, where IIoT acts as a link between information technology and operational technology. This is followed by integration, data analytics, artificial intelligence and scalability. On the way to the connected factory, industry and research still have some challenges to overcome (Dhirani et al., 2021; Sufian et al., 2019):

IT Infrastructure: The amount of data collected from production will increase dramatically, and to process it, the appropriate computing power and networks will

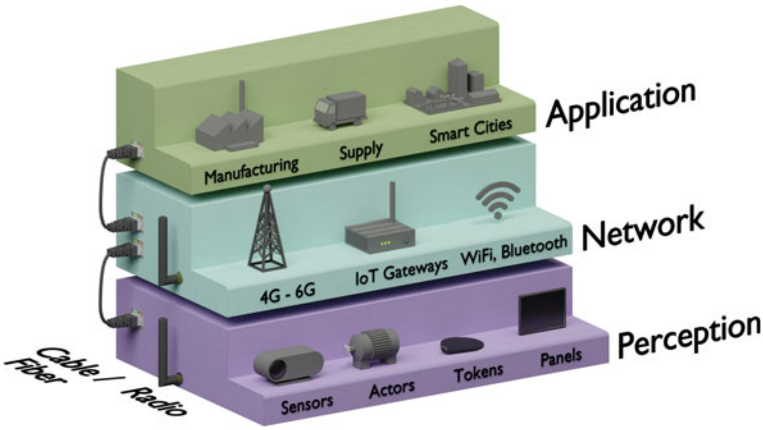

Fig. 1 The three interconnected layers of IIoT according to Zhang (2011) with typical implementations such as sensors and actors in the Perception Layer, IoT Gateways, WiFi and Bluetooth in the Network Layer and manufacturing and smart cities in the Application Layer

be needed. 5G is seen as a possible solution to the need for wireless or wired high-speed and low-latency transmission between millions of devices, and to extend on-premise computing power, for example, cloud services can be used.

IIoT Gateways: The heterogeneous sensor technology, the user and application-oriented software solutions and the network technologies must be coherently linked without interfering with other processes.

Reference Architectures: A standardized reference architecture for IIoT is needed, including a uniform description of machines, standardized communication and corresponding interfaces. There are already initial attempts to establish such architectures, e.g. by the Industrial Internet Consortium (IIC) or the International Organization for Standardization (ISO).

Cyber Security (CS): The connection of countless production devices to each other and the internet brings potential security risks with it that are more serious in industrial environments than in private ones. Existing systems such as enterprise resource planning (ERP) and manufacturing execution systems (MES) must be better protected by the new connections, as well as machine-to-machine (M2M) communication. This requires new security controls and standards.

Those who want to start the transformation to a SF have a wide variety of providers on the market. Choosing the best fitting platform depends on various factors that are individual to each company. For instance, already existing systems, infrastructure and their providers, as well as existing sensors are some important factors. In addition to the desired use cases, the selected system must also provide support for the aforementioned components (Ganguly, 2016).

2 Implications for SMEs

The market is moving towards individual products, which presents companies with major challenges that are to be overcome with the developments that are summarized under the keyword Smart Factory (SF). IIoT is an important pillar of SF, regardless of the size of the company, which enables it to act more agile and flexible, optimize resources and react more quickly to changes, e.g. in demand, by collecting and evaluating data throughout the entire product or production life cycle. IIoT provides the basis for a more secure communication with fewer barriers between all components in a factory and thus helps to optimize business processes by including real-time information about products, materials or equipment. IIoT does not necessarily create new functionalities that would not be possible with existing equipment, but it enables existing processes to be optimized or new functionalities to be made available to the user in a cost-effective, scalable manner and with a centralized access point. The SME Guide for Industrial Internet of Things (IIoT) (Omar Dhaher, 2021), much of its information referenced in this section, lists some more detailed benefits for SMEs in deploying IIoT.

The challenges a company faces when introducing IIoT vary drastically. Depending on the existing infrastructure and envisaged goal, the efforts in terms of time and money can differ greatly. In the beginning, it must be clarified in which areas there is a particular need or which area is particularly representative for the entire company. Subsequently, a solution is developed for this area, so that the initial investment and complexity can be kept low. A later expansion of the solution is usually possible without problems due to the enormous scalability of IIoT. For a solution, the corresponding prerequisites must be created on all three layers of IIoT. To meet the requirements of the Perception Layer, external sensors can be integrated or the machines can be converted to IIoT-capable systems, and it is also necessary to create a short-distance data transmission option. Depending on the sensor technology selected, additional computing power is required to obtain the desired information from the recorded data (e.g. in the case of imaging sensor technology). Within the Network Layer, interfaces to existing systems and a security concept must be integrated in addition to the corresponding gateways and the networking of these. Furthermore, a decision must be made whether the analysis of the data is to be carried out exclusively in the cloud or additionally in so-called edge systems. Finally, the centralized interface to the user is created at the application level. For this, a solution (usually a cloud platform) for data analysis and monitoring must be individually selected or implemented that meets the requirements. This decision also influences the underlying layers through possible restrictions in the support of data transfer protocols, etc.

3 Example

The model factory operated by IMI Brandenburg at BTU Cottbus-Senftenberg (Chair of Automation Technology) is a good example of a constantly changing factory that is successively being digitalized with the help of IIoT. In its function as a model factory for SMEs, new technologies from a wide range of manufacturers and with a variety of tasks are constantly being integrated for demonstration and research purposes, some of which are already IIoT-capable. In addition, there are existing machines without any network capability in the model factory. The aim is to map the model factory completely digital to demonstrate the potential of the digital twin (DT) and exemplary use cases of the DT. As an example, the focus here is on the monitoring of data as a basis for rapid decision-making.

Due to a large number of different processes, an independent platform for the collection, evaluation and visualization of data was necessary. The choice fell on the open-source software ThingsBoard, which offers appropriate solutions across all three layers of IIoT and the possibility to implement own extensions. The platform supports common standards such as OPC-UA and MQTT. Machines and tools (MT) are connected to the platform either by implementing against these standards using sensors and software translators or by simply using interfaces to these standards already provided by the MTs.

An example of an individualized monitoring interface is the visualization of a robot arm in its valid environment based on real-time joint data, which was sent via MQTT from ThingsBoard to the visualization engine Visionary Renderer by Virtalis or Unity. In a virtual reality visualization, all real movements of the robot could be tracked and analyzed, and it was even possible to implement control of the robot arm from Unity.

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Cloud Computing: Key to Enabling Smart Production and Industry 4.0

Niki Nicolas Grigoriou and Andreas Fink

Abstract Cloud computing is one of several important technologies of Industry 4.0 and is a key enabler for Smart Factories and Smart Warehouses. With the 4th industrial revolution, the system architecture seen in larger robotic systems is shifting towards a cloud-based architecture, allowing for easier, more accessible and cost-effective systems. This is a game changer for SMEs, allowing them to gain access to the advanced systems that otherwise are only available for larger enterprises. This chapter provides an overview of cloud technology, its characteristics, and service and deployment models. Furthermore, the chapter details why using the cloud is essential for Industry 4.0 and its challenges compared to current typical systems.

Keywords Cloud computing · Control systems · Cloud-edge

1 Introduction

Industry 4.0 and equivalent terms Smart Factories and Smart Production describe concepts that utilize new and emerging technologies used to modernize and revolutionize manufacturing, production and logistics.

The technologies in focus can be summed up to be a combination of emerging integration, digitalization, robotics and Internet technologies. The combination of these technologies is often referred to as *cyber-physical systems*.

A key-component and essential ingredient in Industry 4.0 is the use of *the cloud* or *cloud-computing*. This chapter will explain the concept of cloud-computing and why it is essential for Industry 4.0 and Smart Production (Popkova et al., 2018).

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1.1 What is the Cloud?

> Simply put, cloud computing is the delivery of computing services—including servers, storage, databases, networking, software, analytics, and intelligence—over the Internet ("the cloud") to offer faster innovation, flexible resources, and economies of scale. You typically pay only for cloud services you use, helping you lower your operating costs, run your infrastructure more efficiently, and scale as your business needs change.

(Microsoft Inc., 2021).

This is a beautiful concise definition of cloud and cloud computing has been used by Microsoft on their website as part of the documentation for their widely-used Azure cloud product.

The term "cloud" has over the years been used with various meanings. Sometimes synonymous with *The Internet* and sometimes in various definitions defining pooled network computer resources of different types. The definition from Microsoft captures what we today see as the cloud, and what is meant with cloud in relation to Industry 4.0.

Cloud computing can be further described to have certain characteristics and use certain service and deployment models.

Characteristics of cloud computing are:

- **On-demand self-service**: Computing capabilities such as server time and network storage can be provisioned automatically without human interaction.
- **Broad network access**: Capabilities are available over the network and accessed through standard mechanisms by heterogeneous client platforms.
- **Resource pooling**: The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model.
- **Location independence**: While the customer may provide a preference for a region, they do not have knowledge of or control exactly where their resources are provided.
- **Rapid elasticity**: Capabilities can be elastically provisioned and released automatically, to scale rapidly outward and inward to match demand.
- **Measured and monitored service**: Resource usage can be monitored, controlled, reported, and optimized automatically, providing transparency for both the provider and consumer of the utilized service.

Service models used in cloud computing:

- **Software as a Service (SaaS)**: The capability provided to the consumer is to use the provider's applications running on a cloud infrastructure.
- **Platform as a Service (PaaS)**: The capability provided to the consumer is to deploy onto the cloud infrastructure consumer-created or acquired applications created using programming languages, libraries, services, and tools supported by the provider.

- **Infrastructure as a Service (IaaS)**: The capability provided to the consumer is to provision server resources where the consumer can deploy and run arbitrary software.

Cloud computing deployment models:

- **Private cloud**: The cloud infrastructure is provisioned for exclusive use by a single organization comprising multiple consumers (e.g., business units).
- **Community cloud**: The cloud infrastructure is provisioned for exclusive use by a specific community of consumers from organizations that have shared concerns.
- **Public cloud**: The cloud infrastructure is provisioned for open use by the general public. It may be owned, managed, and operated by a business, academic, or government organization, or some combination of them.
- **Hybrid cloud**: The cloud infrastructure is a composition of two or more distinct cloud infrastructures (private, community, or public) that remain unique entities, but are bound together by standardized or proprietary technology that enables data and application portability (Mell et al., 2021; Frankenfield, 2020).

1.2 Cloud, IoT and Industrial Internet of Things

Cloud computing is one of the nine technology pillars of Industry 4.0 and an import element of several of the other pillars.

Industry 4.0 and Smart Production break with the traditional hierarchical structure and technology layering of traditional production systems. The shift is the same paradigm change that is seen with the Internet of Things (IoT).

In industrial systems and components, devices become Industry 4.0-enabled and connect in different ways to Internet and cloud services allowing behavior and functionality that differs from traditional devices by adding intelligence and integration capabilities. “Dumb” devices become smart devices. The traditional hierarchical structure of industrial systems, often illustrated as the automation pyramid and layering models like ISA-95 (ISA, 2000), become blurred in the IoT and Smart Production world. This paradigm shift is illustrated in Fig. 1.

Business systems like ERP-systems, CRM-systems and web-shops have for some time been present in the cloud. We now see high-level control systems that provide Industry-4.0 key-feature of *horizontal and vertical integration* also move toward the cloud. These are systems like manufacturing execution systems (MES) and warehouse control systems (WCS). Low-level devices from PLCs or other control devices to smart sensors and actuators can be connected directly to cloud systems, mostly for data collection and monitoring purposes, but also for control of delay-tolerant control. Devices become Industrial Internet of Things (IIoT) devices (Gilchrist, 2016).

Industry 4.0 and *smart factory* concepts also promote *smart products* that either have embedded connectivity themselves or that become smart via being uniquely identifiable and having systems provide them with a data-shadow. Thus, allowing

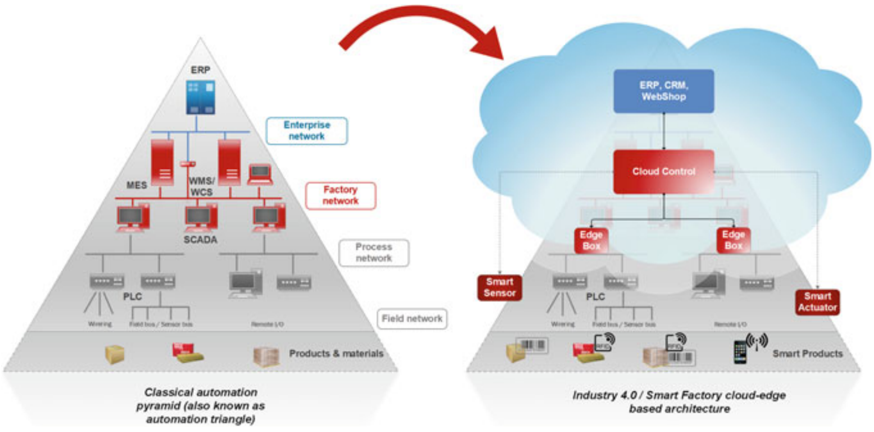

Fig. 1 In Industry 4.0 and Smart Factory, systems are moved from the traditional wired architecture often illustrated as automation pyramid toward a cloud-based or cloud-edge-based architecture

products to be enriched with data properties, history, state and much more that is provided by systems and "the cloud" (GMA, 2014).

With Industry 4.0 the system architecture seen in larger robotic systems shifts toward a cloud-based architecture. This change provides a number of benefits for users. Traditionally business systems and high-level control systems used in factories and warehouses are installed on-premises typically as dedicated client–server solutions that often include a redundant server setup. Both software and hardware are traditionally installed locally. When moving to the cloud, these systems become cloud-based and server hardware resources are virtualized and are available on-demand via the cloud.

Benefits can be summarized as follows:

Easier: Setup and provisioning can be simplified and time used reduced from months to days, hours or even minutes. The same system can be used for multiple sites. Data can easily be aggregated, shared and processed within larger enterprises, distributed organizations and between multiple organizations. Maintenance, system backup, system monitoring, updating of platform and system software can be handled automatically as a service by the cloud system.

Accessibility: Cloud solutions are available when needed and anywhere the Internet is available. There is no need to select, buy and wait for server hardware delivery, setup and installation. Cloud-based platforms and services can be tried and tested with little or no prior effort.

Cost and Resource Consumption Reduction: Hardware and software investments and costs are reduced. Server hardware and computer resources, software and service and maintenance costs are virtually shared between the users. This sharing of resources can also lower the relative resource consumption and environmental footprint (Spicer, 2019).

2 Why is Cloud Important for SMEs?

Benefits of cloud and Industry 4.0 are relevant for larger companies and organizations that work with physical products. For smaller companies and organizations that work with physical products, e.g., companies within manufacturing, production, as well as within e-commerce and warehouse and distribution/logistics, Industry 4.0 and the move to cloud is a game-changer.

Larger companies can afford investments in large scale automation, robotics and digitalization. Their business volume allows them to make investments and harvest the benefits of custom-built large scale integrated systems. This is due to their scale and production volume that allows the cost of the investment to be relatively small per product produced or handled. Large companies and organizations can effort to invest both in systems and human resources that have the competences to specify, build, operate and maintain *smart factories* and *smart warehouses*—even when built upon the technology from the old automation pyramid paradigm.

Within the old paradigm it is not possible for small companies and organizations to develop *smart factories* and *smart warehouses*. Today they cannot afford using integrated automation, robotics and digitalization. *Smart factories* are not within their financial reach and most often also beyond their technical competencies. If they deploy automation and robotics, it consists of unintegrated islands of automation. Production has to be set up, configured and re-configured manually. The idea of *smart factories* and *flexible production* that "mass produces products in series of down to 1" is not a possibility for them—within the old paradigm.

Industry 4.0 and especially the use of cloud, levels the playing field. The benefits of making the integration of automation, robotics and digitalization easy, accessible and more cost-effective are relevant for larger companies and organizations, but for the smaller companies it is a game-changer. It allows them to become more competitive and to utilize the benefits and agility that is inherent in smaller companies.

3 New Problems Introduced by the Cloud

The shift to cloud technology provides a number of benefits, but it also introduces a set of new challenges that have to be met by Industry 4.0 architecture and solutions design.

Key challenges introduced by move to the cloud:

Cybersecurity: The move to the cloud changes the environment and vulnerability of solutions. In traditional industrial solutions the solution existed in a closed environment with networks and devices that were not connected to the Internet. This reality has changed. Even solutions that are not moved to the cloud, have become vulnerable (Baezner et al., 2018). With Industry 4.0 solutions that embrace the cloud, cybersecurity becomes an inherent threat that has to be invested in and be handled by design for Industry 4.0 solutions to be safe.

Reliability: Even though the move to cloud technology can make it easier in many aspects to maintain reliability of systems, e.g., by allowing computer resources to be redundant, backup and maintenance to be carried out automatically as a service, there is an inherent reliability problem for a factory or warehouse that is run from a cloud-based system. The Internet connection is a public infrastructure. If the Internet connection for some reason is down, the automated factory or warehouse will have to stop operations until the connection is reestablished. Even short connectivity interruptions may cause problems. The problem can be addressed in several ways; on one hand enhancing the connectivity to the cloud making this more reliable through redundant connections, on the other hand through allowing the system to run at least for a period without access to the cloud by having the cloud stretch out and partially run on local on-premises hardware and devices, referred to as "edge", "edge computing" or "edge devices" (Gill et al., 2018).

Latency: Automated systems require a degree of real-time capabilities that increases the lower you get in the system stack. For business systems latency requirements can be what is acceptable for humans as response time or what is acceptable for the business, typically seconds to hours (for batch processes). At the middle tier, high-level control systems often have to be capable of fast *close-to-real-time* responses. For many applications typical cloud response times are not acceptable at this level. Response time toward low-level control and machine systems often is required to be within milliseconds. Response time in low-level control and machine systems often is required to be "*hard real-time*". Typical acceptable response times for this level are milliseconds or below. For this reason, a move to the cloud becomes more difficult at lower levels.

3.1 Using Cloud-Edge Solutions to Address the Cloud-Related Issues

Cloud-edge is a system architecture that introduces a local "edge" hardware component that allows the cloud to stretch and be present locally. This addresses the problems of reliability, latency and cybersecurity described in the previous section. Thus the "edge device" becomes a bridge between the cloud and other local devices and systems.

In addition to addressing the above problems, introduction of an edge component into the architecture also provides some additional benefits and opportunities: The edge devices can do processing or pre-processing of data before it is sent out to the cloud, it can reduce the amount of data that must be transmitted to the cloud and allow local processing power to be utilized. An example of that has started to appear are edge devices that include AI-processing capabilities (Calo et al., 2017; Wang et al., 2019).

A number edge devices can be set up to each cover a segment or of a factory. Edge devices can also be redundant and suppliant or serve as backup for other edge devices, depending on the cloud-edge systems capabilities. This requires coordination and synchronization between cloud and edge components. Thus, even though edge computing can solve some of the problems introduced by the cloud, it also introduces new level complexity by itself.

4 Cloud Fundamentally Changes the Game for Industrial Automation (Summary/Conclusion)

Industry 4.0 promises an increase in efficiency, flexible resource management, and the individualization of mass customization (Govindarajan et al., 2018). The cloud is instrumental to making the promise of Industry 4.0, Smart Factories and Smart Warehouses a reality, as this makes automation easier, more accessible and more flexible compared to the current paradigm. It will also reduce the costs and resource consumption, allowing SMEs to obtain the benefits of Industry 4.0. Moving the control systems to an off-site Cloud provider introduces some issues regarding cybersecurity, reliability and latency with varying requirements depending on the application. Nonetheless, using the Cloud is seen as a game changer to make Smart Production a reality.

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Artificial Intelligence and Machine Learning

Emil Blixt Hansen and Simon Bøgh

Abstract With the expanding use of the term AI and its possibilities, it is beneficial for SMEs to understand what the term means and what it can do. This chapter gives an insight into what AI is and which technologies it encompasses. Moreover, the different use of AI within an SME is described along with its different benefits. Additional use cases are also described, along with some studies recommendations for SMEs.

Keywords Artificial intelligence · Machine learning · SMEs

1 Introduction

With the ever-expanding digitalisation, more information or data is generated and is available within the digital ecosystem. The expansion of available data and the increased competition caused by globalisation contribute to why manufacturers are looking for more advanced methods to optimise their production and products. The general usage of artificial intelligence (AI) within different fields is expanding. As part of Industry 4.0, AI is also gaining interest within the industrial sector, where companies are expanding and trying different usages of AI, both within their production and as a product or service. Nonetheless, the term *artificial intelligence* is ambiguous and is a collection of many different methods and fields of statistics, data- and computer science. When the term AI is used as a tool, often it refers to *artificial narrow intelligence* (ANI), which indicates a specific field or problem an

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AI is applied to. Whereas the term *artificial general intelligence* (AGI) refers to an AI which succeeds in multiple fields and is closer to human beings type of intelligence. Examples of ANI is voice assistants like Google Assistant and Siri and image recognition like Google Lens. Moreover, AI's like DeepMind's AlphaGo is also an ANI. As of this paper, there exist no examples of an AGI yet. Thus, we will only refer to ANI when we use AI from here on.

AI is often utilised fields such as robotics, planning, computer vision, natural language processing, expert system etc. The tool used to solve the challenges within these fields is often machine learning and deep learning in recent years. Deep learning is a subset of machine learning which utilises artificial neural networks to learn a given problem. To apply machine learning to a problem generally, three components is required:

- A decision process
- An error function
- An optimiser

The *decision process* is a set of calculations where the algorithm makes a best guess on what the output should be. The *error function* (also known as loss function) then calculates the error between the guess and the correct answer if present. At last, the *optimiser* minimises this error function to improve the decision process; and then the cycle continues until stopped.

Depending upon the task, machine learning can be split into three different paradigms. The three paradigms are supervised learning, unsupervised learning and reinforcement learning.

Supervised learning: It is used when the problem has a specific and known class or outcome, often referred to as a label. This can, e.g. be image recognition and classification. Moreover, it can also be used to solve regression problems such as predicting future sales.

Unsupervised learning: Unsupervised can be used to find unknown patterns in a dataset and to reduce the dimension of a large dataset. Moreover, it can be used to detect faults e.g. a machinery through methods such as autoencoders.

Reinforcement learning: It is often used where a more dynamic approach is suited, where, e.g. labels can be hard to obtain. The reinforcement agent learns from the action it takes within the environment it is deployed. The training of an agent often requires a simulation environment since the agent learns through the means of trial and error. Reinforcement learning can be beneficial in cases of planning where the environment is more dynamic.

In general, it is required to either have a substantial amount of data or the ability to create/collect it to produce a good result with machine learning. This is especially true when dealing with the best-performing algorithms and models. Nonetheless, since this field is seeing a rapid involvement, new methods focusing on how different ways to optimise the algorithms, both for shorter training time, more energy-efficient and dedicated hardware (Reuther et al., 2019). Companies are also releasing either products with build in AI and machine learning or having it as a part of their toolbox for manufacturers, such as Microsoft Azure.

2 The Use of AI in SMEs

In 2021 a survey found a low adoption of AI in SMEs, where only five publications utilised AI in SMEs related to the manufacturing industry (Hansen & Bøgh, 2021). It showed that all though limited, that the SMEs was more focused on the internet of things (IoT), cloud solutions and relevant business opportunities. One of the reasons behind the higher adoption of IoT and cloud solutions is that they are easy to use (Moeuf et al., 2020). This also indicates that SMEs, in general, lack the knowledge and resources to use AI themselves; however, researchers are researching methods to make AI more easy-to-use, applicable and tailored towards manufacturing companies, including SMEs.

Within an SME, there are numerous ways AI can bring value (Watney & Auer, 2021). Some of them are predictive maintenance, resource optimisation, quality control, and logistics. Which subfield of AI is used depends on whether it is predictive maintenance, logistics or one of the other problems AI is applied on. This also leads to one of the shortcomings of AI, e.i. the knowledge required to have a successful integration. Normally AI projects are engineered to the specific task, either in-house or by a consulting company. Which further indicates the challenges and knowledge required for implementation. Therefore, the problem is more present in SMEs where, in general, the expertise and resources is a constraint (Welte et al., 2020). Henceforth, pilot projects are a way for SMEs to get started with AI, either in collaboration with a research institution or an AI consultancy company. Thereafter, the SMEs have gained knowledge of AI in connection with their business. Then can start to build up their own internal AI specialist or group (Ng, 2020).

3 Use Cases of AI

As stated in the previous section that the adoption of AI in SMEs is low, it is possible to look at large enterprises to understand how AI can be used. A survey from Brosset et al. (2019) describe how Bridgestone uses an AI to tune its tire production based upon 480 sensor inputs. It resulted in a 15% more uniformity tire production. Moreover, Nokia implemented a camera surveillance system of the production line, which monitors the production, and if any inconsistency occurs, an operator is alerted. It is not only the manufacturing process AI is used within; Kellogg's has an AI which aids consumers in selecting a recipe they want. Also, logistics and supply chain, along with inventory management, have examples of AI use cases. Some of these use AI to optimise the orders and planning, while also examples of communication with partners with the help of natural language processing.

Charalambous et al. (2019) from McKinsey analytics also published an article where a cement manufacture improved their process. The problem was that the operators had a lot of expertise, and when they went on retirement, it was complicated to replace them with new operators. Therefore they applied AI to control the different processes, and thus the expert knowledge is not lost when an operator retires.

A study from 2021 also showed a use case where an SME wanted to have an *remaining useful life* (RUL) estimation of a critical component (Iftikhar & Nordbjerg, 2022). The study came with different suggestions to SMEs and how to adapt machine learning within their company. The suggestions included the need to join an alliance with non-competing SMEs, consultancies and research institutions in a test-driven environment to enhance the knowledge of the field. Moreover, they also suggested starting with the areas where the problem is solvable and where it is most suitable from a cost perspective.

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5G for Smart Production

Preben Mogensen and Ignacio Rodriguez

Abstract 5G wireless will play a key role in the factories of the future. This chapter provides an overview of 5G technology, and its main features and modes of operation with focus on Smart Production environments. The chapter also discusses the benefits of using 5G as an alternative to Wi-Fi and gives a number of recommendations to SMEs on how to operate 5G from the network, end device, and application points of view. The chapter is concluded with an example of a successful industrial application, exploiting the full potential of 5G: the Edge Cloud-based reliable operation of autonomous mobile robots.

Keywords 5G · IIoT · Smart production · Operation · Integration · Wi-Fi

1 Reliable and Secure 5G Wireless Communication

As today, control of production processes relies on wired Ethernet in those cases where high stability and reliability is required, whereas Wi-Fi is used to provide more flexible connectivity where less stringent reliability is acceptable (Wollschlaeger et al., 2017). It is envisioned that 5G technology will become the "wireless cable", providing performance and reliability like a data cable—but without a cable. Thus, 5G will be capable of bringing the following associated benefits to Smart Production environments:

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- Wireless connectivity for easing enterprise network installations: 5G requires only a few radio access points in the production area to connect the production facilities—as compared to potential km of Ethernet cables if wired.
- Flexibility: with 5G no re-cabling is required when the production layout setup is changed, or new equipment is installed.
- Full mobility support: 5G is essential when it comes to reliable connectivity of mobile production elements such as mobile robots.

5G is the fifth generation of mobile communication systems, currently being deploy massively by public Cellular Service Providers (CSP). Besides offering Enhanced Mobile Broadband services (eMBB), 5G has been designed with simultaneous focus on two additional domains targeting industry vertical use cases: Massive Machine-Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (URLLC). Thus, 5G facilitates lots of new use cases in Smart Production ranging from the massive deployment of Internet-of-Thing (IoT) sensors and the operation of Autonomous Mobile Robots (AMR), to running Augmented and Virtual Reality (XR); connecting everything, and allowing to move Programmable Logic Controller (PLC) intelligence and (mobile) robotic control to the (Edge) Cloud (Rodriguez et al., 2021a).

5G is an open communication specification standardized by the 3rd Generation Partnership Project (3GPP) (Holma et al., 2020). 5G services and features are developed over multiple Releases (Rel.), where the first one, Rel.15, was completed in standardization in 2018 and is being commercially deployed since the end of 2019. The next version, Rel.16 has just been fully stabilized in the standard in the end of 2021. Rel.16 includes a range of additional features dedicated for Industrial IoT (IIoT) and Smart Production, including the support of Time Sensitive Networks (TSN) (5G-ACIA, 2021a). It is expected that Rel.16-capable 5G devices and networks optimized for industrial application are commercially available by 2023. 3GPP is currently working on developing Rel.17, where one of the main features will be the accurate positioning via 5G (Bertenyi, 2021).

In terms of operation, 5G is designed to operate in protected (licensed) frequency spectrum—in contrast with Wi-Fi, which operates in unprotected (unlicensed) spectrum. Operating in licensed spectrum is key to guarantee deterministic reliable performance (Rodriguez et al., 2021a). As a reference, Fig. 1 details the empirical Control-Loop Latency (CLL) performance and Packet Error Rate (PER) of different industrial applications when operated over 4G, 5G, and Wi-Fi, compared to the reference performance achieved over Ethernet. Many European countries have already allocated (or intend to assign) 100 MHz of frequency spectrum for localized 5G networks for industrial use in the frequency range 3.3–4.2 GHz (band n78). 5G also supports much higher frequencies in the mm-wave spectrum, e.g., in the 24–28 GHz range (band n258). Here, 400 MHz (or more) of bandwidth are typically allocated to local 5G networks for industrial use, boosting applications that require extremely high data rates and very low latency (Rappaport et al., 2013). The increased capacity in the mm-wave frequency range comes with the drawback of the need for higher density

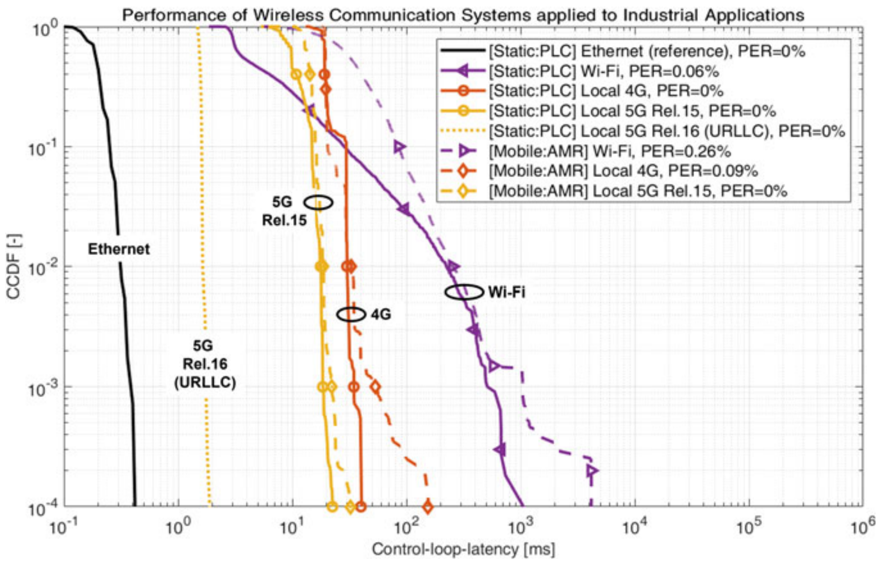

Fig. 1 Empirical Complementary Cumulative Distribution Functions (CCDF) of CLL for the different static (PLC) and mobile (AMR) industrial use cases and technologies (Wi-Fi, 4G and 5G) compared to the Ethernet Baseline. PER for the different combinations is stated in the legend. 5G offers better performance than the other wireless technologies, guaranteeing deterministic low latency at high reliability levels

of 5G radio access points to compensate for the higher wave propagation losses at these frequencies compared to the lower bands.

As part of Rel.16, 5G New Radio-Unlicensed (NR-U) was also specified in the standard. This 5G flavor is designed to operate in the non-licensed spectrum around 5–6 GHz (over the Wi-Fi or extended Wi-Fi bands) (Naik et al., 2020). Operating 5G NR-U on a channel free from Wi-Fi interference, will provide comparable performance to 5G operating in licensed bands. Hence, in many industrial environments, 5G NR-U will also be a very attractive option. Combinations of licensed and unlicensed 5G operation will also possible by means of Carrier Aggregation (CA) (Holma et al., 2020).

5G technology is secure by design. The radio exchange of information via 5G is fully-encrypted and thus, the main security challenges may arise from the integration with the operational industrial networks and equipment. In this respect, a holistic approach should be taken, treating the 5G devices as any other critical industrial network element (5G-ACIA, 2021b).

2 Operating 5G as an SME

Key stake holders in the 5G market are typically, telecom vendors, and CSPs (e.g., mobile operators); but in the near future, we may also see automation system integrators providing 5G industrial networks. Operating a local 5G network requires having dedicated 5G infrastructure (core and radio access network equipment). This might sound complex, but it translates into a one-to-one match to an enterprise Wi-Fi infrastructure including access points and a centralized controller. 5G also requires a frequency license obtained from the official radio spectrum national regulatory body (allowing the use of a specific band at a given location for a fixed period of time). As an alternative, 5G licensed spectrum can be sub-leased from a CSP.

We do not recommend SMEs to build and operate a 5G network on their own unless they have deep insight into the 5G technology. Instead, we suggest SMEs to partner up with CSPs, telecom vendors, or industrial automation integrators who will manage the 5G technology for them. 5G supports by default L3 IP flows, but it does not natively support L2 Ethernet flows. This can be an issue in a brown-field scenario, where L2 connectivity is expected to be provided over 5G. Here, an extra integration step is needed, in order to map the L2 Ethernet traffic to L3 IP by means of a tunneling gateway functionality (Rodriguez et al., 2021b).

The use of 5G terminals for industrial use is expected to become fully plug and play by 2023, when the technology and commercial products have become mature. Already today, in mid-2022, industrial-grade 5G routers are available, but the number of device options and features will keep growing in the coming years. Still, SMEs are encouraged to already start to get prepared for 5G; either as a technology vendor offering products that will need to connect over 5G, or as an industrial end-user that will need to operate production facilities over 5G.

3 Exploiting the Full Potential of 5G for Industrial Applications

5G will allow to re-architecture and optimize industrial applications. As an example, Aalborg University (AAU) has demonstrated, in collaboration with Mobile Industrial Robots (MIR), have worked together in an innovation roadmap and proof-of-concept for 5G AMRs. This roadmap is divided in the two phases depicted in Fig. 2:

1. Basic integration with 5G: in this initial phase, the standard connectivity of the AMR based on Wi-Fi is replaced with 5G.
2. Full exploitation of 5G capabilities: once the basic connectivity is in place, the high-capacity and low-latency of 5G allows for a higher level of innovation, including architectural changes to the industrial application.

In phase 1, the AMR, in its standard mode of operation, is controlled from a centralized Fleet Manager (FM). The FM is used to configure new AMR missions (instruct the robot to navigate from one position to another), and to monitor the progress of the ongoing missions (requesting position updates from the mobile robot every second). When using Wi-Fi for the FM-AMR communication in industrial operational scenarios, a data packet latency of several seconds is not infrequent and, in some cases, it may even exceed 10 s. This is typically caused by mobility of the AMR switching from one to another Wi-Fi access point, in combination with the high load of the Wi-Fi networks. With 5G connectivity, it is possible to ensure bounded latencies well below 100 ms even under mobility and high network load conditions. This makes the MIR fleets of AMRs to operate much more efficient over 5G than over Wi-Fi.

In standard mode of operation, the current MIR AMRs have all sensors, actuators and intelligence for route planning and obstacle avoidance on-board the robot. Software can be updated continuously on the AMRs as long as the on-board computer hardware can timely execute the operation update algorithms. However, with a reliable and fast 5G connection, the most demanding processing on the AMR can be moved to an Edge Cloud computer. This what, in popular terms, we call the "headless robot", was addressed in phase 2. Here, the "brain" is moved away from on-board the AMR to the Edge Cloud. Subsequently, the "Edge brain" is connected to the AMR body sensors (LiDARs, cameras, and proximity sensors) and actuators (motors) by the 5G "nerve system" (Raunholt et al., 2021). The benefits of having 5G "headless robots" are several:

- Reusing Edge Cloud computational power for several AMRs.
- Easing the algorithmic upgrades to, e.g., introducing artificial intelligence, as it only requires hardware/software upgrades at the Edge Cloud, whereas the AMRs remain untouched.
- Making sensor data from all AMRs available at the Edge Cloud, enabling the possibility of having a shared-world representation with common dynamic maps for all AMRs, which can lead to significantly improving the efficiency of operations.

Both phase 1 and 2 were demonstrated at the AAU 5G Smart Production Lab using a local 5G Rel.15 network and devices operating in band n78 with 100 MHz

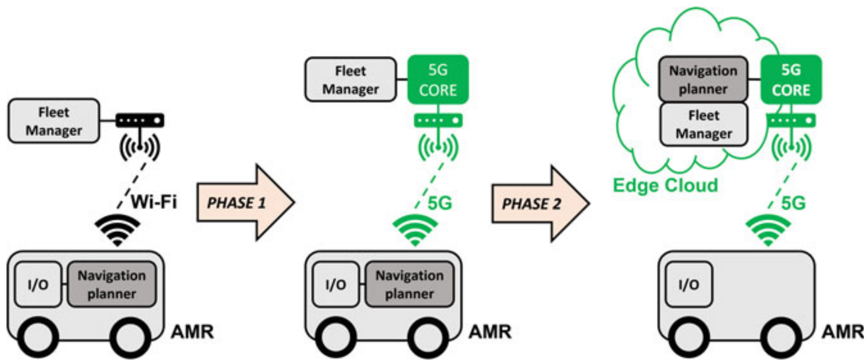

Fig. 2 Overview of a successful 5G AMR innovation roadmap

Fig. 3 Picture of two of the MIR AMRs integrated and operated with 5G technology at the AAU 5G Smart Production Lab, Aalborg University, Denmark

of bandwidth. See Fig. 3 for a visual reference of the implementation. Yet, further degrees of innovation are possible once 5G connectivity is in place and phase 2 is completed. The speed of and AMR is a compromise between efficiency and safety and, currently, MIR AMRs are typically running with a maximum speed of 0.8 m/s to ensure very short breaking distance in case of a person or another obstacle suddenly appearing in their trajectory. The 5G Edge Cloud shared-world will help in those situations where the AMR LiDARs cannot detect sudden obstacles in due time. By tracking positioning of all movable objects and persons in the operational industrial environment, and predicting trajectories, the speed of the AMR can be increased significantly when no potential safety hazard is within range, while the AMR can be slowed down when within range of a potential safety hazard.

4 Summary

5G wireless will play a key role in the factories of the future. Offering high reliability and security, quick installation, high flexibility and mobility support; already with Rel.15 features, local 5G networks are being commercially deployed, as an alternative to Wi-Fi, for basic factory connectivity and initial support of certain industrial applications. In the coming years, when networks will be upgraded with Rel.16 and

Rel.17 features, higher capacity and ultra-low latency performance will be available, which combined with Edge Cloud computing, will allow to fully exploit the 5G capabilities for the control and automation of highly-demanding industrial processes and applications such as cloud PLCs, AMRS or XR. Both the 5G network infrastructure side and 5G user terminal side will exhibit a parallel commercial evolution in terms of available features.

Building, integrating, and operating an industrial 5G network might be a complex task for SMEs (unless they have deep insight into 5G technology) and partnerships with CSPs, telecom vendors, or industrial automation integrators is suggested.

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Information Security: The Cornerstone for Surviving the Digital Wild

Peter Langendörfer, Stephan Kornemann, Wael Alsabbagh, and Erik Hermann

Abstract In this chapter we are discussing the very basics in the sense of how to prepare your company with respect to security. The essential issues are a proper information security governance framework that takes into account the managerial and organizational issues as well as proper technical means. For the latter we introduce network separation as this is one of the prime means to protect your production network from network based attacks.

Keywords Information security · Governance framework · Network separation · Hands on knowledge

1 Introduction

Proper information security (IS)[1] measures are a if not THE cornerstone of being a successful company these days. The importance of IS can hardly be overestimated and will increase in the future. Unfortunately, small and medium-sized enterprises (SMEs) often consider themselves as too small to be attacked, or too unimportant and—due to this wrong self-assessment—do not establish the standard IS hygiene. However, the IS study of the German Bitkom association revealed that in 2021 88% of

[1] In this chapter we use the term *information security* to *cyber security* or *IT security*, since it is broader in scope and also captures physically stored information.

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the companies who answered their questionnaire with less than 100 employees were attacked (Berg, 2021). The percentage of attacked companies attacked grew from 52% in 2017 to 88% in 2021. Thus, SMEs are attracting more and more attackers. In parallel to the increase of the number of attacks, the focus of attacks has broadened. It is no longer only the office IT that is under attack, but more often industrial control systems are targeted. Kaspersky reported that in the first half of 2021 around one third of the industrial control systems (ICS) were targeted by malicious activities (Kaspersky, 2021). According to the Kaspersky report, the main sources of threat in decreasing order are the Internet, removable media, and email attachments. A very recent example of a successful attack against an ICS is the attack against the waterworks in Oldsmar,[2] Florida, USA in 2021. In the last years, prominent attacks include but are not limited to *Havex* (Nelson, 2019), The *BlackEnergy* (Lee et al., 2016), *Triton* (Dudek, 2017), and *Stuxnet* (Chen, 2011).

SMEs' IT and ICS are targeted by attackers, which means that taking IS serious and improving it is of utmost importance. In the remainder of this chapter, focal IS management procedures—as they are essential to any type of company—are illustrated and network separation as a pivotal technical mean to protect the ICS part of the company's network is discussed.

2 Information Security Management

There is a multitude of aspects that has to be taken into account when implementing and maintaining effective and efficient IS measures. If such aspects are not taken seriously, companies can face severe problems (von Solms & von Solms, 2004). Particularly, issues can arise from ignoring that IS is a corporate governance responsibility and governance structures are essential, that IS compliance enforcement and monitoring are decisive, and that IS awareness among employees is crucial. These so-called "deadly sins of information security" (von Solms & von Solms, 2004) cover both organizational (e.g., governance) and personal factors (e.g., employees' compliance with rules). Particularly, IS governance is central to effective IS management. It consists of "the management commitment and leadership, organizational structures, user awareness and commitment, policies, procedures, processes, technologies and compliance enforcement mechanisms to ensure that the confidentiality, integrity and availability (CIA) of the company's electronic assets [...] are maintained at all times" (von Solms, 2005, 444). Figure 1 illustrates an exemplary IS governance framework that comprises the dimensions mentioned above. This chapter will focus on the intertwined dimensions of leadership and employees (i.e., IS policy and compliance, and security education, training and awareness; SETA) and network separation as an example of the technical sphere.

[2] https://www.nytimes.com/2021/02/08/us/oldsmar-florida-water-supply-hack.html.

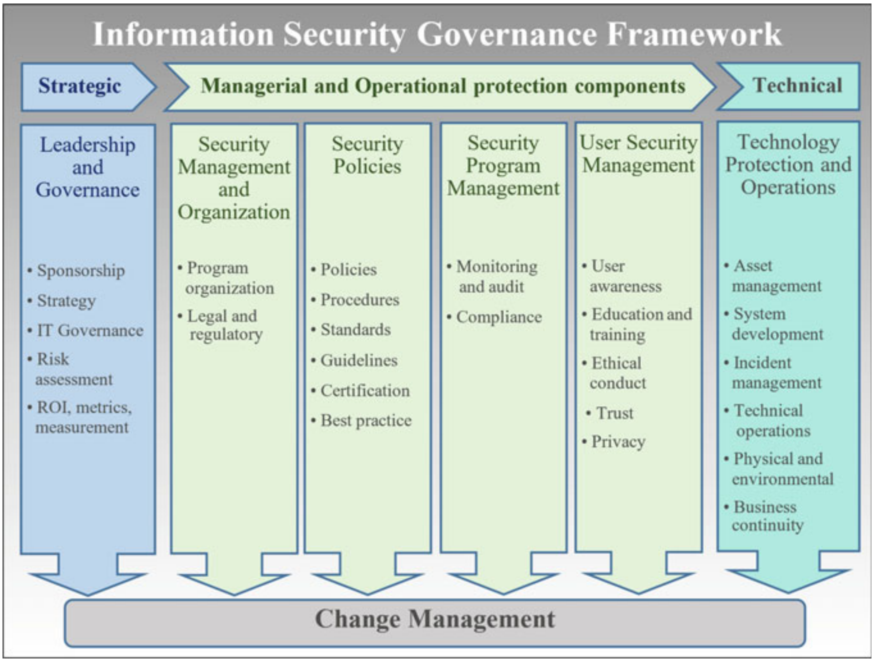

Fig. 1 IS governance framework (based on Da Veiga & Eloff, 2007)

2.1 Leadership Perspective

Leadership is one of the most decisive elements in IS. More precisely, leadership is necessary to establish IS and increase its effectiveness; leadership commitment and involvement improve security measures and affect employees' compliance attitudes, intentions, and behavior (Paliszkiewicz, 2019). Generally, leaders have to realize that employees are "the most important and the weakest part of information security systems" (Paliszkiewicz, 2019, 212).

2.2 Employee Perspective

As the folk saying goes, the greatest IS problem is between the keyboard and the chair. In other words, employees can compromise IS through deliberate activities or through "passive noncompliance with security policies, laziness, sloppiness, poor training, or lack of motivation to vigorously protect the integrity and privacy of the sensitive information of the organization and its partners, clients, customers, and others" (Warkentin & Willison, 2008, 102). Thus, employees are sometimes referred to as "insider threat" or "endpoint security problem" (Warkentin & Willison, 2008).

A focal factor shaping IS compliance is IS awareness, that is, focus of users' attention on security (Hwang et al., 2021). That is, employees have to be aware of IS measures, rules, policies and threats in order to comply with rules. Moreover, (1) the perceived usefulness and benefits of IS policies and rules, (2) employees' perception of being able to comply, and (3) the perceived likelihood of being detected or punished in the case of noncompliance determine whether employees comply (Cram et al., 2019). Conversely, too complex and/or comprehensive IS rules can overwhelm employees, cause stress, and eventually undermine compliance (D'Arcy et al., 2014). In order to raise awareness for IS and empower employees, companies can make use of SETA programs (D'Arcy et al., 2009). As training formats and frequency should be adapted to company and employee requirements, so should be the respective IS-related communication and messages (Johnston et al., 2019). In addition to IS awareness, keeping different entities of a company separate helps to embank effects of attacks.

2.3 Technical Perspective: Network Separation

In many companies the computer network and the ICS network have grown rather naturally over the years, leading to a more or less tight integration of both. The threats associated with this approach as well as countermeasures are often unknown because they exceed basic IT knowledge. Separating the ICS from the office network is considered to be the most important and essentially required IS means for ICS (Homeland, 2016). Potential means to separate the networks are virtual LANs (VLANs) and are Demilitarized Zones (DMZs). VLANs divide physical networks into smaller logical networks limiting broadcast traffic and allowing logical subnets to span multiple physical locations. DMZs are controlling the network traffic between the different zones using firewalls to prevent malicious traffic from reaching the protected network. They should be established between the company network and the Internet to protect the company network and between the office network and the ICS. The security can be further enhanced by enforcing that communication may be initialized only from the ICS to the office network.

2.4 Providing Hands-On Experience

In order to improve the needed skills, a hybrid training system (see Fig. 2) was developed. In the lower left hand corner, a fischertechnik® training factory is shown. It consists of industrial modules that comprise a factory floor. The entire factory is controlled by a SIMATIC S7-1500 PLC. The PLC connects to a so-called Robotics TXT controller via Internet of Thing (IoT) gateway. The TXT controller serves as a Message Queuing Telemetry Transport (MQTT) broker and interface to the fischertechnik® cloud. Although the factory is just a starting point, it is controlled

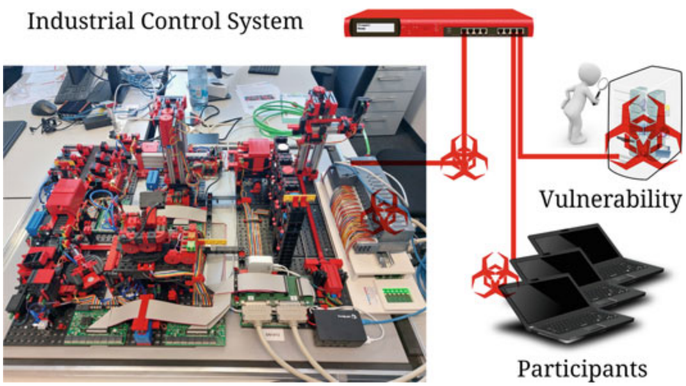

Fig. 2 Hybrid training system

by state-of-the-art devices to be found in real-world settings. This training system was successfully used to instruct SMEs in Germany in order to give them a "hands-on-experience" on how appropriate countermeasures can be implemented in real corporate networks. The training course consists of the following steps:

1. Raising participant's awareness of threats within non-segmented corporate networks.
2. Learn how to identify network components using the Nmap network scanner
3. Perform a vulnerability assessment with the open source software OpenVAS
4. Learn methods for network segmentation
5. Perform a network segmentation with virtual LANs (VLANs)
6. Check the achieved level of security.

The participants will learn how to analyze the corporate network using the Nmap (Lyon et al., 2008) and how to find critical vulnerabilities using the OpenVAS vulnerability assessment scanner (Aksu et al., 2019). A non-updated server was placed in the examined corporate network, which has countless security-critical vulnerabilities, so that root rights can be obtained. Thus, further attacks (e.g., on the ICS) can be carried out from this server. In the next steps, participants will learn how to use segmentation to protect the ICS. In this training, virtual networks (VLAN) are introduced as a means for segmentation. Each participant receives a manageable network switch, an office computer and a computer for accessing the ICS. Then two VLAN are defined. All office computers are placed in the first VLAN and all control computers in the second. The communication between the VLANs is restricted by firewall rules. The participants can now check whether their configurations are correct.

3 Conclusion

Achieving 100% IS almost infeasible, but with the relatively easy to realize basic means such as IS awareness or network separation, the risk to be affected by an attack can be minimized. The former will help to prevent being infected by unintended but careless actions such as opening suspicious email attachments, while the latter increases the burden for attacks to infect the ICS and also helps to embank the effects when being infected.

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Digital Twins: Making It Feasible for SMEs

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Abstract Digital Twin recently became one of the key enablers of Smart Manufacturing. Although several architectures are currently available to support digital twin design, implementation, use, and assessment, most of such procedures are not adapted to the reality of small and medium enterprises. In this chapter, we provide a solid foundation to support SMEs toward adopting digital twins while exemplifying the implementation procedure with two use cases in manufacturing industries.

Keywords Digital twin · SME · Smart manufacturing · Digital manufacturing · Simulation

1 Introduction to Digital Twins

In the past, due to the lack of information technologies, the physical space was the only way to control the shop floors. However, with the emergence of new IT technologies, Digital Twin (DT) became one of the key enablers of Smart Manufacturing (Semeraro et al., 2021). Digital Twin is a dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behaviour, life, and performance in a timely fashion (Zhuang et al., 2018). Therefore, the acquisition and use of this virtual counterpart allow organisations to refrain from wasting physical resources during design-related tasks, as well as diagnostic and predictive analyses (de Oliveira Hansen et al., 2021; Grieves, 2014).

The idea that a digital equivalent to a physical system could be created through the sharing of information and data was primarily introduced by Michael Grieves under the concept of 'digital twin' in 2003 (Assad Neto et al., 2021). After the initial formulation, and subsequent incubation phase, from 2015 onwards DT has

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entered a stage of continuous growth and adoption, with research efforts focused on developing its technological architecture, as well as key IT providers focused on developing platforms to offer its capabilities as a service to early adopters in industry (Neto et al., 2020; Tao et al., 2019).

The digital twin application is supported by a technological architecture, which is generally composed of 5 layers (Tao & Zhang, 2017). A physical layer comprises the physical entities in the shop floor, as well as the sensoring structure utilised to gather operational status indicators from these entities. A digital model layer comprises the virtual models built to replicate behavioural aspects of the physical entities. A service layer comprises the analytics that provides stakeholders with a plethora of monitoring, diagnostic, predictive, and prescriptive services. A data layer comprises the storage of all data utilised or created by the digital twin operation. Lastly, an information layer comprises the timely data transmission between all layers as the digital twin operates.

On the foundations of this architecture, the DT operation process consists of employing the sensoring and data transmission structures to continuously update the parameters of the developed digital models. Subsequently, the outputs of the digital models, in conjunction with the deployment of analytics, can be utilised to provide an array of insights that support managerial decision-making (Neto et al., 2020). Four main types of services are allowed, which depends on the DT scope: **Monitoring services** encompass the use of models to better track the status of aspects such as production schedules, machines' health, or the quality of the production process; **Diagnostic services** encompass providing a better comprehension of machine faults or process quality deviations, through the lens of the digital models; **Predictive services** encompass the use of behavioural models to predict the future state of physical entities of the shop floor, such as machines' health or the production system's expected load; and, **Prescriptive services** encompass the usage of future-state insights, obtained from the behavioural models, to support active decision-making dilemmas of operation managers, such as dynamically determining the scheduling of production jobs given flexibility requirements.

After a conceptualisation phase, and the arrangement of information and communication technologies into a general DT architecture and early applications, the DT technology has entered a more procedural maturity stage, in which studies are focusing on developing processes and technical standards, as well as ideal software tools, to systematically guide organisations with regards to the digital twin design, implementation, use, and performance assessment (Leng et al., 2021; Tao et al., 2019).

Currently, several companies provide technology to develop, control and use DT in manufacturing. Among the most important are GE, Siemens, IBM, Cisco Systems, Ansys, PTC, Oracle, and Dassault Systèmes.

2 Implications for SMEs

Generally, DT provides several benefits throughout all lifecycle stages, allowing experimentation in a risk-free environment for data-driven decision-making. This is because the experiments and optimisation approaches can be applied to the digital equivalent without influencing the physical counterpart. Furthermore, more data can be acquired after the DT deployment, which provides a solid foundation for performing the up-to-date experiments and decision-making related to the DT purpose, supporting continuous improvement.

Even though the value of implementing DT is clear, certain barriers for implementation and operation need to be addressed to reach that potential. The first key barrier is the development of a digital equivalent and ensuring it represents the physical equivalent sufficiently. Typically, off-the-shelf simulation solutions are applied due to availability, support, training options, etc. These simulation solutions rarely cover all aspects of specific use cases, and therefore compromises have to be made, either by developing the digital model from scratch or accepting that certain aspects are not covered in the digital entity. Hence, clearly defining the DT purpose and scope is critical to determine the variable(s) to be controlled. This is especially challenging for SMEs because additional complexity means that more data must be collected, processed, and analysed, making many projects too complex to manage. Therefore, clearly defining the objective and scope is crucial. The second critical barrier for SMEs is that we still face a lack of standardised format for data exchange. In short, this means it is crucial to select the right tools and guarantee interoperability from the beginning since data exchange between competing digital solutions is complex and often incomplete. That relates to the third barrier, which is ensuring an uninterrupted stream of verified and validated data between the physical and digital equivalent. Note that the quality of the data determines the decisions in the digital equivalent, which later is transferred to the physical equivalent.

Therefore, to successfully implement DT, certain competencies are beneficial to increase the success rate and lower the resources needed for implementation. Among the most important, competencies within (a) simulation, (b) sensoring the physical system, (c) the data stream, and (d) management of such projects, are generally needed to ensure efficient development and implementation. Furthermore, it is crucial that all team members thoroughly understand how the system works to ease intraorganizational communication. Typically, the competencies are represented through specialists in the company, although cross-disciplinary skills are beneficial to strengthen system understanding. Finally, it is essential to highlight that when the DT transitions from development to operation and maintenance, the future success depends on how well the competencies to operate and maintain the solution are transferred.

In a nutshell, a typical process for DT development starts with a clear definition of the purpose (e.g. production scheduling, maintenance) and scope (e.g. equipment, cell, line), which will directly influence the selection of appropriate solution(s). With the scope and solutions defined, the digital equivalent modelling starts, as well as the sensoring of the physical system for data collection. The next step is to guarantee the data stream between the physical and digital equivalents. Note that, when this connection is established, it is crucial to create procedures for verifying and validating the data between the two equivalents, since the value of DT remains on this data quality. With that in place, near real-time experimentation can now be performed for data-driven decision-making.

3 Examples of Digital Twins

In manufacturing systems, DT shows great potential to optimise and improve both greenfield and brownfield productions. In this session, we present two short examples with different purposes, scopes, and tools to illustrate how DT can be used in different ways.

3.1 Example 1: Digital Twin for Matrix Production

In the following real application example, we highlight the values of DT in developing and optimising a cell manufacturing setup, although the benefits can easily be transferred to the design and implementation of other manufacturing systems. The main focus of having a DT was first, in the design phase, to develop experiments and reliably evaluate different solutions without any material costs, and second, in the operations phase, continuously optimise the operations based on the current production needs and status.

In the design phase, in the risk-free environment, a reliable digital equivalent developed in Visual Components, and Siemens Tecnomatix Plant Simulation for the operations phase, enabled experimenting to optimise several aspects of the cell, such as the robot's reach, tool integration, development of the system controllers and similar. Later, with the physical equivalent connected through the data stream, in this case, OPC UA, a second benefit was achieved in the operations phase. The data initially applied in the digital equivalent is now verified and validated, thus ensuring the digital equivalent is as close to reality as possible. It is important to highlight that, in this specific case, the OPC UA functionality was a selection criterion determining the simulation software used to develop the digital equivalent, since that would guarantee the needed data stream.

The data from the physical equivalent increased visibility and transparency, thus highlighting how improvements would directly influence performance. For instance, identifying the bottlenecks that resulted in low utilisation rates and inefficient material flow. This also led to a greater understanding of how dependent variables are connected at a much earlier stage. This increased the system's understanding and enabled a more resource-efficient approach to find and correct errors in the physical equivalent.

All in all, DT played a central role in the development phase, supporting continuous improvement for the cell and manufacturing system based on valid and verified data from the physical equivalent. In the operations phase, the DT provided greater visibility and transparency, leading to a better understanding of the dependent variables in both the cell and manufacturing system, which supported achieving the expected results earlier. Besides, with the up-to-date data stream, the impact on optimisation decisions can now be monitored directly on the key performance indicators.

3.2 Example 2: Digital Twin for Preventive Maintenance Scheduling

In the following real application example, we highlight how a DT supports decision-making within the context of maintenance management. To illustrate this application context, we may consider the existence of a production system in which preventive maintenance interventions are periodically performed to prevent machines' failures and breakdowns. Since these interventions generally cause a loss of production throughput due to the necessity of machine shutdowns, the capacity of predicting when machines become idle—as a result of natural flow unbalances or any other source of disturbances—is valuable, as it enables interventions to be scheduled with a minimal level of throughput penalty. The concept of the DT can be employed to provide such a solution, since a process behaviour model of the shop floor can be created, so that short-term simulations of the flow of production are executed and idle time slots are identified.

To deliver such an application, a discrete-event simulation model of the shop floor was created using the Python 3.6 programming language. Virtual objects were created to represent both the machines and the buffers along with the manufacturing systems. To ensure its updated status, the digital model was connected to a near real-time data stream connected to three data sources: (i) the latest production planning data was utilised to parametrise the discrete-event simulations; (ii) industrial engineering data was utilised to update machines' cycle time and setup parameters; and (iii) RFID sensoring structure was utilised to track the position of work-in-process pieces' in the shop floor.

Upon request, a short-term simulation of the updated digital model can be executed. Based on the results of these simulations, time slots in which machines were expected to be idle could be identified, leading managers towards a preventive maintenance schedule that minimally impacts production throughput.

4 Conclusion

Digital Twin enables experimentation in a risk-free environment for data-driven decision-making, allowing different services and business opportunities. However, ensuring data quality is critical to guarantee a valuable model and accurate results. Therefore, a new set of tools, processes, and technical standards are emerging to facilitate DT implementation by companies. This is critical for enabling SMEs to react faster to market changes and follow the industry's growth.

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Augmented Reality: Increasing Availability and Its Implication for SMEs

Vadym Bilous, Ronny Porsch, and Konstantinos Spanoudakis

Abstract The Augmented reality (**AR**) technologies have been first discovered in the third quarter of the twentieth century. However, the wider development of them has taken place only in the last two decades. By now, the research has shown that AR can be used in various areas of human activity. In industry, AR simplifies human-machine communication and improves human-machine interfaces (**HMI**) for fast and feedback-provided retrieval of training/guidance information for operation pattern study, error correction, machine maintenance, assembly assistance, etc. In spite of that, the broad practical implementation of AR in industry, including small and medium-sized enterprises (**SMEs**), has faced considerable problems. As a result, the following controversy emerged: the comprehensive study of AR is combined with a rather narrow practical use primarily for advertising and demonstration tasks. This chapter attempts not only to overview the current state of AR in the industry, but also demonstrate the current challenges the AR is facing, as well as to analyse their respective causes and suggest solution ideas. It is also intended to assess the prospects for further development of AR and its continued integration into the industry. For this purpose, several examples of AR projects, their development, practical use and upgrading (performed by the authors of this study as well) are presented.

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1 Introduction

Augmented reality (**AR**) is an interactive experience of a real-world environment that involves overlaying computer-generated visual, auditory, or other sensory information onto the real world in order to enhance it. Augmented reality offers the possibility to highlight real-world features, visualize information for audio features, relevant or expert knowledge (Ciupe et al., 2020; Glover & Linowes, 2019).

Nowadays, implementing AR is mostly a matter of software, as the hardware technology is already commercially available. There are numerous examples of AR usage in a large variety of areas (Cranmer et al., 2020; Yeung et al., 2021; Rosales et al., 2021). There is an established ecosystem of AR application development environments that creators can access (Glover & Linowes, 2019). AR is already available on more than 700 million devices with the arrival of ARKit and ARCore, not to mention third-party apps, and lastly, a considerable number of users have already used some form of AR, supporting the consumer readiness (Lizano, 2019).

However, the level of the integration of such technology seems to be hugely limited in terms of applications related to real-time production (Jalo et al., 2021). This chapter is aimed at the detailed study of the controversy between the respective issue and the evident advantages of AR for the small and medium size enterprises (**SMEs**), the maturity and widespread approval of it according to the formal metrics (Gartner Hype Cycle) and high consumer interest. The work is also going to present the possible causes of the phenomenon mentioned above, as well as support the discussion with relevant examples and the suggestions for future work in the overviewed research area.

2 AR in SMEs—Benefits

There are various reasons why an SME could profit from the use of AR technology. Cost reduction is one of the major advantages enabled by a mobile collaborative AR technology or any similar concept introduced into the production process. Cost reduction primarily derives from the reduction of traveling time and expenses for deploying, instructing, and supporting field service technicians, trainers, specialists, and other business-related staff (Anshari & Almunawar, 2021; Bottani & Vignali, 2019). Another major, non-production-related benefit of AR is the use of the technology in marketing, advertisement, and customer communication, increasing the overall consumer satisfaction, withstanding competitive pressure, and broadening the sales network (Chaffey, 2016; Masood & Egger, 2019). Moreover, AR can be used to relay essential information directly to the user considering any action happening in his/her closest environment. As a result, it leads to reducing the time spent by engineers, technicians, or maintenance staff referring to manuals, thus diminishing the service time, number of human-injected critical and acute errors, and the pressure on service employees (Bilous et al., 2022).

Despite seemingly offering a considerable spectrum of profitable features to the SMEs, the AR technologies still experience a lack of integration into the real industrial processes. There are many methods to represent the maturity, adoption, and social application of specific technologies, for example a so-called method of technology readiness levels (**TRLs**) (Héder, 2017). However, the implementation of a new technology in industry requires more than just technical assessment. For example, the economic and promotional components are essential. That is why comprehensive evaluation methods are required to assess the AR technology from this particular perspective. One of the most popular evaluation patterns is the so-called Gartner Hype Cycle (**GHC**) developed and patented by Gartner, Inc (Steinert & Leifer, 2010). According to this evaluation method, there are five key phases of a technology's life cycle, which represent the complex state of the technology and the attitudes of developers, investors and the public towards it.

Concerning the GHC results for AR, it rapidly reached a state of maturity, much earlier than experts expected. Steadily climbing up the GHC in the last years, AR slid down in 2018, and in 2019 it was not considered anymore an "emerging" technology (Bit, 2019; Herdina, 2020), but it had graduated as a mature one. The GHC did not include AR after 2020. This means AR has theoretically reached maturity and became an industry-proofed technology that can be safely invested into. However, the theoretical possibility of broad implementation of AR in the industry, in particular in SMEs, is still poorly realised in practice (Jalo et al., 2021; Anshari & Almunawar, 2021). This is highlighted by a number of problems and challenges concerning AR technologies and their wide implementation in industry, which have already been reported (Jalo et al., 2021; Anshari & Almunawar, 2021; Bilous et al., 2022; Berger et al., 2016). This issues are described and structured in the following section.

3 AR Implementation—Current Problems and Challenges

One of the main problems with AR technologies is the complexity of the field, which includes more than just software and hardware, but rather an extended spectrum of the scientific, industrial, and social aspects (Glover & Linowes, 2019; Jalo et al., 2021). In contrast, AR is widely regarded as only an overlay of the virtual information over the real world, therefore, seemingly completely excluding the knowledge background (Ciupe et al., 2020). The practical applications show that this assessment is true for simple training and demonstration tasks. However, once AR goes beyond these boundaries, the technology experiences the following challenges.

Implementation and adaptation issues. An innovative organizational culture is required for the development and for the adaptation of AR products in the SME industrial processes (Jalo et al., 2021). Furthermore, testing and integration of AR applications into the industrial environment of companies requires the flexibility of staff and their willingness to continuously exchange work experience (Jalo et al., 2021; Bottani & Vignali, 2019). At the same time, AR research continues apace and, consequently, requires constant tracking of new development examples, projects and concepts in the field. Therefore, the demand for constant communication within the developer community is rising (Jalo et al., 2021; Glover & Linowes, 2019).

Technical (hardware and software) problems. The problem of data transfer between industrial environment (for example, programmable logic controllers, **PLCs**) and AR hardware is getting even more complex if the solution has to be scalable, i.e., effective not only for one unit, but also for several ones (Berger et al., 2016; Bilous et al., 2022). Moreover, the problem of User Activity Indication (two-way communication between personal and industrial environment) requires the ability to identify each user interaction with the industrial plant. A large number of additional sensors is required as a result (Bilous et al., 2022). Importantly, in the automation industry, new plants (an alteration in the overall construction, number and quantity of components, adjusted plant part positioning, etc.) appear to make a visible difference in the maintenance, operation process, and development environment. The creation of an application for a novel unit tends to become a task "from scratch" considerably fast. However, not many articles are dedicated to solving this problem now (Um et al., 2018).

4 Examples

Assembly, Repair and Maintenance. The introduction of AR into the field of maintenance tends to improve the process safety, reduces operator/assembly worker confusion, and withdraws the extra pressure from engineers to require expert knowledge in a wide variety of technologies and infrastructures. An example of using the AR assistant for assembly of plants' components is shown on the Fig. 1. It should be noted that the usage of AR as an assistant system for the assembly, repair and maintenance tasks is currently implemented in mostly large companies. For example, DIOTA has developed such a system for Rolls-Royce (Ababsa, 2020), which uses an AR application to assist the maintenance of jet engines.

In assembly tasks, AR technologies provide more reduction of human error rates rather than shortening of completion times. A good related example is presented in the work of Uva et al. (2018). The results outlined the improvement of the operators' performance in a seven-task maintenance procedure on a motorbike with respect to the paper manual study as a control group case, and the level of user acceptance of the new concept showed a certain increase.

In the context of the project **RepAIreality**, some of the authors of this study are currently implementing an AR-powered assistance solution for railway carriage technical management with their project partner Zedas. The proposed solution is meant to support workers while they are doing maintenance or repair work on railway carriages. To achieve this, important information is being presented to them via either a tablet or smart glasses. Using this approach together with digital work instructions, inexperienced workers can be enabled to perform the tasks that they are not yet familiar with faster (Koteleva et al., 2021). It would also be conceivable to develop an adjusted version for other kinds of repair or maintenance work, so that a greater number of SMEs could profit from the presented AR approach.

Improving Human–Machine Interaction and Error Correction. To illustrate the practical use of augmented reality in an industrial environment with the goal of improved machine-human interaction, the chair of Automation of Brandenburg Technical University of Cottbus - Senftenberg developed a model of a laboratory facility to showcase the usage of AR in machinery debugging and correcting errors by non-expert users (Fig. 2) (Bilous et al., 2022).

The developed AR application was tested on a large user number (more than 100 respondents for the first version of the application and 30 respondents for the second version), and the experimental results showed that 100% of testers were able to fulfil the service requirements in the laboratory unit for the first time in an error situation.

User Manual. In 2015, Hyundai became the first mainstream car manufacturer to introduce AR user manuals (Halim, 2018). Consumers received instructions for repair, maintenance, and vehicle equipment guidelines via their smartphones or tablets.

The example of Hyundai seems to have demonstrated that inexperienced individuals are able to exploit the AR overlays with step-by-step instructions to identify problems and perform machinery repair without expert assistance. It should be noted that such user ability is also important for SMEs, as far as it greatly reduces the work of the customer support department, increases customer satisfaction and may profitably influence the future product purchase.

Fig. 1 Example of using the AR assistant for assembly of the plants' components

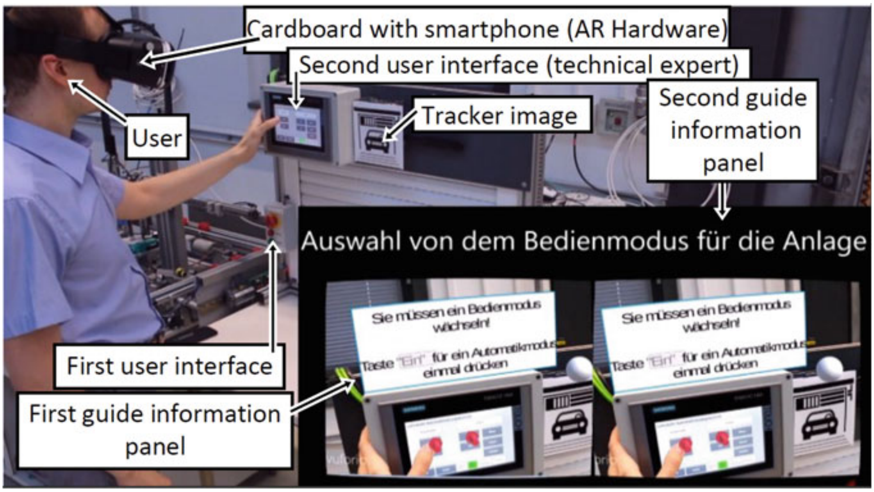

Fig. 2 Laboratory unit (small doors) and all AR elements (Bilous et al., 2022)

Marketing and advertisement. Considering this particular field, SMEs might clearly take advantage of the AR technologies to create unique user experience and strengthen the own brand. Regarding the currently available research and industry examples in this field, the company Theia Interactive has recently created the AR app to provide a virtual shopping experience that allows customers to experiment with different shapes, seats, lights and other options to achieve a truly custom bike design (Bosset, 2018). It should be noted that such customer AR applications are quite easy to develop, since they do not require active data exchange with, for example, laboratory units or industrial plants. The authors of the current chapter suggest that the combination of easy creation process support and captivating demonstration effects tends to make the increase of AR technology usage in this area particularly attractive to SMEs.

5 Conclusion

The further development of AR and the introduction of AR technologies in the field of SMEs appears to be prominent in the following categories:

Hardware. The solutions available on the market are already adequate to launch rather large (in terms of hardware requirements) AR applications. If the demand for the AR does not decrease, it is logical to expect a gradual reduction in the price of technical support devices. At the same time, a radical change in the design of AR hardware might not be the primary idea to expect in the next ten to fifteen years.

Software. The further development of modular solutions may be applicable in this field, both regarding commercial and freeware areas. It is possible that semi-automated and automated AR application generation projects will be started, but the authors of this article, based on their experience and analysis of current projects, anticipate that such projects will be purely scientific for a relatively long time.

Implementation and modifications of the AR applications. If the interest in AR for SMEs remains sufficiently high for a prolonged period of time, the community of both AR application developers and firms creating environments for their development/template packages for these environments will possibly expand. Nowadays, this has been already observed in physical engines. In this way, one can hope to create a similar database for new AR applications with the necessary AR element templates, program scripts, etc. Further progress in this direction may allow to build new AR applications literally in hours.

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Additive Manufacturing

Jeppe Byskov and Nikolaj Vedel-Smith

Abstract Additive Manufacturing is an extremely promising technology, and we see a dramatic increase in organizations utilizing the technology. Previously it was mainly used for prototyping but today the focus is on using it for serial production. In this paper we provide a short introduction to the Additive Manufacturing technologies and underlying processes, we discuss how the technology creates value in SMEs, and provide a few examples on how Danish companies have utilized Additive Manufacturing to produce high value components with increased performance.

Keywords Additive manufacturing · 3D printing · Industry 4.0

1 General Introduction to Additive Manufacturing

Additive Manufacturing (AM) is, as the name indicates, an additive process where material is added to form the final product. It is often used interchangeably with the term 3D printing. It was developed in the 1980s and until recently primarily used as a prototyping technology. Being a digital manufacturing process where individual parts could be made in a very short time and with no tools needed it quickly proved a valuable method for product development and prototyping.

Additive Manufacturing is a collective term for a wide range of technologies operating in very different ways and in many different material types as shown in Fig. 1. For a nice overview article on polymer 3D printing materials and technologies see Dizon et al. (2018).

In recent years AM is labelled one of the cornerstones in the Industry 4.0 framework and the major interest and development is within the field of AM for final part production. Many of the technologies are now at a level where price, quality

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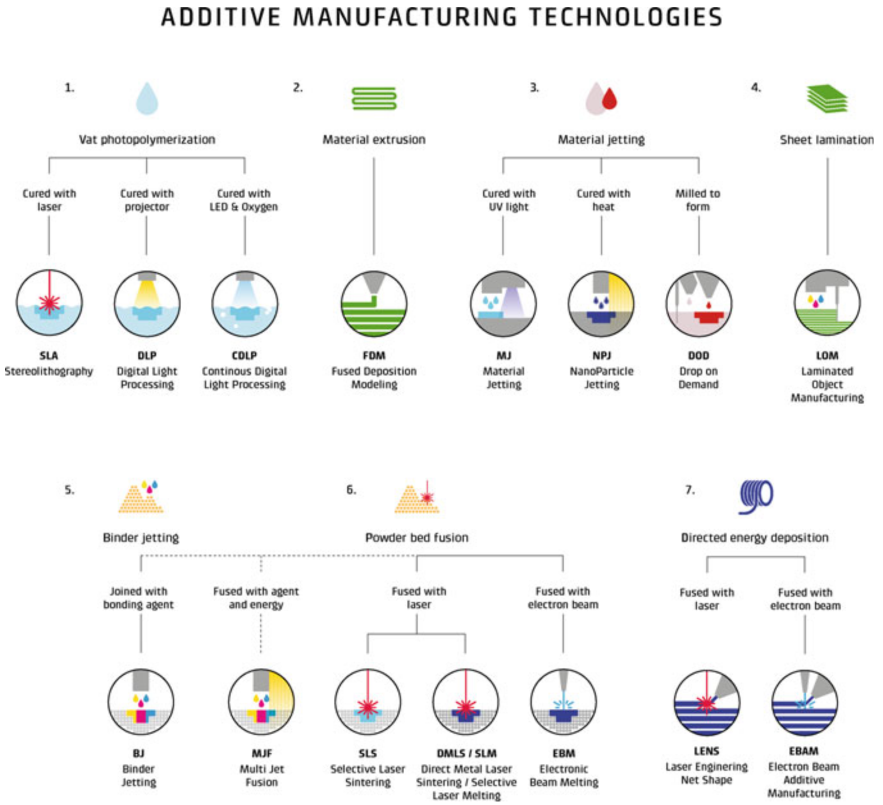

Fig. 1 An overview of the major additive manufacturing technologies in 2022

and performance make it more competitive than traditional manufacturing—even in product series of hundreds of thousands.

Over the past 10 years the marked has grown significantly from approximately 1 billion dollars in 2010 to approximately 15 billion dollars in 2021 (Wohlers, 2022). The development and growth have been headed by large industrial companies within the automotive, aeronautics, and medical sectors—but in recent years as the technology has become more industrialized, many more sectors, including consumer products, contributing to the growth.

For a more elaborate discussion of Additive Manufacturing and its role in the fourth industrial revolution please see Manjaiah et al. (2021).

2 Implications for SMEs

Additive Manufacturing creates value mainly in manufacturing companies where it enables manufacturing of better performing parts along with an often simpler and more robust supply chain. Since AM provides the product designers with ultimate geometrical freedom it enables "Design for Functionality" instead of "Design for Manufacturing"—i.e., the real value is created when companies use the benefits of AM to create innovative products. Furthermore, AM can dramatically reduce the time-to-marked which is important in modern flexible production. Most significantly creating value in the earlier production phases like product development, ramp-up and pilot-production where you can get products quickly on the marked and get feedback and revenue without big investments in equipment and tools.

A distinction is often made between "Desktop 3D printers" and "Industrial 3D printers".

Desktop 3D printer are relatively inexpensive and easy to operate. They are often of the type "Material Extrusion" widely known as "Fused Deposition Modelling (FDM)" or "Digital Light Processing (DLP)" which is a subcategory of "Vat Photopolymerization" costing as low as a few hundred Euros. In 2020 more than 750,000 desktop 3D printers were sold worldwide. They can be purchased online and in many hardware stores.

Industrial 3D printers are more to be compared to traditional manufacturing systems like CNC machines. They are more expensive and more difficult to operate—but provides better quality and are more suitable for tooling and production whereas the desktop 3D printers are mainly for prototyping. The industrial 3D printers include types like "Laser Powder Bed Fusion (L-PBF)" where the subcategory "Selective Laser Sintering (SLS)" suitable for series production of polymer parts and "Selective Laser Melting (SLM)" or "Direct Metal Laser Melting (DMLM)" is suitable for series production of metal parts.

An often-used recommendation is to start with desktop 3D printers as they are easy and inexpensive—but at the same time partnering with a provider of industrial 3D printers to start building competencies on the industrial systems.

Many Research and Technology Organizations and commercial players, including the machine vendors, provide services to get started and to acquire the needed competencies. Basic competences needed include:

- **Design for AM (DfAM)**: Needed to design components that take advantage of the benefits offered by the technology
- **AM Technologies**: Needed to choose the right AM technology for the right application
- **AM economy**: Needed to assess the value creating with AM and to build business cases

3 Examples

Numerous good examples of AM within a wide range of industries could be presented here. Most often examples are shown from the aeronautics and automotive industries where light-weighting and optimized performance provides excellent business cases (BMW, 2019; GE, 2018).

However, the potential may be even bigger when looking at more mainstream applications and it is estimated that AM can generate value in all market segments.

The big Danish company Danfoss is a good example of a strategic approach to implementing AM. As a part of their digitization AM was identified as a focus area and a business unit was setup to implement the technology throughout the organization. DfAM was taught to many development engineers and a central AM center was setup to handle requests from the whole organization. Some technologies were purchased for in house use while other technologies were sourced to close collaborators.

A specific example from Danfoss is the “Stator assembly tool” shown in Fig. 2.

Using AM, the weight of the component was reduced from 1100 g to 382 g—a significant benefit since the tool is lifted by an operator approximately 180 times per day. The material was changed from Aluminium to titanium making it 5 times more

Manufacturing Method	Lead Time (days)	Cost (Euro)
Conventional (CNC)	31 days	750€/pcs
Additive Manufacturing	14 days	1375€/pcs (lasts 4-5x longer)
Savings	17 days	1625€/pcs

Fig. 2 “Stator assembly tool” from Danfoss. Left = Original part; Right = AM part; Bottom = Business case compared with traditional

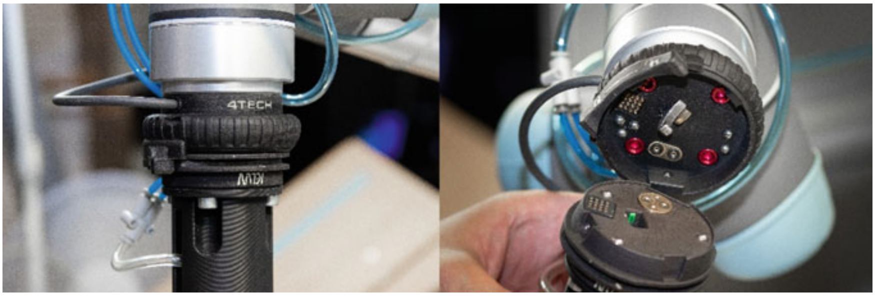

Fig. 3 "Tool changer" from 4tech. Left = AM part fitted on a Universal Robot; Right = disassembled AM part showing complex and flexible internal structure

durable and in this way the price per year of the component was decreased by 63% (Byskov, 2021).

The specific tool is not produced in large quantities. However, Danfoss has a very large number of similar tools where AM is equally beneficial and thus there is great potential for a large-scale production of tools.

The Danish SME 4Tech is a great example for a small company using AM throughout the product development. The company specializes in tools for automation equipment, and we see a beautiful fit between the flexibility inherent in the AM technologies and the need to customized solutions within automation processes (Nielsen, 2020). The tool changer was originally 3D printed in polymer as shown in Fig. 3 and then subsequently the production material changed to Aluminium to obtain higher strength whilst keeping weight low.

4 Summary

Additive Manufacturing is an extremely promising technology, and we see a dramatic increase in organizations utilizing the technology. Previously it was mainly used for prototyping but today the focus is on using it for serial production. The development is going very fast and new materials and processes are arising monthly. Barriers preventing a more widespread use are rapidly being broken down, and where it was previously mainly used in high value applications within the automotive, aeronautics and medical industry we now see widespread use within the mainstream manufacturing industry.

For further reading see e.g. https://www.dti.dk/specialists/additive-manufacturing/40479, https://www.hubs.com/knowledge-base/ and https://www.3ders.org/3d-printing-basics.html.

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Collaborative Robots for Smart Production in SMEs

Daniel Díez Álvarez and Lars Væhrens

Abstract On the road to smart factories, industrial digitization, automation, and flexible production play a key role when it comes to fulfilling customer demands. In terms of customization and wide catalogue and continuous evolution of products, what derives in small batch production and requires fast adaptation. This is especially challenging for Small and medium-sized enterprises (SMEs), where automation is significantly more difficult and reconfiguration is a challenge in terms of cost and effort penalizing efficiency. Collaborative robots, specifically designed to be deployed close to or side-by-side with human workers, enable process automation, human-machine interaction and fast reconfiguration. However, fully exploiting collaborative robots is still a challenge due to the specific additional technologies and know-how required. In this chapter, we evaluate challenges and opportunities with a special focus on manufacturing environments in SMEs and with relevant industrial use cases.

Keywords Collaborative robots · Smart production · SMEs · Robot reconfiguration

1 Introduction and Motivation

Unpredictable constant changes in demand together with a growth of the desired degree of customization of the products motivates smart factories as a necessity and a growing tendency (Sjödin et al., 2018) if companies want to be efficient (Petit, 2019). Flexibility and adaptability are crucial factors and all the required technologies

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are crucial as well from enablers (technologies that do not interact with the product itself but allow building others on top, e.g. 5G) to actuators (those in direct contact or specifically developed for the manufacturing sector, e.g. collaborative robots). When demand becomes flexible, so must the production as well. Other solutions like large inventories or waiting lists are either expensive or do not satisfy the users.

Collaborative robots have been design as enablers of smart factories allowing to meet the requirements of smart production. Collaborative robots, or cobots, are robotic devices able to operate manipulating objects or tools together with a human worker, sharing a defined workspace and acting synchronously on the same task. The cobot provides assistance to the human operator and by setting up dynamic virtual surfaces to constrain motion. Advances in safety control, added safety-related functions and features in the robots (e.g. sensors) along side with dynamic motion planing and robot control have made the implementation of cobots in real factories possible. Cobots have the capability to improve faster adaptation and multiply efficiency when the synergies of humans and robots are combined (Bloss, 2016).

This chapter gives an insight into what cobots are, how they can be used in the industry, challenges and opportunities with a special focus on manufacturing environments in SMEs and, as an example, presents a real industrial use case.

2 Overview of Technology

2.1 Collaborative Robots: Definition

The term collaborative robots or “cobots” refers to a group of robots designed with the primary objective of being an extension of human workers supporting them in manufacturing processes working together in the same space at the same time (see Fig. 1). These are tasks that are repetitive, require heavy lifting, or are not ergonomic, but yet too complex to fully automate. Furthermore, compared to traditional robotics, cobots are easier to install and take up less footprint by not requiring expensive safety precautions. However, cobots do come with some drawbacks including limited payload, complicated risk assessments, and hesitations from the worker collaborating with the robot.

From the design point of view, cobots are multi-joint actuators with a wide reachable spectrum of positions and are able to get around intermediate obstacles. Their light design orient their working focus to tooling control and limits object handling according to payload restrictions ranging from 5 to 20 kg.

When a robot and human worker share the same workspace, safety is a major topic and eliminating safety elements, such as fencing or restricted areas, requires extra sensors to prevent collisions. Exteroceptive and proprioceptive sensors can be used to avoid collisions, typically, torque sensors are placed in the joints to stop movements and minimize impact forces when the robot meets unplanned resistance. Advance systems allow dynamic analysis of the environment, live motion calculation and

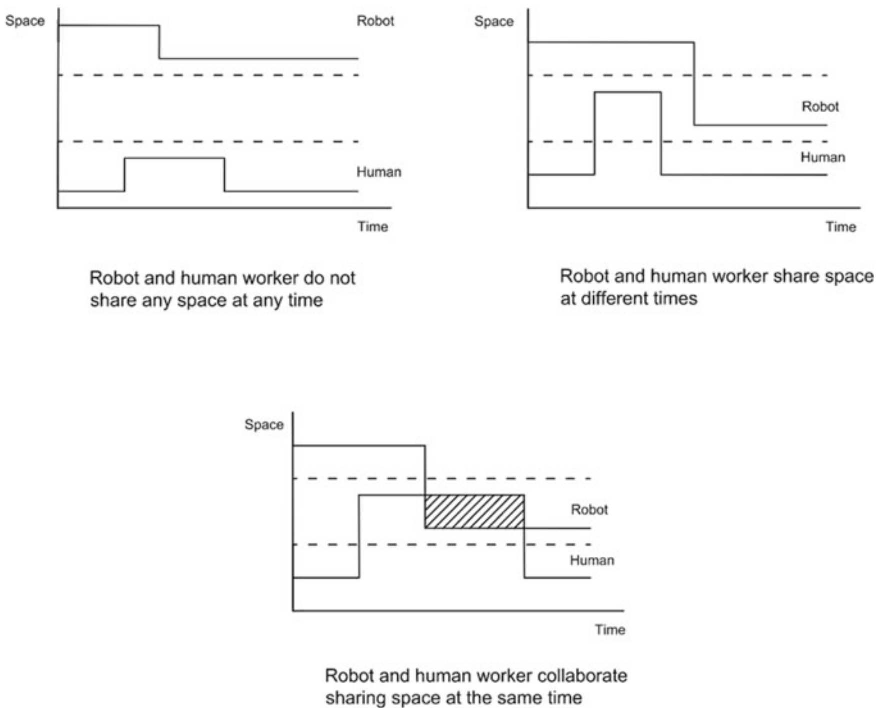

Fig. 1 Diagram comparing occupation of the spaces along time for different human-robot interactions. (top-left) Robot and human do not share the same space at any time, (top-right) robot and human share the same space but not at the same time and (bottom) human and robot share the same space at the same time (collaborative robots)

3rd party trajectory estimations. Moreover, these features improve the active safety mechanisms and ultimately the human's safety while collaborating with the cobot. These milestones make cobots even more flexible and open the doors to move from automated scenarios to fully autonomous ones (Fehrenbacher, 2016).

2.2 How Cobots Can Be Used in the Industry

The ideal implementation scenario for cobots are tasks that involve a sequence that requires human capabilities, know-how, or decision making. In this way, the task can be automated leveraging the capabilities of both humans and robots to improve the manufacturing process over traditional manual labor. The robots are best suited for dynamic manufacturing environments where human adaptability can be applied and fully automating the process is not possible or efficient.

Fig. 2 Comparison of a robot versus a cobot. From the left to the right: (1) isolated robot working surrounded by fences and (2) collaborative robot working along side a human worker without physical separation

Specific advantages of cobots should be considered to maximize the improvement: cost efficiency per unit, easy installation, fast programming and integration which is ideal for highly changeable processes, less installation footprint and not needing expensive safety precautions like fences (see Fig. 2), that is, lower capital allocation and lower risk on deployment.

2.3 Challenges and Limitations

Cobots can work in the same workspace as a human, though some users may be reluctant to operate in the same space. Furthermore, cobots do not require traditional safety measures which can be expensive and require significant floor space in the factory, however, carrying out a risk assessment is required. Such a safety analysis can be conducted using the framework provided in ISO/TS 15066:2016 (IO, 2016). The risk assessment focuses on identification and mitigation of hazards, for example, related to transient or quasi-static impacts between the human and robot. And furthermore, taking steps to eliminating risk and evaluating whether the reduction in risk was adequate.

They are highly reconfigurable because the cobots typically come with additional degrees of freedom than traditional robots meaning one robot can carry out many different tasks when repurposed. A downside of this is that the programming becomes more complex if robot kinematics and dynamics are used. But initial setup may be much easier if using a hand guidance mode which is not be an option with traditional industrial robots.

The main limitations of cobots do not come from the physical properties of the cobot itself, though the limited payload may be a limiting factor, but from the software and extra technologies required in order to securely and efficiently manipulate and control it. Understanding the task and the environment is crucial when aiming for flexibility and when a predefined trajectory and synchronous execution times are not enough. Perception systems and analysis algorithms are under research and development to provide the most relevant and accurate information to the decision-making units. On the motion side, classic control methods are combined or expanded with new technologies such as machine learning to equip the robot with real-time trajectory calculations able to respond and perform in dynamic environments without prior heuristics being given to the system. The algorithm learns to operate in an unsupervised manner, for example, using reinforcement learning with a cost function that optimizes the task the system should perform. Automatic programming is the next challenge in moving from automated tools to fully autonomous entities.

3 Implications for SMEs

We identify the capability of manufacturing new products, not only new variants of old products, and a quick ramp-up for these new manufacturing processes as a must for SMEs to be competitive in a highly competitive and aggressive market. Fully dedicated and automated production lines are not always possible nor desirable in these scenarios and even less when investment risk is considered.

Collaborative robots, despite requiring a higher initial expenditure than other types of robots, cover a wider range of automation levels from fully automated tasks to support tasks when working alongside humans. Also, the ease of programming reduces the specific know-how required and makes reconfiguration most cost-effective. All in all: cobots are flexible tools able to work alone exploiting their own capabilities or next to a human expanding their capacity to properly adapt and perform in uncertain future scenarios and manufacturing requirements by reducing reconfiguration costs and effort.

4 The Battery Sealing Process

Even in serial production and especially if time efficiency is considered, the requirements of each of the working stations change at high frequency and the manufacturing solution should be able to adapt to different designs and scenarios. This is the case, for example, of automotive battery assembly lines when different types of seals are considered and the amount of batteries to deliver per day is far from being constant.

In terms of sealing, a battery can be considered as a box containing the battery cells and other electronic components with a lid covering it. The union of the two parts must be hermetic to prevent corrosion of electronic components. This hermeticity is achieved by applying glue to the joint and pressing both parts at a certain level. How to press the parts together is what defines the two different processes covered here.

4.1 Fully Automated Scenario

In the fully automated scenario, two robot arms are involved: the first robot takes the lid of the battery from the supply cart holding it via a vacuum grip system and moves the lid to a specific position in the working area of the second robot. The second robot spreads a layer of glue on the frame of the lid following the contour. The first robot takes the lid and places it on the top of the battery in its final position, the vacuum grid is released and the robot moves away. The sealing process ends after a hydraulic press acts on the battery ensuring the correctness of the gluing process and the hermeticity of the case.

This not-flexible production line is design to produce a nominal amount of batteries per day. Increasing this number requires a long term decision and investment and, as peaks in production are not constant, would lead to inefficiencies as for several periods of time, the new line design to cover maximum production won't work at nominal speed but slower.

4.2 Semi-automated Scenario

A semi-automated solution combining cobots and human workers has been tested to solve these peaks in production. Flexibility is achieved as follows.

When a peak in production is detected, extra resources are added to the production line in the form of two cobots and a human worker per station. With this configuration as many stations can be deployed just by moving the cobots to the desired position and programming them in hand guidance mode.

One cobot is programmed to handle the lid from cart to glue middle stop where the second cobot applies glue. Once done, cobot one drives the lid to final position. As resources are limited and big machines are less flexible, required pressure between parts is achieved now via screws without using the hydraulic press. As programming a cobot to insert screws in corresponding holes is not efficient as high level of accuracy is needed, a human worker performs this tasks.

4.3 Benefits and Insights

Thank to cobots, the not-flexible production line of batteries can be rapidly adapted to delivery requirements without long term investment or commitment in terms of resources (space, capital...). When peaks in battery production are over, the extra cobots can be used for other productive activities minimizing stand-by time what allows an efficient holistic design of the factory based on nominal production necessities while providing the capacity to adapt to production peaks.

To be mentioned, as the human worker is trained but not used to the specific routine in the newly deployed station, a lower working rhythm when compared to the same permanent station should be expected. Anyways, this lower efficiency is definitely worthy if the other option is not matching market requirements.

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Part 5
Competences

Introduction to Part 5: Competences for Smart Production

Astrid Heidemann Lassen

Abstract This chapter introduces Part 5 in the book and turns focus towards the competences needed for smart production. The line of reasoning presented here, is that I4.0 poses a significant challenge for the development of new systemic competences in the organizations. This topic is address through five chapters which demonstrate the types of competences needed, how competences are developed and which approaches for competence development are particularly suitable in the SME context in relation to Industry 4.0.

Keywords I4.0 · Competences · Learning · Digital transformation

1 Introduction

In the previous parts of this book, we have been introduced to the vision of I4.0, a range of the supporting technologies, and insights on how SMEs work with the transformation process towards I4.0. This knowledge in conjunction forms an image of the significant estimates of the potential for the manufacturing industry.

Yet, it has also become clear that the concept of I4.0 is born based on a technology-centric vision, and that this approach faces certain shortcoming when it comes to implementation, utilization and value appropriation. What emerges is that the realization of the vision of I4.0 will alter products, services and production systems alike, and this will inevitably also modify the workforce profile considerably. Manual activities and low-skilled jobs will become significantly less prevalent due to the automation of processes. But the nature of manufacturing jobs in general will also change significantly towards data-based competences (Lassen and Waehrens, 2021).

This means that in order for SMEs to take advantage of the new technological opportunities, they must also develop of a new set of skills, competences and capabilities. To this end, a multitude of questions arise on which competence to develop, how to develop the competences and how to use the new competences in relation to

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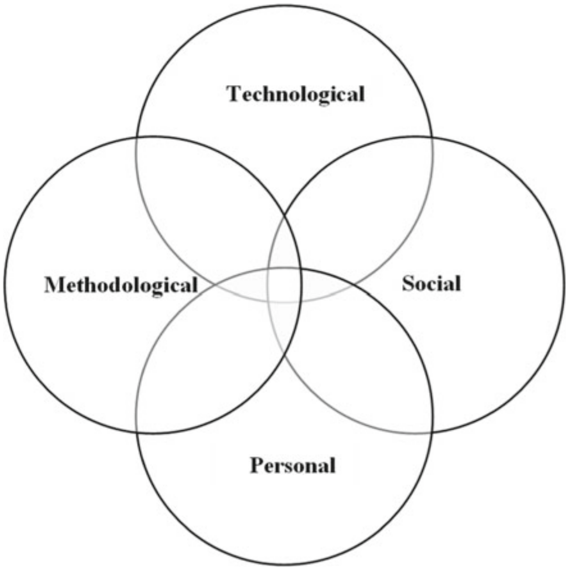

Fig. 1 Systemic competence needs for I4.0

implementing new technologies. Several recent studies (e.g. Abelen, 2016; Hecklau et al., 2016; Larsen et al., 2021; Hansen et al., 2022a, 2022b) have revealed that the lack of focus on developing complementary competences in the context of I4.0 are amongst the most significant barriers for digital transformation. The complementarity or systemic view on competences include technological, methodological, social and personal competence. This view lends itself very well to discussing central questions on how to create the digital transformation (Fig. 1).

In this fifth part of the book, we introduce five chapters which each focus on providing insights to such questions. Each chapter has a particular point of departure, but all recognize the dependency on interconnected competence development for digital transformation.

2 Content of the Following Chapters

The chapter by Hansen et al., (2022a, 2022b) offers a discussion on competence considerations for Industry 4.0 in light of changing work environments, and advocates for a human-centric approach to digitalization. Based on current literature on competence requirements, an overview of key competences for I4.0 is developed utilizing a categorization based on three distinct areas; *management*, *backend,* and *frontend*. This categorization highlights the fact that in order to benefit from the systemic potentials of I4.0, the needs for new competences are not merely at the operational level. Rather, new competences are also required at management level, in order to be able to perceive the right digital opportunities and provide the prober strategic conditions, and at back-office functions, in order to be able to work fully data driven throughout the company system. The chapter furthermore points to recent developments in inclusive and human-centric approaches to manufacturing development.

Next, the chapter by Lassen et al. (2022) discusses the needs to supplement the current technology-centric view on Industry 4.0 with an understanding of how to prepare the workforce for the new competences required in the future of manufacturing. The discussion is elaborated through an empirical analysis in 31 Danish manufacturing companies of how SMEs prepare their workforce for digital manufacturing. The analysis demonstrates that while many companies provide enabling learning environments, the lack of explicit competence strategies is widespread and causes unfocused and faltering exploitation of the potentials offered by Industry 4.0. The insights we gain through this chapter underscore the necessity of approaching digital transformation strategically as an agenda which requires introduction of new technologies as well as new competences.

This need for upskilling, is also the central focus for the chapter by Rehe et al. (2022). Here empirical experience is provided from the work carried out at the Competence Center Cottbus. This competence center works particularly with SMEs on the aspect of digital transformation. The authors introduce the specific instrument, the LTA-FIT concept, which is consistently applied by the Center, and discuss why each element of the approach is important. This concept is designed to impart the required knowledge and competences in accordance with the distinct qualification level of SMEs and their employees. The insights provided in this chapter confirm that systematic assistance provided to SMEs on how to approach the digital transformation from a systemic approach, is needed and yields successful results.

In the subsequent chapter, Larsen et al., (2022a, 2022b) also turn focus towards the question of how companies may start to acquire new competences for I4.0. In this chapter, the particular interest is the potential for manufacturing innovation which arise in connection to I4.0. The authors present an approach for manufacturing innovation, which is labelled a "sandbox approach". The sandbox approach relies on experimenting with Industry 4.0 solutions in settings that resemble a production environment but with no or restricted interruptions in daily operations. Case examples are presented of three small and medium-sized Danish manufacturers that have all used the sandbox approach as a first step to develop an I4.0 solution to understand the potential of this approach and the effects this creates in the companies. The cases reveal that the sandbox approach is highly useful under circumstances where the company is not familiar with the technologies they want to exploit, do not understand their own requirements for the solution, or are not sure about the value of a solution they consider implementing and thus cannot make a realistic business case. These insights underscore the necessity to allow for experimentation and development as part of gaining new knowledge and competences on how specifically to move towards I4.0.

In the final chapter in Part 5, Sorensen et al. (2022) introduce the concept of Learning Factories as a means to experiment with and learn of Industry 4.0. As also argued by Larsen et al., (2022a, 2022b), the authors of this chapter point to the fact that SMEs can benefit substantially from an experimental and explorative approach to finding and creating value of new knowledge. Learning factories can provide companies with such an environment for pilots, demonstrations, and experiments. They are deemed highly suitable for Industry 4.0 learning in both industry and academia due to the fact that they provide a semin-authentic setting for experimenting. The close resemblance of a learning factory to a full-scale manufacturing system, can let companies explore their concrete challenges, and test out solutions and technologies in a context close to their own, without interfering with ongoing operations, and at a lower level of complexity than a full-scale manufacturing system.

3 Summary

In combination the chapters in this part demonstrate that the need for understanding how to develop the appropriate competences for Industry 4.0 is challenging and highly needed if SMEs are to activate the promise of Industry 4.0. The chapter show that:

- Broad-scoped competence development is needed, not merely focusing on the technologies themselves but also on the ability to build systemic solutions across the companies.
- Competences strategies help drive the adaptation and value appropriation from I4.0 technologies, and need to be developed parallel to technology strategies.
- Upskilling is a widespread challenge for SMEs, which can be addressed through systematic assistance from knowledge providers.
- Experimentation and small-scale probes (sandbox environments) are key for gradually developing knowledge on relevance and potential of technologies.
- Learning factories provide a highly useful setting for SMEs to develop Industry 4.0 competences in an authentic manufacturing environment without interrupting the daily operations.

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Competence Considerations for Industry 4.0 and Future Trends

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Abstract This chapter offers a discussion on competence considerations for Industry 4.0 in light of changing work environments, and advocates for a human-centric approach to digitalization. Based on current literature on competence requirements, we present a brief overview of some key competences in a *management, backend,* and *frontend* typology. We will highlight some research initiatives, which focus on human factors, and end with an outlook on future directions within manufacturing, which seems much more inclusive and human-centric than what we are currently experiencing today.

Keyword Competences for industry 4.0 · Human-centricity · Human factors · Industry 5.0

1 Introduction

Industry 4.0 has been a major buzzword since its inception in 2011. The digital work environments proposed for this next industrial revolution entails complicated cyber-physical production systems (CPPS), which merge physical and virtual environments across entire process chains by interconnecting both people and machines. Yet, despite big advances in the availability and ease of use of cloud-based services and autonomous systems, we have failed to really see a complete paradigm shift, which unlocks the interconnected vision of the proposed industrial revolution- this is especially apparent within smaller and medium-sized enterprises (SMEs). Undoubtedly, Industry 4.0 brings changes to work tasks and the associated skills required to engage efficiently in such a digital work environment. This makes workers with digital competences crucial when moving forward (Chryssolouris et al., 2013; Flores

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et al., 2020; Jerman et al., 2018; Neumann et al., 2021). However, manufacturing companies struggle to identify the needed skills and competence profiles and fail to come up with strategies surrounding competence development as a result. Thus, it is not only competences of the shop floor workers but also competences of the managers who should be capable of understanding the concepts and relevancy of Industry 4.0. Effectively this means that the managers need the capability to identify crucial skills, develop the right strategies for digitalization, and lead the change management processes. In many ways this will require a new mindset. Openness to modern technologies, forms of work, and communication must be cultivated and supported by a digital-friendly corporate culture.

Industry managers cannot expect a fast transition to Industry 4.0 work environments without considering their corporate culture and human capital (Flores et al., 2020). Research on systematic ways to incorporate human factors into Industry 4.0 solutions stress the importance of including affected industry workers early in the design process of proposed Industry 4.0 technologies (Neumann et al., 2021; Rangraz & Pareto, 2021) and to consider the usability and overall user experience (Brauner & Ziefle, 2015). Yet so far, the focus of industry 4.0 has primarily been on developing technological solutions without much consideration towards the target group of factory workers, who need to interact with these modern technologies daily (Lassen & Waehrens, 2021; Neumann et al., 2021). This commonly skewed focus reveals a discrepancy: Human workers remain crucial to the continued operation of smart manufacturing environments, and yet, the stakeholders affected by the digital change are not properly prepared nor seriously considered in the decisions surrounding the digital technologies. This leads to barriers to the use and implementation of Industry 4.0 technologies. The role of the human workers is still too vital for their needs to be an afterthought only after big investments into new digital tools have been made.

This chapter intends to introduce a view on current competence considerations for industry 4.0 and will touch on the importance of human factors as part of the journey towards Industry 4.0. We end with an outlook of where the industry is headed in the future, specifically with a focus on the balance between humans and technology.

2 Changing Work Environments and Competence Considerations for Industry 4.0

Firstly, we need to address how we in this chapter define skill and competence. It seems that the terms skill and competence (or competency/competencies) are often used interchangeably, which sometimes makes discussions and research on the topic hard to decipher. In some areas, like nursing, competence and competency are distinguished from another, where competency refers to the *demonstration* of skills for specific tasks, and competence are more related to the *knowledge* of how to approach these tasks (Moghabghab et al., 2018). For this chapter we turn to Merriam

Webster, who defines competency in the same manner as competence: “the quality or state of having sufficient knowledge, judgment, skill, or strength (as for a particular duty or in a particular respect)” (Competence, 2022). Within academic topics on digitalization, competence is also understood as the combination of knowledge, skills, and attitudes (Rangraz & Pareto, 2021). In many instances both competence and competency are used interchangeably, thus, to avoid confusion, here we merely stick to competences as a terminology as understood by Merriam Webster, and with the addition that competences comprise of knowledge, skills, and attitudes. This way we satisfy both the Merriam Webster definition and align our understanding with what has already established in our academic field.

As an example, competence and skills can be viewed in the same way as methodology and methods: A methodology is an approach often comprised of many different methods to achieve a desired outcome. Similarly, competence is the ability to efficiently solve specific problems by relying on a plethora of knowledge, skills, and attitudes. With that out of the way, let’s dive into the competences of Industry 4.0.

Technology use in everyday life has grown and evolved rapidly over the last 10 years. Despite this trend, the use of technologies in manufacturing is still lacking behind and has not seen the same widespread availability as with consumer technologies in everyday life. Consequently, the skills and competences required within manufacturing may not be present or evolved enough to handle the major push for connected digital technologies, which has happened in recent years. Additionally, there is a shift away from fixed repetitive workstations to more flexible setups, where a broader set of skills outside purely technical areas are valued, including transdisciplinary skillsets, problem solving, creativity and lifelong learning (Kagermann et al., 2013; Kipper et al., 2021; Liboni et al., 2019). Industry 4.0 relevant skillsets are required to make use of new technologies and both managers and shop floor workers need to adjust. Due to the interconnectedness and strong focus on digital communication technology, Industry 4.0 presents challenges to the manufacturing industries, and especially their workforce.

The changing work patterns and the need to manage change in the wake of Industry 4.0 were highlighted in a large survey conducted by the World Economic Forum on the future of jobs in 2016.[1] It analyzed questionnaire responses sent out to chief human resource officers in large corporations and identified immediate focus areas such as agile and flexible work structures using online platforms, focus on talent diversity and rethinking the way HR departments identify skill gaps using data analytics. Among the long-term focus areas identified were strong incentives for life-long learning, rethinking education systems to close the skill gaps, and collaboration between industries and the public–private sector to help manage the change processes. In order to exploit the potential of CPPS’s, there is a dire need for the right skills and competence profiles. So which skills and competences have been identified for Industry 4.0?

That question is more difficult to accurately answer than one might think. As touched upon in the beginning, skills and competences are hard to accurately define

[1] https://reports.weforum.org/future-of-jobs-2016/ (Accessed 2021–10–14).

Table 1 A far from exhaustive list of some competences (knowledge, skills and attitudes), which have been identified for industry 4.0 based on (Abele et al., 2019; Belinski et al., 2020; Erol et al., 2016; Flores et al., 2020; Ghobakhloo, 2020; Hecklau et al., 2016; Jerman et al., 2018; Kipper et al., 2021; Liboni et al., 2019; Shet & Pereira, 2021)

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

in general, which also shows in Industry 4.0 literature dealing with the topic in complex work environments. In the following we have tried to condense the major findings from various publications (cf. Table 1) and how they relate towards smart manufacturing.

For our interpretation, we have borrowed the *backend* and *frontend* terminology often used in software development as a typology to distinguish different areas of competences. Other typologies make use of more abstract levels to distinguish between types of competences i.e., operational and cognitive skills or divide them into technological, personal, and socio-communicative, methodological, or action-related competences (Abele et al., 2019; Hecklau et al., 2016).

We present the skills and competences in a rather operational way that tries to classify competences in themes needed for *management*, *backend (technical backbone)*, and *frontend (end users)*. Many of the competences and skills listed in Table 1 are relevant to a plethora of workers in manufacturing, from management to shop-floor, and thus hard to contain in rigid boxes as the competences bleed into one another. For example, cyber security is important in all corners of an organization but is here classified under backend as deep technical knowledge is needed for its proper implementation and maintenance. This does not mean that management or frontend should be oblivious to cyber security. One person may fluidly move between *management*, *backend*, and *frontend competences.*

Management

Effectively, the digital transformation of companies starts with the management, as they have the power to initiate strategic initiatives and secure funding in their organization. However, these strategic initiatives only start if the managers are aware of Industry 4.0 and which technologies, skills, and competences are relevant to cultivate their business (Ghobakhloo, 2020). E.g., perceived benefits of digital technologies, clear strategy and support from management, and acknowledgement and identification of competences. A plan for competence development and how to foster the right organizational culture for communication and collaboration is needed for continuous learning throughout the organization. It requires certain managerial competences (Shet & Pereira, 2021) in order to acquire relevant knowledge, recognize the importance, and assimilate it into actionable business strategies (also called absorptive capacity, Sjödin et al., 2019). The managerial competences identified by Shet & Pereira cover broad areas such as disruptive leadership, collaborative mindset, project leadership, problem solving and decision making inter alia. They overlap with other findings from studies trying to generally identify important skills and competences needed for Industry 4.0 (Jerman et al., 2018; Kipper et al., 2021), which is why clearly discerning competences for managers and other employees may prove challenging. The initial push for digital transformation, however, needs to happen from the management (Ghobakhloo, 2020), where they will be able to continuously adapt based on the feedback provided by their organization, either directly through their colleagues, or via the increased information available through growing connectivity. This feedback loop will be useful for continuously defining the digital strategy moving forward while considering the needs, challenges, and considerations of the organization.

Backend

Refers to the technical backbone, which will enable effective use of ICTs, ensuring the wireless network provides coverage and sufficient bandwidth, setup, and maintenance of automation technologies, which requires specialized knowledge within programming, data analytics, and product specific knowledge etc. Oftentimes the technical backbone proves to be a bottleneck for companies, as it requires specialized system and technical knowledge, which is in high demand, and rarely present within SMEs. Most of the competences listed in the backend category refers to hard skills, which are crucial to the setup and maintenance of Industry 4.0 technologies. As such, it is no mystery why the focus of Industry 4.0 has been heavily centered around technology and its technical implementation. However, to reap the benefits of technology, people need the ability and willingness to operate it.

Frontend

Encompasses a lot of the soft skills, which are crucial to effective operation of manufacturing processes. Especially within changing work environments, workers need excellent communication skills and the motivation to learn. The competences listed under frontend are often the processes closest to the production environment. The end users here need to understand how to operate the various interfaces and communicate effectively via Information and Communication Technologies (ICT) presented to them. These end users may encompass both managers, engineers, and shop floor workers who are presented with various Industry 4.0 interfaces. Ever more flexible work environments also call for higher interdisciplinary profiles, and knowledge-sharing capabilities. The frontend category encompasses the largest group of people engaged in manufacturing processes, which underlines the importance to include their needs in decisions surrounding Industry 4.0 solutions.

A common thing that managers struggle with is how to create and maintain support for digital initiatives in their organization. A greater focus on the frontend and how the end-users can create an impact on the strategic decisions appears a promising approach, yet one still overlooked in Industry 4.0 literature (Neumann et al., 2021). Management of digitalization initiatives needs a holistic stance to provide benefits to all stakeholders rather than single, local improvements. That means, stakeholders from different areas such as management, administration, shop-floor workers, customers, and suppliers should be asked and involved in the design process of proposed Industry 4.0 technologies (Rangraz & Pareto, 2021). As work environments change, managers may even be required to adopt new roles and act as learning facilitators in their organization to develop their human capital and the capability to learn as part of the company culture (Saabye et al., 2022).

3 Human Factors in Industry 4.0 Initiatives

So far, we have looked at the required competences from both the shop-floor workers and the management by explaining how the initial push effectively must come from the top. We have established that the changing roles of workers in industry, as a result of increasing digitalization, requires a focus and commitment to change. This commitment to change involves deliberate management and is very unlikely to occur organically without persistent and focused effort. Considerations into human factors are thus important in order to achieve the necessary support and participation of the employees otherwise the change most likely will fail (Fischer & Pöhler, 2018; Moeuf et al., 2020; Saabye et al., 2022). One of the approaches to this is to ensure that the employees understand the benefit to their own daily work tasks and that they do not perceive new digital tools as a hindrance, which in turn may sustain a certain resistance to change. For this, fostering a culture of learning by involving employees in decisions and small experiments concerned with new digital tools is a promising approach (Kaasinen et al., 2020; Leonard-Barton, 1992; Saabye et al., 2022). Ensuring a focus on human factors and employee involvement benefits the general wellbeing and productivity of the workers (ACE Factory Cluster, 2019).

In an effort to address both the need for the right competences and the heavy technology push envisioned by Industry 4.0, Romero et al. devised a typology for the type of operators we need, or expect to see, in future factory setups. This typology was dubbed *Operator 4.0* and identified eight different types of operators, shown in Table 2 (Romero et al., 2016). The different operator roles should not be seen as fixed roles, rather as capabilities necessary to engage and utilize Industry 4.0 technologies. As such, an individual may be expected to work across operator 4.0 roles.

If we view the Operator 4.0 typology in the light of competences for *management, backend*, and *frontend*, this Operator 4.0 typology is mainly part of the frontend category, as it only describes how end-users need the capability to interact with

Table 2 Operator 4.0 typology from Romero et al. presenting a symbiotic view on operators' use of technology in industry 4.0 (Romero et al., 2016)

Augmented	Virtual	Collaborative	Social	Super-strength	Healthy	Smarter	Analytical
Capable of using AR/VR technologies	Capable of using virtual factories	Capable of smooth interaction with and programming of cobots	Skilled in sharing knowledge using ICT to expose tacit knowledge	The use of exoskeletons to increase safety and reduce fatigue	Using wearable devices concerned with well-being	Capable of using artificial intelligence for operation and planning	Capable of understanding and using analytic tools

specific types of technology and leaves out the emphasis on managing this transition and ensuring that the technological backbone is in place to enable the technologies for the operator 4.0 let alone ensuring that the competence development of the operators is in place. However, this typology inspired important research on human-centered factories across various research projects joined in a cluster called ACE Factories[2] funded by the European Union's Horizon 2020 research and innovation program. The cluster adapted their own vision for the Operator 4.0 typology as: The Augmented and virtual operator, Social and collaborative operator, Super-Strong operator, Healthy and happy operator, and the One-of-a-kind operator, where the focus was on adapting to the individual. Spanning five research projects and multiple years, these Operator 4.0 typologies have been tested with a human-centered focus in mind with multiple case companies. The results pointed towards the added value by adopting such a human-centered approach, where the technology adapts to the workers and not the other way around and led to a series of key learnings and recommendations. These were summarized in the ACE Factories white paper, which provides a condensed overview of the work (ACE Factory Cluster, 2019).

Some of the key takeaways from the research projects were the importance of the human-centered approach, which allowed for co-design of workplaces and solutions. The use of augmented technology such as AR/VR for both online and off-line training as well as remote support proved very intuitive and inclusive to a wider range of workers, while reducing the time spent on finding information. By using such augmented technology, it enabled easier on-the-job training, which is needed to cultivate the operator's competences continuously. Employing human-centered solutions showed an increase in both productivity and well-being of the workers. Some of the pilot projects investigated real-time measurement of workers' mental and physical strain to adapt systems and tasks accordingly or to provide positive feedback to increase motivation. These initiatives showed promise as long as the workers were part of the design process, and it was not used for performance management, had the option to opt out, and a transparent use of their data was available in compliance with General Data Protection Regulation (GDPR), (ACE Factory Cluster, 2019).

Oftentimes it is too difficult for SMEs to start up these initiatives by themselves, which is why external cooperation with academic institutions remain very important for SMEs such as Learning Factories (Walter Colombo et al., 2021). Such collaborations help create awareness of how recent technology enablers can benefit their business and provide a direction for the SMEs to pursue moving forward.

4 Outlook and Future Trends

Despite the somewhat isolated focus on Industry 4.0 technologies, which was highlighted in the beginning, the future use of technologies in manufacturing is expected to have a much more human-centric approach than what is broadly seen today. The

[2] http://ace-factories.eu/.

research and pilot projects described in the ACE Factory Cluster support this trend. Moving forward, the focus will not only be on productivity alone but also on creating better work environments for the manufacturing employees through easy and intuitive workspaces, where repetitive and physically demanding tasks are heavily minimized. This approach has multiple benefits, as increased well-being and motivation leads to greater productivity and possibly less work-related injuries or sick leaves. Today, the technology is mature enough to introduce collaborative human robot workstations and autonomous guided vehicles or mobile robots (AGV/AMR's) on the production floor. However, moving forward there is a push to introduce better communication between these various man–machine interfaces, both between devices, but also between humans and machines. E.g., a collaborative robot, which can adapt to the operator in front of it via monitoring of the operator or based on historical data tied to the specific operator. Capabilities such as adaptive interfaces also bring greater flexibility in the production, as it could free up the need for dedicated operators, where any available employee could engage with the work-cells and only need minimum training. This capability becomes increasingly important as we are faced with an ageing workforce and young workers seek careers outside of manufacturing. Introducing natural-speech commands to intuitively program the robots may gain popularity as voice recognition steadily improves. AI technologies for decision support, production planning for manufacturing tasks, or AI empowered robots will likely become prominent too, aiding non-experts in increasingly complex work systems, and allowing them to focus on higher-level cognitive tasks, while delegating repetitive or dangerous tasks to autonomous systems.

The push towards greater accessibility and overall simplicity of Industry 4.0 tools for the fronted users makes sense, and is already well underway e.g., with plug-and-play cloud solution services from a wide range of providers (Moeuf et al., 2020). Within research, there has recently been a wider interest in human-centered solutions, which is starting to show in legislative bodies as well. The European Commission is already talking about Industry 5.0 before the vision of Industry 4.0 has come to fruition (Breque et al., 2021). The keywords currently driving Industry 5.0 are Sustainable, Human-centered, and Resilient manufacturing. The Covid-19 crisis cemented the need for up-to-date in-house competences and in many ways pushed digitalization forward quicker than expected, especially in the use of information and communication technologies (ICTs) for communicating internally and externally with customers. Manufacturing enterprises around the world also suddenly realized that they cannot confidently rely on external partners to handle critical processes of their operations. This has revived ideas of local manufacturing and the desire to move most of the production closer to home. In doing this, the distance the product must travel is vastly reduced, and while this is ticking the sustainability box by producing lower emissions, it also spawns the need for acquiring or building the right competences in-house.

Strategies for digitalization need to take a holistic look beyond the horizon. That means, stakeholders from different areas such as management, administration, shop-floor, customers, and suppliers should be included and involved in the design process of proposed Industry 4.0 technologies. Through such a holistic approach it will be easier to focus more on benefits for all parties instead local and singular improvements.

Meanwhile, we continuously need focused efforts to support up-skilling or re-skilling of existing workers, while providing inclusive and fruitful career opportunities for both young and aging workers.

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Labour 4.0: How is the Workforce Prepared for the Future of Manufacturing Industries?

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Abstract This chapter presents a discussion of the needs to supplement the current technology-centric view on Industry 4.0 with an understanding of how to prepare the workforce for the new competences required in the future of manufacturing. The discussion is elaborated through an empirical analysis of 31 Danish manufacturing companies. This concludes that while many companies provide enabling learning environments, the lack of explicit competence strategies is widespread and causes unfocused and faltering exploitation of the potentials offered by Industry 4.0.

Keywords I4.0 · Competences · Learning · Digital transformation

1 Introduction

As seen through the previous chapters, Industry 4.0 (I4.0) involves a plethora of distinct technologies and impacts companies in numerous ways. The previous chapters have demonstrated how I4.0 aims to enable intelligent factories to produce personalized output utilizing greener and more efficient processes. The vision of I4.0 is to be able to manage all the different units' tasks and activities of the manufacturing system, from the supply chain to distribution, as one central system. This relies on a constant interchange of data among all the subsystems, and promises faster decision making, better monitoring and control of the shop floor, more efficient use of resources, better forecasting of demands and more flexible production.

Such industrial innovations will alter products, services and production systems alike, and this will inevitably also modify the workforce profile significantly (Kipper et al., 2019; Motyl et al., 2017). In particular manual activities and low-skilled jobs

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will be sharply reduced due to the automation of processes. But the nature of manufacturing jobs in general will also change significantly towards data-based competences (Ananiadou & Claro, 2009; Lassen & Waehrens, 2021). According to Oztemel and Gursev (2018), I4.0 technology will not substitute human beings in manufacturing, rather, this will encourage companies to adopt new approaches, assisting their employees to develop skills such as: problem solving, analysis of failure, flexibility for dealing with constant changes and complex new tasks, interconnectivity, innovation, as well as knowledge of technological components and digital transformation (see e.g. Mohamed, 2018; Larsen et al. 2020). Similarly, Lorenz et al. (2015) argues that this will give rise to entirely new job functions such as industrial data scientists; robot coordinators; simulation experts; digitally assisted field-service engineers; 3D computer-aided R&D.

It is apparent that the digital transformation requires employees who are capable of continuously developing new knowledge, technological competences and skills (Gorecky et al., 2017; Bauer et al., 2015). And in order to harvest the significant benefits ascribed to I4.0, companies must hence rethink the way they address the human factors, such as knowledge, competences, demography, motivation etc. [e.g. Lassen & Waehrens, 2021; Mahlmann et al., 2021)]. Yet, the question remains; how do companies actually approach this challenge; how is the workforce actually being prepared for the future of manufacturing? In this chapter we present an analysis of the competence strategies applied by SMEs in manufacturing industries and discuss how this influence the transition towards I4.0.

2 Strategies for Competence Development

Before turning to the analysis of competence strategies, we must first understand what competence development means. In this chapter we use the term as proposed by Kock and Ellström (2011); in a relatively broad sense as an overall description of the various activities that can be used to affect the development of competence in a firm. As such, it refers to a wide range of activities, including education and training of employees (for instance by means of internal or external courses), but also changes of the work organization with the objective of furthering learning at work (e.g. job rotation, team organization, and systems for continuous improvement), or even recruitment of specific new competences with the purpose of developing this into a firm competence (Delamare & Winterton, 2005; Ellström, 1997).

The manner in which companies pursue competence development is what is here referred to as their competence strategy. A strategy can be approached in numerous ways. Mintzberg (1990) suggested that one key distinction is the degree of explicit and rational planning involved in the strategy deployment. This is also a useful distinction to apply when researching differences in competence strategies, where it will focus on the degree of planning and organization involved in the particular learning activities. Three broad categories of learning activities are applied; formal learning activities, non-formal learning activities and informal learning activities (Colardyn & Bjornavold, 2004; Marsick et al., 1999).

Formal learning activities are by design intentional, organized and structured. As planned and organized learning activities, these are mainly financed by the employer and often take place during working hours (see e.g. Saabye et al., 2022). Formal learning also implies that participants are certified or given a certain grade. In practice, formal learning is often organized through internal or external courses. These are taught by various types of education institutions and are guided by specific formal programs. As a learning process, formal learning is characterized by a high degree of planning and organizing.

Non-formal learning activities may or may not be intentional or arranged in a course format, but is usually organized in some way, even if it is loosely. There are no formal credits granted. It is a very common form of on-the-job training (Eraut, 2000). This is also supported by Mawer and Jackson (2005) who found that the majority of small-to-medium sized companies were involved in substantial amounts of unaccredited, structured and semi-structured workshops and seminars. Semi-structured training was often provided by product suppliers and equipment manufacturers conducted at the work site. As a learning process, non-formal learning is characterized by some degree of planning and organizing.

Informal learning activities are often referred to as a residual category to describe any kind of learning which does not take place within, or follow from, an organized learning programme or event. Rather than being guided by a curriculum or plan, it is often thought of as spontaneous. This means that informal learning takes place in the daily work. As used here, informal learning refers to learning that occurs regularly in work, but subordinated to other activities (e.g. work practices) in the sense that learning is not their primary goal. That is, learning takes place while you are primarily focused on performing another task, and there is no deliberate intention to learn and no awareness of learning at the time it takes place. Reber (1989) defined informal learning as 'the acquisition of knowledge independently of conscious attempts to learn and in the absence of explicit knowledge about what was learned' (p. 219). As a learning process, informal learning in and through the daily work is characterized by a no planning or organizing.

From a theoretical point-of-view, this distinction between formal, non-formal and informal learning activities allows us to propose three types of competence development strategies for the purpose of subsequent empirical analysis:

- Formal learning activities = *deliberate strategy of competence development*
- Non-formal learning activities = *emergent strategy of competence development*
- Informal learning activities = *non-strategic competence development.*

In the remainder of this chapter, we will focus on these three types of strategy, the conditions under which they are likely to be used, and their effects in terms of progression of digital transformation.

In addition to the characteristics of the competence strategy, Kock et al. (2008) also find that the organizational environment in which the competence strategy unfolds also plays a significant role. Learning environment here refers to conditions in an organization that are likely to enable or constrain learning (Ellström et al., 2008). The likelihood of successful learning in this sense depends on the extent to which the workplace is designed not only for the production of certain goods, but also for supporting learning and competence development (Shani & Docherty, 2003). An enabling learning environment is characterized by work tasks with a high degree of learning potential; opportunities to learn new work tasks; support of individual and organizational learning; manager's recognition of learning; opportunities for feedback and availability of learning resources. A constraining learning environment on the other hand does not offer such conditions. Fuller and Unwin (2004, 2006) define the constraining learning environment as characterized by less stimulating work tasks, barriers to learning new work tasks and lack of organizational support.

3 Research Design

With this conceptual backdrop of competence strategies and learning environments, we proceed to explore empirically the question of how companies approach the competence challenge of I4.0 and prepare the workforce for the future of manufacturing.

3.1 Data Selection

The empirical analysis is based on case studies of 31 Danish manufacturing SMEs. The companies were selected based on criteria of SME size (max 250 employees); within manufacturing industry; and engagement with I4.0. These criteria provide a suitable context for studying the question of how the digital transformation of manufacturing SMEs is influenced by their approach to development of new competences amongst their workforce. Table 1 provides an overview of the companies, sorted in size and type of industry and their approach to I4.0 engagement (proactive/reactive).

All 31 companies were engaged in a research program with the purpose of increasing their awareness of the potentials provided through I4.0. All completed their planned activities within this program.

3.2 Data Collection

Amongst other analyses, the 31 companies were evaluated through a 360° maturity assessment (see description in Chap. 2). One of the dimensions of this assessment focused specifically on the competences of the companies related to I4.0. The companies were asked to describe and evaluate their current competences related to I4.0. as well as their thoughts on future competence needs and how to achieve these.

Table 1 Overview of case companies

Company	Size (# of employees)	Industry	Approach to I4.0
1	10	Water cutting	Reactive
2	56	Steel and metalwork	Reactive
3	60	Food	Proactive
4	20	Software	Proactive
5	109	Entertainment equipment	Proactive
6	79	Process manufacturing	Reactive
7	85	Steel and metalwork	Proactive
8	115	Industrial freezing	Reactive
9	83	Steel and metalwork	Reactive
10	183	Steel and metalwork	Reactive
11	90	Steel and metalwork	Reactive
12	159	Steel and metalwork	Reactive
13	116	Home and living	Reactive
14	198	Ventilation	Reactive
15	200	Technology provider	Reactive
16	10	Technology provider	Reactive
17	69	Steel and metalwork	Reactive
18	40	Ventilation	Reactive
19	15	Automation	Reactive
20	59	Energy	Reactive
21	88	Automation	Proactive
22	73	Industrial freezing	Reactive
23	60	Electronic hardware	Reactive
24	45	Hydraulics	Reactive
25	11	Electronic hardware	Reactive

(continued)

Table 1 (continued)

Company	Size (# of employees)	Industry	Approach to I4.0
26	36	Food	Reactive
27	11	Food	Reactive
28	123	Home and living	Reactive
29	85	Wood processing	Proactive
30	50	Energy	Reactive
31	80	Steel and metalwork	Proactive

The analysis was conducted qualitatively through an intensive workshop format and follow-up sparring dialogue. All data was documented in scoreboards and protocols. From the qualitative data 128 individual statements expressing various aspects of competence development were extracted.

3.3 Data Analysis

At the analytical stage the 128 statements were first individually coded and categorized in relation to the three types of competence strategies and the two types of learning environments. This enabled descriptive insight into the partitioning of companies relative to each dimension. Subsequently, a transverse analysis was conducted to create 2×3 potential clusters with distinct features and distinct patterns of how how companies approach the competence challenge of I4.0. The clustering was performed based on manual coding. Upon population with the empirical data, this resulted in identification of four distinct clusters. As part of the analysis of the four clusters, the qualitative statements were used to create further insight into what characterizes the case companies in each cluster. This approach parallels the approach suggested by Gioia et al. (2013).

4 Results and Discussion

In the section, we present the results and discuss the interpretation hereof.

In the first part of the analysis, we partitioned the companies relative to their use of difference strategic approaches and their learning environment.

As seen in Table 2, the use of formal learning activities and thereby deliberate competence strategies is very limited. Only 3 of the 31 companies utilized this. The use of non-formal learning activities and thereby application of an emergent strategy of competence development was present in 10 of the 31 companies, and the majority

Table 2 Partitioning of types of competence strategies

Competence strategy	Learning activities	# of comp
– Deliberated strategy of competence development	Formal	3
– Emergent strategy of competence development	Non-formal	10
– Non-strategic competence development	Informal	18

Table 3 Partitioning of types of learning environments

Learning environment	# of comp
– Enabling	22
– Constraining	9

of 18 out of 31 companies related only to informal learning activities and thereby applied non-strategic competence development.

From this first coarse analysis it is apparent that at least part of the answer to the question on how the workforce is prepared to the future of manufacturing is that this does not take place in an organized and strategic manner. This could potentially be part of the explanation of why we are seeing relatively slow digital transformation of SMEs in manufacturing.

When turning focus towards the learning environment, the partitioning in Table 3 showed that 22 of 31 companies in fact identified as providing an enabling learning environment, whereas 9 identified as providing a constraining learning environment.

This insight provides a positive base line for learning activities in general and could indicate that the barriers for engaging in I4.0 are not predominantly based on a lack of interest in or support of learning new knowledge. The vast majority of the companies actually do provide enabling conditions for learning.

At the next stage of the analysis, we conducted a transverse analysis in order to explore further the relation between the competence strategies and the learning environments. We applied the 2×3 possible clusters created from the conceptual backdrop. The result is shown in Fig. 1.

Notably, none of the companies identified as using a deliberate or emergent strategy to competence development whilst also having a constraining learning environment. This means that only the remaining four of the six possible clusters are empirically relevant to understand more in depth.

We find that in the case of companies with constraining learning environments, only the non-strategic approach to competence development was applied. This could indicate that there is a close relationship between lack of strategy for competence development and lack of enabling learning environment.

We find that in the case of companies with enabling learning environments, three companies follow a deliberate competence strategy, ten follow an emerging strategy, and nine do not approach competence development strategically.

The deliberate strategy of competence development is found in combination with enabling learning environments. But very few companies actually do apply

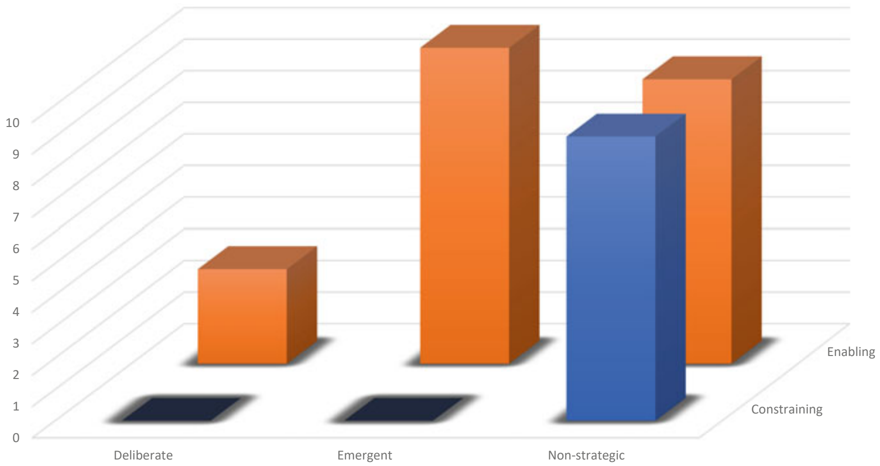

Fig. 1 Clustering of approaches to competence development

such deliberate approach to develop their I4.0 competence. The three case companies in this cluster emphasize especially the following aspects:

– Tailored education for employees is needed. It is difficult to find, but they have managed to do so.
– Support from management level both in terms of resources, time and interest.
– Strong understanding of the need to develop systemic solutions, rather than one-off solutions.
– Recruitment of new profiles as a means to change the competences in the company.

The deliberative strategy is also expressed in the approach to I4.0 engagements, where all three companies are proactive is their search for new insights. This in total provides a profile of companies with a relatively advanced understanding of the need to develop new competences in order to capture the potential of I4.0. With a more detailed and strong understanding of which I4.0 solutions to target, it is also possible to identify the specific competence needs, and tailor more formal education to serve this need. What really sets this cluster apart is the strategic approach to recruitment of new profiles which match future needs. Here it is apparent that these companies combine their technology strategy with considerations on competences needed to exploit such new technologies.

The emergent strategy for competence development is also found in combination with enabling learning environments. This approach is the one single approach followed by most companies. This means that while the companies do have intentions of improving I4.0 competences, this happens in a nonformal and often unorganized manner. The case companies following this pattern were characterized by:

– Recent interest in I4.0
– Difficulties in identifying competence needs

- Focus on cross functional competences
- High degree of employee involvement
- Bottom-up approach to I4.0
- High degree of tacit knowledge
- Lack of planning and communication regarding I4.0
- Non-systematic upskilling of employees
- Change willingness.

In combination, this provides a profile of companies that more recently have become aware of potentials related to I4.0 and have a less developed understanding of how to convert this into specific projects and plans. The emergent approach is also apparent in the approach to seeking out knowledge on I4.0, where the majority (7 out of 10) of the companies are still reactive in their approach. This is a clear indication of an undefined strategy.

Instead, employees are supported and encouraged when they themselves identify a need for upskilling. This emergent approach could be preferable in circumstances where it is still unclear which specific direction to take. Here, more exploration and possibly experimentation is needed. Yet, the consequence of the unsystematic nature of upskilling of employees is also that the digital transition is slow-paced and not necessarily well coordinated with the demands created by the introduction of new technologies.

The two first approaches to preparing the workforce to I4.0 capture the case companies with the most mature reflections on what I4.0 can be used for in their context and what is needed in order to activate this potential. However, as seen in the initial partitioning analysis, the majority of the case companies, 18 out of 31, in fact follow what we have labelled a non-strategic approach (enabling + constraining learning environment). This means that while learning may indeed take place, this is as indirect effect of other activities. Coarsely put, in these companies the employees learn about I4.0 if they happen to be engaged in activities that in one way or another relate to this; learning happens if it happens, and if it doesn't, it doesn't. This non-strategic approach to competence development is found equally associated with enabling as constraining learning environments. The fact that the type of learning environment has no significant influence on the learning output achieved, further underscores the random nature of this type of learning.

The case companies with an **enabling learning environment, yet a non-strategic approach to competence development**, are characterized by:

- Expressed wish to be involved in I4.0 activities
- Have realized investment needs related to new technologies
- Have technology roadmaps, but still no considerations on supporting competence needs
- Express doubts about how to approach I4.0
- Experience some resistance amongst employees
- Employee involvement is important.

This pattern characterizes a group of companies with identified needs for new technologies, but very little considerations on the competence needs these technologies will trigger. In several of the companies, the I4.0 activities were carried by one or two people, often from a manufacturing technology department. As such, the I4.0 initiatives were not strategically anchored, but were of a more operational nature. This non-strategic, and thereby more random, approach often leads to "islands" of competences, emerging where individual initiative has created it, rather than integrated processes across the organization. The non-strategic approach is further mirrored by a strong pattern of reactive approach to seeking out new knowledge of I4.0 (8 out of 9 companies).

The case companies with a **constraining learning environment, and a non-strategic approach to competence development**, are characterized by:

- Low focus on digitalization in general
- Intrinsic knowledge
- Focus of development activities, but not in production
- Training would halt the production
- No infrastructure to support I4.0 activities
- No overview of current competence
- Lacking strategy
- Low support from management in terms of resources and prioritization
- Fear of loosing employees as soon as they learn more.

The companies in this cluster were characterized by two dominating patterns. One, companies with high degree of highly specialized manual labour, which would be difficult to automate or digitalize. Here focus was on further specializing in the knowledge domains already in focus, or on development activities not directly related to production. And two, companies with a very pressured production where any disturbances would be felt significantly. These patterns led to low motivation for introducing new initiatives. Here time spent on anything but the daily operations, would be perceived as a disturbance. It was also a significant concern that educating employees would only cause them to be more attractive for other companies to recruit. All 9 companies in this cluster furthermore have a reactive approach to seeking out new knowledge of I4.0.

5 Conclusion

The results of the analysis demonstrated several interesting aspects of how companies approach the matter of preparing the workforce for the future of manufacturing. In summary we find that:

- The majority companies in fact provide enabling learning environments for I4.0, which includes e.g. attention to I4.0, support from management in terms of resource and/or attention, and employees involvement. This is according to Kock

et al. (2008) a fundamental premise for successful development of new competences. This finding also indicates that the environment for applying an experimental approach is present, which is several studies has been found to be key in relation to I4.0 (Lassen et al., 2009; Larsen et al., 2022)
- In spite of the enabling learning environments, the lack of explicit competence strategies is widespread. This includes in particular a lack of use of formal education. But, also dedicated non-formal learning activities, e.g. organized based on roadmaps or competence overviews are lacking. This finding suggests that the companies have only to a limited degree managed to build competence development on the foundation of an enabling learning environment.
- The informal approach to competence development for I4.0 is the most prevailing. This means that gaining new competences for I4.0 is not a strategic focus point, but rather develops spontaneously or even by chance.

In conclusion our analysis demonstrates that the workforce in Danish manufacturing SMEs is only to a limited degree being thoroughly prepared for taking on the new tasks and jobs created through the digital transformation. Most of the companies do have a positive foundation in their learning environment, but still have a long way to go before they are able to tie their technological efforts into an efficient support of employees continuously developing new knowledge, technological competences and skills.

Hence, the results may also provide explanations as to why we are experiencing a slow-paced digital transformation amongst SMEs in particular. So far arguments such as lack of resources and technology investments have mainly been used to explain this development. Yet, our analysis suggests that perhaps the approach to development of new competences also plays a significant role. Following this line of interpretation, it would stand to reason that increased efforts in developing deliberate strategies for competence development should be prioritized by manufacturing SMEs, as a key mechanism for activation of the potential of I4.0.

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Qualification in Small and Medium-Sized Enterprises as the Key Driver for a Digitalized Economy

Grit Rehe, Sascha Vökler, and Robert Schneider

Abstract Transformation processes towards a smart production reshape the way we work. Digitalization and the application of new technologies lead to additional interfaces between man and machine and thus, result in a tremendous change of employment, work environment and workforce qualification. This in turn means, to take full advantage of digitalization employees at all levels and sectors have to be evolved in the transformation process and need to be skilled for the upcoming challenges. To meet this need for qualification and to sensitize especially small and medium-sized enterprises (SMEs) to the matter of digitalization, the Competence Center Cottbus was founded.

Through a four-step approach, the Center addresses SMEs at all digitalization levels, from beginners to innovators. The central instrument for the Centers' work is the self-developed *LTA-FIT* qualification concept. This concept is designed to impart the required knowledge and competences in accordance with the distinct qualification level of SMEs and their employees.

Keywords Digital key competences · Digital qualification · LTA-FIT · Competence center Cottbus

1 Preamble

This chapter is supported by the German Federal Ministry of Economic Affairs and Climate Action. The Competence Center Cottbus (Mittelstand 4.0-Kompetenzzentrum Cottbus) is one of today's 27 federal SME competence centers

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in Germany. They are complementary structured and regionally placed in order to reach towards all SMEs and form an interdisciplinary approach.

The centers are committed to transfer actions enabling the access of digital technologies for the economy through demonstration centers, a network for the exchange of experience and practical examples as well as the impartment of knowledge by experts. All centers are performing a long-term agenda and will, based on their individual success stories, eventually be transformed into so called "German SME Digital Centers". Considering this background, the chapter reports from practice.

2 Introduction

Digital transformation comes along with both, unique opportunities for improved profitability, and new challenges to manage. Considering the technological and organizational complexity of such a transformation in particular, small and medium-sized enterprises (SMEs) face great challenges. Past experiences[4] have shown that SMEs often do not have the necessary personnel, organizational and financial resources to take comprehensive steps in addition to their day-to-day business to develop and implement further digitalization measures. However, SMEs are the backbone of Europe's economy and a core part when it comes to the EU's industrial strategy (Communication from the commission to the European Parliament, 2020). Therefore, special support regarding the analysis of technological potentials, the evaluation of efforts and benefits as well as technology demonstrations for a better understanding are basis for a successful development of those companies.

Atop the named challenges, the qualification of employees for the implementation and usage of digital technologies is essential for success. The application of new technologies and the implementation of newly created business operations have a great impact on the roles and job profiles of employees. Thus, work density tends to increase demanding simultaneous handling of various tasks. In addition, transitions resulting from digitalization measures typically occur quickly, sometimes abruptly, but above all continuously and forces employees to consistently adapt and reorient.[1] Therefore, employees do not just acquire knowledge about digital technologies themselves, but require the ability to cope with the complexity of future productions systems and working environments towards a resilient mindset.

The Competence Center Cottbus is found to support German SMEs in coping with the difficulties of a digital transformation. For this purpose, the Center developed a modular portfolio providing SMEs with appropriate digitalization measures, solutions and expertise that are in accordance with their individual maturity level. Those modular offerings base on the self-developed concept *LTA-FIT* and mainly focus on the qualification and competence development within the companies to ensure a sustainable transformation.

[1] Experiences of the Competence Center Cottbus: https://www.b-tu.de/en/automation/research/projects/current-projects#c174887.

In order to transfer the approach of the Center, the following chapter will firstly exemplify the competences and abilities of employees required to sustain in an digitalized economy. Subsequently, the *LTA-FIT* concept and its field application through the Competence Center is described. Thereby, the methodological approach as well as the transfer to technological applications is introduced.

3 Competences for a Smart Production

The application of digital technologies, the automation of processes and the interconnection of machines cause a shift of tasks from human workers to machines, especially in the production sector. This progressive automation of routine tasks leads to a significant decrease in low-skilled repetitive work and shifts the employees' role from work execution to process steering and supervision (Hirsch-Kreinsen, 2014). This shift in work entails the acquisition of new skills, knowledge and abilities in order to handle the novel work scope. In this regard, the pure application of technologies play a minor role. More important is the adaption of the underlying conditions, such as the steering of human–machine-interactions or the processing of real-time generated information. Employees must be empowered to deal with unprecedented situations and require an adaptive and flexible mindset to handle their quick-changing work environment (Hirsch-Kreinsen, 2014).

In order to provide a structured insight on the tangible competences required in a digitalized work environment, (Ehlers, 2013) suggest a classification of personal, social, action, and domain-related competences. Based on this, Erol et al. (2016) compiled a taxonomy of output oriented skills and competences for employees at worker, engineer and manager level. Thus, the following competence categorization may be assumed: (1) *Domain-related competences* is the ability to classify, obtain and apply domain specific knowledge to process a jobs or task; (2) *Action-related competences* refer to the ability to implement ideas or concepts and thus, bring them to action; (3) *Social competences* mean the ability to interact with other persons in a socially appropriate manner through communication, cooperation and the establishment of social structures; (4) *Personal competences* regard a person's ability to act reflective and autonomously, while developing cognitive abilities and "an own attitude and ethic value system" (Erol et al., 2016). This categorization provides a sophisticated view on competences and found a number of applications e.g. in Hulla et al. (2019) or in Lassen and Waehrens (2021). Table 1 breaks those four categories down to the previously mentioned workers, engineer and manager level.

Further literature review such as the one of (Hulla & Ramsauer, 2020) revealed additional competence classes, (e.g. administrative competence, learning competence, human skills, methodological competence) which however can be subordinated by the approach of Ehlers (2013) and Erol et al. (2016).

Table 1 Required competences for a digital transformation in accordance to Erol et al. (2016)

	Competences		
	Level: worker	Level: engineer	Level: manager
Domain-related competences	Capability to understand the basics of network technologies and data processing	A deep understanding of interrelations between the electrical, mechanical and computer components	
	Ability to interact with subsystems through appropriate interfaces	Ability towards abstract thinking and modeling with support of specialized software	
		Statistical methods and data mining techniques	
Action-related competences	A strong interdisciplinary "out-of the-box" orientation	Strong analytical skills and an ability to find domain-specific and practicable solutions without losing the overall goal	Ability to break down complex concepts into realistic work packages,
			A strong interdisciplinary "out-of the-box" orientation
	Ability to deal with the existence of parallel structures		
Social competences	Ability to understand relations between processes, the information flows, possible disruptions as well as potential solutions		Ability to build/act as mediators that enable social processes
	A mindset that is oriented towards building and maintaining expert networks		
	Problem solving ability and creativity		
	Ability to communicate complex problems		
Personal competences	Ability to capture the "bigger picture" for the society beyond the personal situation		Ability to transform their management style from power-driven to value-driven
	Commitment of lifelong learning		
	Personal flexibility with regard to work time, work content and work place		

Table 2 Required competences for a digital transformation in accordance to Müller-Frommeyer et al. (2017)

Professional and methodological competences	Knowledge of sciences and mechanics
	Presentation skills
	Technical knowledge
	Analytical thinking
	Application of knowledge
	Measuring energy
Social competences	Capacity for teamwork
	Communication skills
Personal competences	Motivation
	Affinity for technology
	Personal responsibility
	openness

A similar clustering of competences has been conducted by Müller-Frommeyer et al. (2017). Based on the developments of Kauffeld (2006), they used the categories "professional competences (e.g. knowledge about processes), methodological competences (e.g. techniques to structure yourself), social competences (e.g. socially appropriate behavior in interactions) and personal competences (e.g. strategies to handle yourself, e.g. self-reflection)" (Müller-Frommeyer et al., 2017). Table 2 enlightens their identification of competences, which, however, do not substantially differ from the ones found by Erol et al. (2016).

The competences an employee hold are alterable and can actively be strengthened and built through new and challenging tasks. Advance requirement for such a staff development is a didactical concept which directly addresses the development and expansion of certain skills and knowledge. Under the direction of the Chair of Automation technology[2] at the Brandenburg University of Technology Cottbus-Senftenberg (BTU), the Competence Center Cottbus developed such a concept which will be regarded in the next chapter.

4 Competence Development in a Digitalized Environment

4.1 Framework of the Competence Center Cottbus

The Competence Center Cottbus[3] supports SMEs in Brandenburg (Germany) to recognize and use the potential of digitalization. Thereby, it assists with expert knowledge, demonstration centers, a network for the exchange of experience and

[2] https://www.b-tu.de/fg-automatisierungstechnik/.

[3] https://www.kompetenzzentrum-cottbus.digital/.

Fig. 1 Four-step digitalization approach of the competence center Cottbus

practical examples aiming to increase digital skills and overcome obstacles of digitalization processes. The focus of its activities is on employees and the raise of their digital skills in the field of automation, production, logistics, IT security, assistance systems, robotics and New Work. The center has initially established an advisory board, complementing industrial associations, workers unions and economic development agencies in the German federal state of Brandenburg. The advisory board consults the centers strategy and overall directions and recommends future steps. In alignment with the divergent backgrounds, competences and development stages of the SMEs the Center follows a four-step digitalization approach, which may be applied in a sequence, but can also be used modularly in accordance with individual needs (see Fig. 1).

Inform: This module aims to sensitize SMEs about issues related to digitalization in general and provides information about the advantages and opportunities arising from a digitalized production facility or processes. Within this module, SMEs get introduced to modern technologies and have the opportunity to test them by mobile or stationary demonstrators. Through network events, SMEs may also go into an exchange to learn from others and best practice digitalization projects.

Analyze: In cooperation with the Competence Center, SMEs may also record the degree of digitalization and qualification of their company and employees. This analysis gives a status quo of an enterprise and allows a deduction of measures in the field of technology adoption and staff qualification.

Qualify: Through the application of a sophisticated qualification concept (*LTA-FIT*), the Competence Center uses this module to impart specific knowledge and competences, with the purpose to qualify SMEs and their employees for the challenges arising from a digitalized economy and to enable them to realize their own digitalization projects.

Implement: Based on the acquired competences and knowledge, the Center generates best practice digitalization projects in SMEs. The implementation level ranges from conceptual work to the execution of specific ideas, always considering strategic, technical and organizational conditions and issues. Realized projects are processed for media purposes and service as an example and encouragement for others.

4.2 Qualification Through LTA-FIT: Learning-Training-Assistance

Following the superior purpose to increase the digital competences in SMEs the Competence Center Cottbus applies the self-developed *LTA-FIT* qualification concept. The concept is designed to address the specific needs in German SMEs and offers both, a low-threshold approach for beginners and simultaneously qualification modules for advanced enterprises. The specific target group ranges from shop floor staff members to manager and working council and thus, includes all company levels.

Core component of the concept are the qualification level "Learning" (L), "Training" (T), "Assistance" (A), the didactical framing in terms of "Formats" (F), "Issues" (I) and "Tools" (T). Basis for the application of the concept constitutes an initial analysis which reflects the digital maturity and the qualification degree within a company and its employees.[4] Based on the results a classification is accomplished ranging from low (0 = lowest degree) to very good (3 = highest degree) digitalized and qualified. Following this, an assignment to the qualification level is ensued, which corresponds to the individual needs.

The "Learning" level is considered to aid those who are valued to be not or low digitalized and qualified. Here, rather broad and basic knowledge and competences are provided (e.g. introduction to human–machine-interaction, self and time management). A successful completion of the "Learning" leads to the "Training" sequence. During the "Training" knowledge and competences get solidified through practical work with technologies, demonstrators and use cases. This fosters for instance analytical skills and trains the handling with unknown machines. In the "Assistance" module SMEs address concrete digitalization obstacles and projects, if possible on-the-job. This enables a strong implementation guidance and high practical relevance (Rehe et al., 2020). The qualification level are framed by the didactical approach. In accordance to the individual obstacles and needs, all three level offer different formats, issues and tools. Thus, depending on the addressed topic specific formats (e.g. webinar, workshop, e-Learning) and tools (e.g. videos, virtual walkthrough, digital twin) are used. In Fig. 2 depicts the systematic of the *LTA-FIT* concept. The gradual systematic of *LTA-FIT* shows good impact. Both, quantitative and qualitative evaluations depict a high satisfaction of the trained SME (see Fig. 3).

After proving the high satisfaction of SMEs with the *LTA-FIT* concept in Fig. 3, Table 3 shows the workshops conducted in each field of competence according to the required competences for a digital transformation in Table 1. For each of the four areas of expertise, the appropriate workshops and the associated target groups are listed in

[4] Details on those three core elements are described in Rehe et al. (2020).

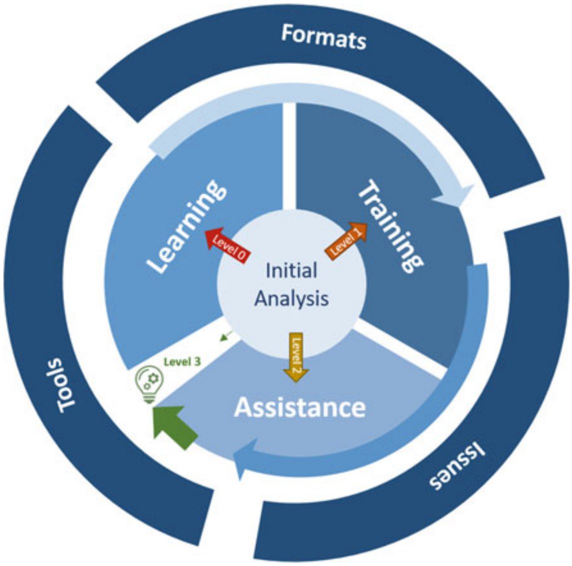

Fig. 2 Structure of the LTA-FIT concept

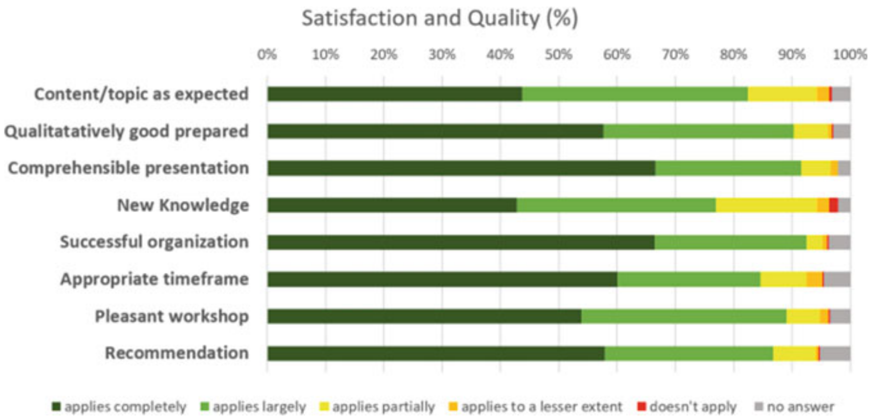

Fig. 3 Evaluation results: satisfaction and quality of LTA-FIT application in German SMEs (n = 416; by December 31st, 2021)

Table 3. For the effective digitalization of SMEs, it is of great importance to address all three target groups. The workshops also cover each dimension of the *LTA-FIT* concept. For this purpose, there are basic workshops that map the learning phase (L) of the *LTA-FIT* concept. In addition, special workshops are offered in which employees or management go through the Training phase (T). For the Assistance phase (A), there are two options that are used: on the one hand, the center heads towards the companies and assist the employees in the implementation of concrete problems on site. On the other hand, it assists the employees at its premises in dealing with new

technologies in relation to their concrete use cases. In general, it is noticeable that the centers workshop formats are primarily assigned to the first two competence fields, domain related competences and action related competences. The reason for this is that SMEs must first be empowered to deal with new digital technologies. The fast-moving business world as well as the strong competitive pressure require above all a quick adaptation to the technical dimension. In the upcoming, the centers builds on offers in social and personal competences based on the technical skills that are now available.

The *LTA-FIT* concept works very well in collaboration with SMEs. In the centers experiences, it is particularly well received because the SMEs are better known throughout all *LTA* phases. The problems of the SMEs are understood more deeply, which allows the center to tailor measures specifically to their needs. Continuous work over a longer period of time creates a relationship of trust between the SMEs and the center. The SMEs get to know and appreciate the numerous experts through learning and training. This is important for the third step of the *LTA-FIT* concept, the Assistance phase (A).

The broad expertise of the center's staff is another important success factor, which leads to the fact that the center's services are regularly recommended to other SMEs. Through this, the performance of the *LTA-FIT* concept is confirmed in addition to the satisfaction from Fig. 3. Another big advantage of the *LTA-FIT* concept is that SMEs are taught to "think in new technologies". Every time new technologies arise, there are new ways of tackling existing problems with more efficient methods or even new interesting fields emerge for SMEs. One example of this is AI. The traditional way of thinking is to give a computer program data and rules to get answers. For AI, the new way of thinking is to give the computer program data and answers to get rules. The same applies to other technologies like augmented reality and virtual reality. SMEs have to learn and practice new ways of thinking to solve their existing problems more efficient to keep up with competing companies that already employed new technologies to their portfolio. In the fields of social and personal competences, an important issue that must be addressed is the fear and the reservations of many employees in SMEs to lose their jobs through the usage of new technologies. Therefore, the center seeks to embrace a positive tech attitude among the employees due to the fact that in every industrial revolution the way of working changed, but not the necessity of good and motivated employees.

Critically, the *LTA-FIT* concept does not work with every SME. Some SMEs are only looking for quick success in implementing new technologies. The center usually lose these SMEs after the training phase (T) at the latest, because they do not have the patience needed to digitize business processes or use new technologies in a meaningful way. In order to retain these SMEs in the future, the center is working on strategies to teach them patience, but also to match the SMEs' expectations with the centers ideas from the outset.

Another area of tension that the *LTA-FIT* concept faces is the varying levels of knowledge and expertise among SMEs. For some SMEs, it is difficult to keep up with the workshops, while for others, more in-depth knowledge is already required. This

Table 3 LTA-FIT concept for building the required competences for a digital transformation in accordance to Erol et al. (2016)

Field of comp.	Workshop (L…learning; T…training)	W	E	M	Example of competence
Domain related comp.	Key figures for SME (T)	x	x		Output overview, optimization of machine adjustments
	Conversation AI (T)	x	x		Building chatbot in cloud
	Optical character recognition (L)		x		Overview and usage of OCR software
	Human–robot collaboration—implementation and programming (T)	x	x		User and programming skills
	Social media—together through the jungle (L)	x			Usage and application of social media tools
	Train-the-trainer: how to create a virtual 3d tour (T)	x	x		Programming skills in 3d environment
	Data protection and information security management—a crash course (L)	x	x		Overview and technical issues
	AI in SMEs: overview and applications (L)				Potential and use cases of AI in SMEs
	Churn prediction with AI: learning how to do it (T)				AI for preventing customer churn
	Localization technologies (T)	x			How to use them in special situations
Action related comp.	Work 4.0—Lego serious play (T)		x		Process understanding and optimization
	Blockchain—understanding the technology and the potential (L)			x	Overview and use cases in transportation and logistics
	Successful strategy development (T)			x	Business strategies in highly competitive environments
	Not being yourself for once—recognizing target groups (L)			x	How to identify the right customers
	Reality is a matter of definition—possible applications AR&VR (L)			x	Overview and applications

(continued)

Table 3 (continued)

Field of comp.	Workshop (L…learning; T…training)	W	E	M	Example of competence
	Inventory management—a system for multi-channel sales (T)			x	Showing digitalized workflow
	Knowledge 4.0—building learning organization (L)			x	Knowledge management in enterprises
	Modeling business processes (T)		x	x	With software tools
	Business model canvas (T)				How to build digitalized business models
Social comp.	Involving employees—relevance and starting points for corporate communication (L)			x	Ways of not losing employees through digitalization
	Brave new digital world? (L)	x			Understanding of new relations and process implementations
	Train-the-trainer: works councils as a target group (L)			x	Enabling multiplicators
Personal comp.	How to manage a home office team (T)			x	Leadership
	Compliance—how your employees follow safety regulations (L)			x	How to raise awareness under the employees

Legend W…worker, E…engineer, M…manager (see Table 1)

point needs to be addressed more strongly in the future and broaden the offerings for different levels of competence.

The *LTA-FIT* concept is not perfect and is continuously improved based on feedback. Nevertheless, it can be stated that in its current form the concept contributes significantly to the digitalization of SMEs in Brandenburg. Which is confirmed by the offered opportunity to become one of the German SME Digital centers.

4.3 Technological Scope of LTA-FIT[5]

Besides the standard curriculum application of the *LTA-FIT* concept the Competence Center Cottbus also approaches its application in technical solutions. This strategy

[5] A comprehensive insight on this application can be obtained online: https://www.youtube.com/watch?v=gYrLtsY6AOc.

aims to encourage SMEs to adopt qualification procedures in the daily business and thus, create a continuous learning environment.

One of the first implementations was realized by using Augmented Reality (AR) glasses. AR enables the transfer of additional information (e.g. job instructions, operating plans) and may support workers during operations such as assembling, remote maintenance or production processes. Similar to the standard curriculum the technical solution offers the level “Learning”, “Training” and “Assistance” (see Fig. 4).

Here the “Learning” sequence gives a basic understanding of a process, namely to assemble cube and cylinder. Thereby, a visual assembling is displayed accompanied by a short insertion text. The “Training” solidifies the information of the previous

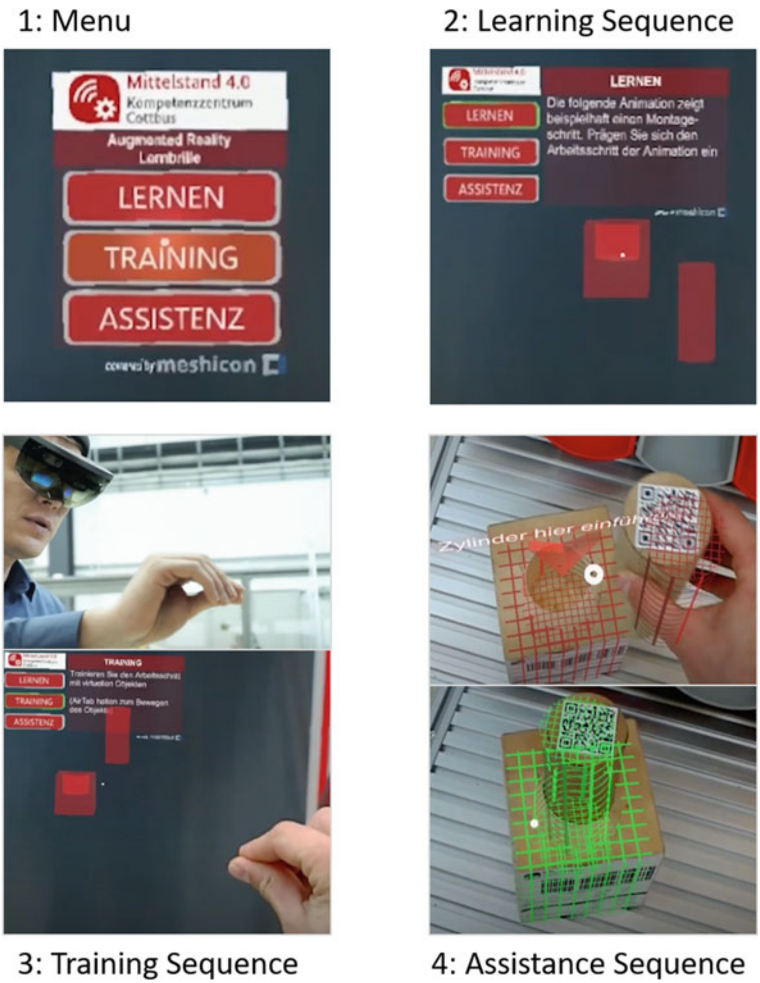

Fig. 4 LTA-FIT applied technical solution for an assembly process

level and request the user to accomplish the assembly process virtually. Subsequently, the user should be prepared to conduct the real process. Thus, in the final level "Assistance" the user has to assemble a physical cube and cylinder. These physical items are tracked by the AR application and a response about the assembling process itself as well as its success can be given.

Another example of a successful AR application is represented by an SME that offers individual murals, posters and wallpapers. After determining the digital maturity of the company, various workshops on AR were held in which the SME's employees learned the basics and possibilities of AR. The center then empowered the employees in the training phase to identify and implement AR use cases. This resulted in the idea of visualizing the murals, posters, and wallpaper through AR using an app on the screen (see Fig. 5). During implementation, the center assisted in creating a prototype. The SME developed this prototype to production readiness and can now drive its own innovations in the AR field through the LTA-FIT model.

Due to the high flexibility and the standardized and automated workflow, the LTA-FIT model can also be extended to other technology areas. An example of this is an SME from the field of artificial intelligence (AI) that checks websites for GDPR compliance (General Data Protection Regulation). For this, first the SME was trained in AI workshops on the possibilities of Natural Language Processing, which is used to process texts in an intelligent way. After the business use case was defined during the "training", a proof of concept could be implemented using an automated machine learning workflow. During the introduction of the productive application, the center

Fig. 5 A poster of a coast line is visualized onto an empty wall through a sophisticated AR application developed by the SME and the competence center Cottbus

AI experts actively supported the SME. In conclusion, the SME is now capable of identifying, planning and implementing such applications on its own.

This concept is applied to many other SMEs. The LTA-FIT model, with its high degree of standardization and automation, is a real guarantee of success and has been very well received by the SMEs.

5 Discussion

In general, it is difficult to quantify the success of the measures in the LTA-FIT model. The competence center did assess the digital maturity of many SMEs in advance so that the offers are tailored in accordance to their needs. However, this is an enormous and very time consuming effort, not only for the center, but above all for the SMEs. Nevertheless, empirically measuring in at least the "Learning" area have been succeeded (see Fig. 3). For the other two areas "Training" and "Assistance" a qualitative analysis through interviews and observation with some SMEs afterwards were conducted. This ex post analysis of the results obtained so far provides several insights. Thus, the implementation of novel and innovative technologies has to be communicated with the workers in the field and has to be accompanied with a thorough risk assessment and development of sound mitigation strategies. The forming of cross-generation working groups respectively tandem working is fostering the LTA-FIT approach especially during training and assistance phase. Complementary standing points and levels of expertise, both in the field of digitalization and automation have to be maintained in the group. A way and methods of introducing "digital ethics" principles improves the applicability. The addressing of aspects as cyber safety and cyber security are highly appropriate. In the competence center a distinct partner is especially taking these aspects into consideration.

In addition, digital infrastructural limitations in remote regions of Brandenburg cause severe difficulties in maintaining a sound digital agenda. These aspects have already been communicated to ministries and municipalities. The center plays a pivotal role here, at is more and more used as voice of the SMEs. The digitalization of the work force causes several disruptions in the ways of collaboration. Digital signatories, time stamps and other means of validation have to be communicated and agreed well.

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A Sandbox Approach for Manufacturing Innovation: A Multiple Case Study

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Abstract This chapter presents an approach for manufacturing innovation, which we refer to as a "sandbox approach". The sandbox approach relies on experimenting with Industry 4.0 solutions in settings that resemble a production environment but with no or restricted interruptions in daily operations. We present a case study of three small and medium-sized Danish manufacturers that have used the sandbox approach as a first step to develop an Industry 4.0 solution to understand the potential of this approach and the effects this creates in the companies. The sandbox approach is an appropriate approach for manufacturing innovation in cases where the company may not be familiar with the technologies they want to exploit, do not understand their own requirements for the solution, or are not sure about the value of a solution they consider implementing and thus cannot make a realistic business case.

Keywords Experimenting · Manufacturing innovation · Production innovation · Industry 4.0 · Sandbox approach · Prototyping · SME · Manufacturing industry · Case study

1 Introduction

The opportunities emerging from Industry 4.0 technologies seem immense, and Industry 4.0 is highly driven by a push of multiple technologies such as Industrial Internet of Things, collaborative robots, and additive manufacturing for the manufacturing industry (Lasi et al., 2014). Previously the introduction of manufacturing technologies (e.g. those associated with Lean) have often been initiated by an application pull or a technology push where the technologies have had specific applications in the industry, such as ERP systems and industrial robots. As opposed

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to this, the relation between technology and application is not predefined for several of the technologies associated with Industry 4.0. Even though the vision of Industry 4.0 is to interconnect processes not only within the organization but also across its boundaries to suppliers and customers, the technical solutions enabling this vision are not predefined (Kagermann et al., 2013; Lasi et al., 2014). Rather it is up to the manufacturers themselves to define the applications based on the available technologies. At the same time, the technologies are still rather new, which implies that industrial applications of these are still limited. This complicates matching technologies and applications for industrial use. Hence, it is required that companies are capable of generating and identifying Industry 4.0 ideas worth pursuing. However, manufacturers, and in particular SMEs, are not used to approach manufacturing innovation in this way where creativity plays a defining role (Larsen & Lassen, 2020; Larsen et al., 2021). They have been used to adopting mature innovations which are much more standardized at the time of adoption, and where the companies are able to get clear instructions on how to implement and operate a solution, and which benefits to expect from such a solution similar to following a recipe in a cookbook. This is for instance the case with Lean methods and tools.

Sometime in the future, the number of Industry 4.0 applications may also be high enough to do a "cookbook" full of recipes for Industry 4.0 solutions. However, the fourth industrial revolution is ongoing, and if high-wage countries do not exploit its potential, they risk losing competitiveness. Despite many companies have the intention to introduce Industry 4.0 in their operations, they do not know how to translate the potential of Industry 4.0 into value in their organization. This is one of the main problems for getting the digital transformations started in industry (Larsen et al., 2021). Therefore, new methods and approaches which can support the companies in introducing Industry 4.0 in their production are needed.

One approach which has proven valuable in several Danish manufacturing companies to explore the potential of Industry 4.0 is the use of experimentation with an Industry 4.0 solution. From this, the companies learn what may be feasible to do, which problems the company may face with setting up the solution, and what value they can expect to obtain (Larsen & Lassen, 2020). We refer to this as a sandbox approach to manufacturing innovation in an Industry 4.0 context where the experimentation refers to a process in which the company "plays" with technologies before deciding which solution(s) to proceed with. The motivation of the process is thereby to explore opportunities and expand horizons rather than solving a specific problem (Garvin, 1993). Furthermore, as the experiments aim to test solutions, they should reveal which solutions work and which may not work (Thomke, 2020). Afterwards, the company may use these learnings to design the final solution to be implemented. In order to avoid interruptions in the daily operations, the experiments are preferably conducted in a way that does not interfere with operations but at the same time the experiments should be conducted in an environment representing the area of application. This can e.g. be achieved by testing on equipment that is not running, testing outside of operating hours, or testing in facilities such as learning factories (Larsen et al., 2019; Pisano, 1997).

2 Methodology

The case studies presented in this chapter are collected during research activities with three Danish manufacturers who have all started their digital transformation but are at different stages of the process. Common to all three cases is that they use the sandbox approach to develop, test, and introduce new technology in the company.

Case company A is a medium sized manufacturer producing customized components for industrial ventilation systems. The company is in the process of a digital transformation and has initiated several initiatives internally. One of them is to test out the use of digital tools in stocktaking. The project is initiated by a young planner in the company, who wants to test out a simple solution to figure out whether it may be valuable to invest in a digital stocktaking system.

Case company B is a medium sized local manufacturer producing small subcomponents in metals which are used in a variety of products ranging from consumer products to heavy industrial machinery. Most of the company's production is mass production of standardized products, manufactured in large batches for a variety of customers. Within the last three years, the company has started their digital transformation journey. Their profits are highly sensitive to the utilization and efficiency of their production equipment for which reason they have decided to install an overall equipment efficiency (OEE) solution on their equipment.

Case company C is a small sized manufacturer producing highly customized components in metal for manufacturing and offshore industries. The company is continuously testing new technologies to improve their competitiveness. One of the projects they are running is to explore whether 3D printing some of their metal components is a feasible solution compared to casting as they do today.

3 Cases: Applications of the Sandbox Approach

3.1 Case A: Digital Stocktaking System

Company A produces customized products and has a production which is highly unpredictable as only approximately half of the orders to be produced within a month are known when the month begins. Until recently, case company A did all their stocktaking of raw materials and parts by shutting down the production one day every six months, and then 120 employees assisted in counting all parts in stock. This was done manually by counting all components and writing down the number of items in stock on a piece of paper. Then ten employees would collaborate to enter the numbers written on the papers into an Excel spreadsheet. The spreadsheet was then uploaded to the company's ERP system and the data in the ERP system was then updated.

The company applied the sandbox approach when an employee suggested to try out an app. Instead of noting down the number of items in stock on a piece of paper, this was entered into the app. Once the employees finished stocktaking, they would send the data directly into an Excel spreadsheet which was afterwards sent to the employee responsible for updating the ERP system with the actual stock levels. This employee would then upload the Excel spreadsheet into the ERP system and the inventory levels would be updated. The app solution costed 9 DKK (app. €1.2) per license and was installed on 20 smartphones, and the risks of testing this solution out would in worst case imply that it would not work, and the employees instead had to do the stocktaking manually as they were used to. While testing the app, the company also decided to change the procedure for doing stocktaking. Instead of shutting down the factory one day twice a year, the company started doing cyclic stocktaking, and at the same time began allocating parts to specific positions in the inventory. Until then, storage space had been allocated randomly, and employees had made separate inventories all around the production, meaning parts were not stored in one common place, but spread across locations. The new way of organizing their stock and in particular the use of the app for stocktaking resulted in the company saving between 200,000 and 300,000 DKK (app. €26,900–40,000) per year in terms of man-hours. In addition to the direct measurable benefits such as cost reduction, the company also improved the traceability of their stock levels remarkably, which implied better planning, and a lower safety stock level.

At first, both white-collar and blue-collar employees were skeptical about digitalizing the stocktaking process. To get the blue-collar employees onboard with the app solution, the management convinced the blue-collar employee with the highest seniority (40+ years) to embrace the solution and assist in getting the rest of the organization on board. The sandbox experiment convinced both white- and blue-collar employees, and today the company is very satisfied with the new way of doing stocktaking.

Currently, the company is in the process of implementing a full-scale digital solution as the app was not a feasible permanent solution but worked out as a sandbox approach and for experimenting with the technologies.

When asked about key learnings of doing a sandbox experiment the Vice President of Supply Chain and Manufacturing stated: "*It has surprised me how much you can do without committing to large investments […] we usually consider projects like this to be very large projects […] but there are a lot of things we can do which will bring us very far in the process.*" Hence, sandbox experiments can in some cases make companies progress with new projects as they do not require an allocation of large investment budgets to the projects from the beginning.

3.2 Case B: OEE Measurements

Since case company B is a mass producer, they are highly sensitive to changes in productivity, which means that small productivity improvements can have remarkable impact on the company's bottom line. Therefore, the company was interested in exploring sensor technology to understand how they might improve their productivity by using sensor technology. The company had limited experience in introducing digitalization in the production, so understanding the requirements and expected value for such a solution was an important aspect. Therefore, the company chose to take a sandbox approach on one of their machines which was not used very often in operation. Thereby the activities could be planned to not affect operations.

In the experiment, the company wanted to build and test a sensor solution which could track the OEE on the machine. At first, the company wanted to achieve this by mounting sensors that would count the number of products produced on the machine which met the quality levels and those which did not. However, after a few iterations using the sandbox approach, where initial attempts had been made on setting up a sensor solution which could do this, the company learned that it would be of more value to them, if they could instead track the OEE on the machine. The company therefore spent the remaining part of the process on building a small-scale OEE measurement system by adding sensors to the machine that would detect whether the machine was operating or not and connected the data to an online, real-time dashboard.

When asked about key learnings, the production engineer responsible for conducting the experiment said:

> Performing this experiment with the OEE system has provided us with a better hands-on experience. Through [the experiment] we have been able to work and play with the data to figure out how to configure the solution on the machine to make it collect the data that we are interested in.

Another important aspect pointed out by the CFO of the company was that choosing and accepting that the sandbox experiment is a low-cost experiment has moved focus away from finances and instead focused on the technical aspects: "*[…] the low-cost technologies may imply that the solution breaks down frequently, but we can see that there is value in such a solution and we can understand it by looking at our own machines. Now we have reached a point where we have to look for a better quality [to use the solution in operations]*".

From the learnings of this experiment, the company decided to implement a full-scale solution. At first, they installed the solution on ten of their machines in the production, but once they have completed the final design of the solution and tested it out for a given time period, they will continue the installation on the rest of the machines.

3.3 Case C: 3D Printing Components

Case company C produces highly customized products which are cast in metal, requiring the company to make new molds for all new designs. The company was, therefore, interested in figuring out whether 3D printing some of their metal components would be a feasible solution instead of casting them as they do today. However, buying a 3D printer for metal printing is expensive and at the same time the company had no experience with 3D printing. They did not know what benefits to expect or what their requirements would be and thereby which 3D printer to buy. Consequently, they were not able to make a valuation of whether it would be most economically feasible to 3D print or cast their components. At the same time, they did not understand which consequences and benefits each of the two solutions might have. Therefore, the company chose to start out with the sandbox approach and experiment with 3D printing. The company bought a 3D printer for plastics and used this to figure out what they can do with a 3D printer, its limitations, and thereby what their requirements would be if they were to invest in a 3D metal printer. Based on this knowledge, the company may be able to determine which value they can expect to harvest from 3D printing some of their components. From these learnings, the company will know what to seek in the market and make an informed decision on whether to invest in 3D printing and thereby change their production method or not. The company started their experiment by first understanding the technology, its limitations and possibilities, and then afterwards looked at the value of the technology once they have a clear understanding of how it works.

About the value of taking a sandbox approach, the CEO said: "*I think that sometimes you need to have the'tools' in your hands to understand'what is this? And what can it do?' then afterwards you can figure out which purpose to use it for*". This indicates that to fully understand the potential of the technologies, you have to understand the technologies first through hands-on experience, which can be accommodated by using the sandbox approach. Furthermore, the CEO pointed out that by using the sandbox approach, competences are built up internally: "*We could have just invested in 3D metal printing from the beginning, but I know that our employees do not have the competences to design 3D prints, and they do not know what it is and what it takes to get it running. Therefore, we have to experiment in small scale by making small constructions and printing them in plastic […].*" Thus, sandbox experiments may also be used to build competences in new technologies within an organization. A third benefit of using the sandbox approach is the opportunity to explore the potential of the technologies for the company and use this as input to make a business case: "*If we had started out with 3D printing in metals then we would end up getting cost prices which would not be profitable […] because we would not be utilizing the potential of the technology*". From these statements it is evident that the benefits of using a sandbox approach for manufacturing innovation in an Industry 4.0 context are multi-faceted.

3.4 Characteristics and Potentials of Using a Sandbox Approach

The three cases show that a sandbox approach is valuable for SMEs to explore the potential of Industry 4.0. Common to the three cases is that they do not have well-defined problems which they are actively seeking solutions for as they start using the sandbox approach. Rather their initiatives come from being curious to explore the potential of certain technologies related to Industry 4.0. To explore this potential, the companies use the sandbox approach which relies on an iterative process in which small-scale experiments are conducted. Learnings from prior iterations are used as inputs for the following iteration(s) and new knowledge is thereby built about how the technology in focus may be used to generate value in the company.

From the cases, we can deduce three characteristics of a sandbox approach. These are:

- An approach for exploring the potential of new technologies.
- Experiment with new technologies at a low cost and low risk.
- The next step in a sandbox experiment is determined continuously based on the learnings obtained so far in the experiment.

The sandbox approach is relevant when companies want to start up a project where the company is:

- Not familiar with the technology (or digitalization of the production in general).
- Not sure about their own requirements for the solution.
- Not sure about the value of the solution and hence cannot make a realistic business case.

Furthermore, we can identify five drivers for using the sandbox approach for Industry 4.0 development which are:

- Cheap to conduct and does not require allocation of a large budget upfront.
- Can be used to develop new technical competences through hands-on experience.
- Can be used to explore and understand a company's requirements for a solution.
- The learnings from the sandbox experiment can be used to draw up a more realistic business case.
- May be used to convince other people in the organization about the value of digitalization.

Following the sandbox approach, the solution design from the sandbox approach must be scaled into a design for implementation. This implies that the company must choose technology suppliers for the solution. Also scaling the solution from a prototype to a full operating solution involving e.g. several machines, plants etc. may require further decisions to be made as these may not have been considered in the sandbox approach. Once the final design for the solution is made, the solution must be installed, and e.g. new operating procedures may have to be introduced to the organization. Hence, after finalizing the design by applying the sandbox approach, an effort must be made in making the final design of the solution, introducing it to the organization, and ensuring successful adoption such that value is generated from the solution.

As SMEs are not used to manage manufacturing innovations, one of the main challenges with the sandbox approach is to convince the management that they need to have a more active role in the process for manufacturing innovation in the context of Industry 4.0 as they cannot expect to find solutions that are ready to be installed now. Furthermore, as SMEs are not used to managing these kinds of projects, it also puts forth requirements for the organization to embrace this new way of adopting new technologies, where they may face several failures and must accept that this is part of the process to achieve a great solution at last.

4 Conclusion

Industry 4.0 requires new approaches which can support the manufacturers in the development of these new solutions, such as the sandbox approach which relies on experimentation with new technologies at a low cost. The three cases presented in this chapter have all used the sandbox approach for manufacturing innovation in an Industry 4.0 context to explore different kinds of technologies and investigate its potential in the companies. Common to all three cases is that the sandbox approach is used to explore Industry 4.0 technologies and their applications in a way that is not heavy on resources but at the same time builds up the company's knowledge on the technology and their requirements for a potential solution.

The use of a sandbox approach is highly relevant in SMEs where both Industry 4.0 competences are low and the budgets for investments in new technologies are limited. As the three cases show, the sandbox approach is valuable when the company possesses highly limited knowledge about the technology and/or the solution and therefore needs to explore the potential and understand their own requirements which is the case of many Industry 4.0 innovations in SMEs.

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Learning Factories for Learning and Experimentation on Industry 4.0 in SMEs

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Abstract SMEs risk being left behind, as the fourth industrial revolution progresses. Waiting until Industry 4.0 is a commodity offered by larger manufacturing and technology companies, means SMEs could miss the opportunity to have their specific needs and concerns met. Learning factories can help SMEs lessen the gap, providing a way to experiment with and learn of Industry 4.0.

Keywords Learning factory · Industry 4.0 · Experimentation · Value-discovery · SMEs

1 Introduction

Larger manufacturing and technology companies are spearheading the ongoing industrial revolution, developing lighthouse factories and systems showcasing the immense potential in Industry 4.0. The technological development is occurring at a significant pace, potentially leaving SMEs, lacking the resources of their larger brethren, struggling to keep up.

With the significant resources available them, larger companies leading the fourth industrial revolution can take advantage of a more aggressive strategy, than their SME counterparts. Larger companies can afford to be less worried about each individual project creating a large amount of value, instead relying on the number and scale of projects to make the strategy valuable (March, 1991).

Such an approach to creating and finding value is less ideal for SMEs. Rather than taking advantage of the economy of scale, SMEs can benefit from a more experimental and explorative approach to finding and creating value through innovation. Research indicates that experimenting and exploratory approaches to innovation can help companies introduce system-wide changes, like those needed for Industry 4.0 (Garvin, 1993; Jerez-Gómez et al., 2005; Li, 2020). Taking a more exploratory

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approach, SMEs can investigate numerous areas with potential value, whilst postponing the commitment of larger investments. If the experiment demonstrates that the potential value is too low, projects can quickly be shut down, and SMEs can move on to new areas. This approach requires a more agile and iterative approach, highlighting an incremental way to value discovery or exploration.

Learning factories can provide companies with such an environment for pilots, demonstrations, and experiments. They are deemed highly suitable for Industry 4.0 learning in both industry and academia (Abele et al., 2017; Andersen et al., 2019). The close resemblance of a learning factory to a full-scale manufacturing system, can let companies explore their concrete challenges, and test out solutions and technologies in a context close to their own, without interfering with ongoing operations (Pisano, 1997), and at a lower level of complexity than a full-scale manufacturing system (Abele et al., 2019; Küsters et al., 2017).

The following sections introduce the learning factory as a way for SMEs to engage in the implementation and exploitation of I4.0 technologies. Firstly, the learning factory is defined, and current trends and benefits from using learning factories are outlined. This is followed by a look into how learning factories can be used as a center of experimentation, helping SMEs on their journey to Industry 4.0.

2 What Are Learning Factories?

A learning factory is, briefly summarizing the CIRP Encyclopedia (Abele, 2016), a learning environment closely resembling a real value chain, with authentic technical and organisational processes. It can be used for both competence development and innovation through formal, informal, and nonformal learning. Learning factories can be used to learn and demonstrate a wide variety of technologies and paradigms. Existing configurations, for instance, showcase reconfigurability and changeability (Abele et al., 2017; Andersen et al., 2019), process improvements (Abele et al., 2017; Cachay & Abele, 2012; Kreimeier et al., 2014), and resource and energy efficiency (Abele et al., 2017; Kreimeier et al., 2014; Kreitlein et al., 2015).

Based on the definition above, the CIRP Collaborative Working Group on learning factories (Abele et al., 2019) developed a descriptive model of learning factories. The model combines the most recent research on how to understand and characterize a learning factory. It deals with (1) design of new learning factories, (2) capturing characteristics of existing learning factories, and (3) identifying learning factory designs for specific situations. The model groups 59 characteristics and their respective attributes into seven dimensions (Operational Model; Targets and Purpose; Process; Setting; Product; Didactics; Metrics). It is considered a solid overview of recent research on learning factories, and widely cited in research on learning factories (e.g. Enke et al., 2017; Küsters et al., 2017; Mavrikios et al., 2017).

Within the descriptive model and existing research on learning factories, two primary applications are highlighted: (1) environments for education and training of university students and industry participants and (2) learning factories as research validation environments. Learning factories for education and training focus on improving the knowledge and experience of participants, such as students, engineers, or blue-collar workers, e.g. with installing and using Industry 4.0 technologies (Faller & Feldmüller, 2015; Karre et al., 2017; Merkel et al., 2017). This type of learning factory is characterized by relatively well-defined learning goals, and a static set-up and design of the learning factory itself (Abele et al., 2017, 2019; Kreimeier et al., 2014; Larsen et al., 2019; Tisch et al., 2013, 2016).

Learning factories, when used as a research tool, enable researcher to test their hypothesis and research results on a system closely resembling a real value chain. Such learning factories, as previously mentioned, allows continuous testing, frequent changes, and interruptions on a working system with no or little interference to ongoing production operations (Pisano, 1997). This also makes it less complicated than validating research in real-world scenarios (Abele et al., 2019; Küsters et al., 2017).

Outside these two applications, learning factories also serve as a three-way link between industry practitioners, researchers from academia, and students, providing significant benefits to all three parties. They can also help connect researchers and teachers from universities with students, thereby improving education and engagement. Figure 1 shows how learning factories can help connect industry with faculties at research institutions, as well as students at the faculties.

From an industry point-of-view, learning factories provide a pipeline for potential future employees, and a way to identify world-class engineers-in-training. Should companies make their challenges available to students as projects, they can get an outsider's look on the challenges, and some out-of-the-box ideas that can help address the challenges. Looking towards the researchers in academia can provide companies with a way into the world of academia, which can be an otherwise daunting task, without having already established contacts. This can help companies keep on top of the latest research, making them more aware of what is going on at the bleeding edge of their fields, both in terms of technology and methods. For technology in particular, learning factories provide a solid platform to test the newest technologies, and determine their value for the industry.

Naturally, the industry is not alone in benefitting from such a connection. Linking researchers and students with industry can propel forward both research and teaching. Researchers get to work and test their hypotheses on real-world problems, which can provide valuable results and context for their future research. It helps researchers understand industry needs, which may be difficult to articulate without a close collaboration.

For students and faculty, the learning factories help link theory and practice, letting students experience putting the theories and concepts they learn in the classrooms into practice. Through this, students achieve a better understanding of theory, and the learning factory opens up for new ways to enrich the classroom experience. Moving the center of experimentation or learning closer to a real-world scenario changes the learning mode from learning before doing, more towards learning by doing, as shown on Fig. 2 (Pisano, 1997). All of this helps increase student engagement, as they work on non-trivial problems and gain valuable experience and skills, which the industry

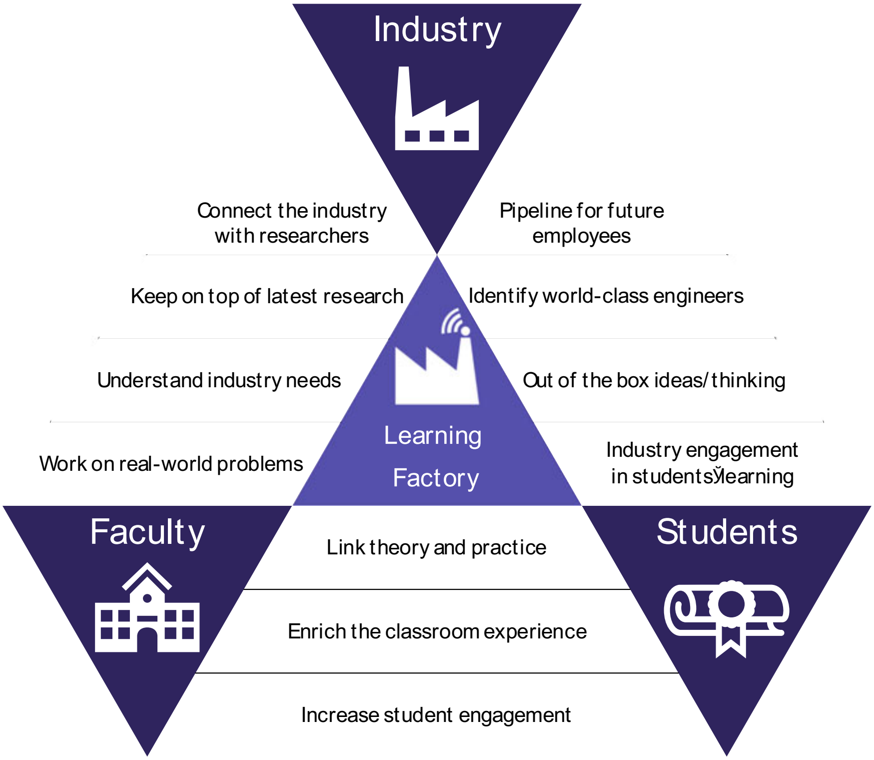

Fig. 1 Learning factories can serve as a three-way connection between industry, faculty, and students. Adapted from Bernard M. Gordon Learning Factory at PennState College of Engineering. https://www.lf.psu.edu/

is calling for (see e.g. Abele et al., 2017; Wagner et al., 2015; Ziemiean & Sharma, 2008). This benefits both academic students, and students from the industry, who can better relate their learning experience with the learning factory to what they see in their daily work.

3 SMEs and Experimentation

Recent research shows that an agile and experimental approach can greatly benefit SMEs working on their transition towards Industry 4.0 (e.g. Larsen et al., 2021). Looking closer at Fig. 2, experimentation can be carried out in a variety of circumstances and conditions and take on many different forms. The lowest form of representativeness, or closeness to the working environment, is using theory, algorithms, and heuristics. These are not simply to be discounted because their abstraction level

Closeness to working env.	*Center of Experimentation*	*Learning Mode*
High	Full-scale factory	By doing
↕	Learning Factory at production site	↕
	Learning Factory at development site	
	Laboratory	
	Computer-aided simulation	
Low	Theory, algorithms, heuristics	Before doing

Fig. 2 How the closeness of the center of experimentation to the working environment relates to the learning mode. Adapted from (Pisano, 1997)

is high. They act as the foundation for the more representative types of experimentation. Alongside the second lowest level, computer-aided simulation, they provide a way to experiment with and test hypotheses in a virtual manner, committing only the necessary processing power to perform the needed calculations and simulations. Both these types of experimentation represent a learning-before-doing mode of learning. Simulations creating virtual factories and virtual training brings simulation more towards the learning-by-doing end of the spectrum.

As the closeness to the working environment increases, the outcome of the experiments is greatly affected. Solutions, processes, and technologies developed and tested under laboratory conditions, or at lower levels of representativeness, cannot always achieve the estimated performance shown in the laboratory, when implemented and running in a full-scale factory. Several conditions of the intended final working environment, which are difficult to capture at the lower levels of representativeness, can affect the performance of the solution. Pisano (1997) highlights this as "…not a problem of technology *transfer*, but one of technology development."

Learning factories come in at the fourth and fifth levels of representativeness, depending on the physical location of the learning factory. These learning factories, allow experimentation with equipment and process closer to those in the real factory, without using up resources and capacity required for ongoing operations. Learning factories also enable developers to control more aspects of the testing process. In full-scale factories, the highest level of representativeness, it can be difficult to identify all relevant conditions and variables, and nigh on impossible to replicate future conditions. Testing and learning in full-scale factories do lead to more accurate results, but at a higher cost per experiment. Experimentation on learning factories can help cut down the needed number of experiments, by creating valuable knowledge and experience of the involved equipment, technologies, and processes, before full-scale tests in real factories.

Using learning factories for experiments supports the previously mentioned exploratory approach to value discovery and creation. It can help SMEs adopt a more agile approach to development and accelerate the overall process. Learning factories are well-suited to opportunity-driven value discovery approaches where iterations and speed are in focus, such as lean start-up, highlighting creation of prototypes and minimum viable products through the build-measure-learn cycle.

Research has found that focusing on technical competences is not sufficient for a successful fourth industrial revolution. Instead, a broader conceptual understanding of the value chain, systems, and processes, is needed to properly innovate for Industry 4.0 (Lassen & Waehrens, 2021). Exactly which skills and competences are needed is difficult to say, as this will depend on the specific solution in focus. Through hands-on experience, learning factories help build up the technical and conceptual competences needed to understand and make decisions regarding a company's challenges and potential solutions.

4 The Case for Learning Factories

To illustrate how learning factories can be used for experimenting in industry, three cases are described below. All three cases were carried out as a collaboration between Aalborg University, and a number of manufacturing companies and technology companies. Each case is outlined below in terms of what was experimented with and demonstrated, how a learning factory (specifically the Aalborg University Smart Production Lab[1]) was used, who the participants were, and what was learned.

4.1 Case 1

For the first case, the intention was to demonstrate a smart manufacturing system enabling efficient production of personalized products. To achieve this, the learning factory was used to build a demonstrator using two conveyor belt modules, separated from the main production line of the learning factory. This allowed on-going research and operations to continue on the main part of the learning factory. The demonstrator further made use of the learning factory's MES and ERP systems.

Participants included: three middle managers from a manufacturing company; four middle managers from a technology company; one middle manager from another technology company; and six researchers from two research institutions. Through the demonstrator, a manual workstation was constructed, demonstrating how the goal of efficient personalization could potentially be achieved.

The participants from the manufacturing company learned how to create value in the production by applying various Industry 4.0 technologies, such as sensors

[1] https://www.smartproduction.aau.dk/Laboratory/

and data integration. Furthermore, participants gained experience in working more systematically with the development of Industry 4.0 solutions. A full Industry 4.0 production line was built, where technologies and processes were closely integrated, and changes to one part of the production affected the remaining system.

4.2 Case 2

The second case built upon the manual workstation developed during first case. New technologies, such as pick-by-light, was added to the smart manual workstation. None of the companies from the first case participated in the second. Participants included: a middle manager and three engineers from a manufacturing company; an internal consultant from another manufacturing company; a middle manager and a consultant from a technology consultancy; and two researcher and a laboratory engineer from a research institution.

Participants from the manufacturing companies gained in-depth insight into the problems and challenges which could occur when building Industry 4.0, and how to manage them. Since a physical demonstrator was built, new technical competences were also acquired, relating to the specific technical solutions used for the demonstrator, as well as how separate technologies can be combined to obtain a full stand-alone solution. Furthermore, an agile development process was employed, providing the participants with experience on how to work in and manage Industry 4.0 projects in an agile manner.

Based on the physical demonstrator built on the learning factory, one of the manufacturing companies decided to proceed with the solution in the own company. They concluded that it suited their organization best to pay consultants to further develop this solution. However, it was noted that working with the demonstrator provided participants with the knowledge and competences to enter a dialogue with the consultancy, and helped the participants clarify their needs.

4.3 Case 3

In the third case, the focus was on data collection and utilization through sensor technology. The demonstrator was built both on the main learning factory production line, as well as on one of the modules used in case 1. None of the companies from case 1 and 2 participated in the third case. Participants were: three top managers from a manufacturing company; a top manager from another manufacturing company; a consultant and a top manager from a technology consultancy; a top manager from a technology company; and nine researchers.

Participants gained competences and knowledge on Industry 4.0 technologies including sensors, the value these can create when integrated into a more extensive solution, and how to solve occurring problems with these technologies. They learned how to use experimentation and an agile development process to manage Industry 4.0 projects. Working with the demonstrator, the participants have learned what it takes to get the solutions they want, and how to realize them by combining technologies to develop a full solution for their production. One of the manufacturing companies used these learnings to start an internal project, leading further development themselves, rather than outsourcing this task to a consultancy. They have since turned the demonstrator into an operational solution.

5 Discussion and Concluding Remarks

Learning factories, as changeable environments with authentic technical and organizational processes closely resembling real value chains, can be powerful tools for learning about and experimenting with Industry 4.0. At learning factories, engineers and managers from industry can meet with students and researchers of academia and find a common ground to work on real challenges, using the latest technology. With experimentation and knowledge creation at its heart, learning factories can help companies accelerate their development and value-discovery process. SMEs, lacking the resources of larger companies, should pay particular attention to learning factories in the future, as a way to catch up on Industry 4.0 technologies.

Below, the main characteristics of learning factories highlighted in this paper are listed. They represent a summary of five important areas of learning factories, that one should be aware of when working with and designing learning factories.

- A setup closely representing the real working environment of the developed solution. Depending on the intended working environment, the setup should have both a physical (hardware) and logical (software) component. Cyber-physical systems are particularly interesting in the context of Industry 4.0. The setup itself should be changeable, to support the test of as many different hypothesis and technologies as possible.
- Exploratory and experimental approach to development and value discovery. Build prototypes and carry out experiments to gain hands-on experience with the solution and determine its value.
- New technologies undoubtedly play a big part in Industry 4.0. Learning factories intended for experimentation and learning about Industry 4.0 should support this. It should be equipped with the relevant technologies for communication and integration, enabling collection and usage of data, as well as both automated and manual manufacturing processes.
- Work on real problems. A problem-based-learning approach supports critical thinking, and can foster both engagement and knowledge creation, letting participants relate their learning experience to their own context.
- Technical and conceptual competences are both needed in the ongoing paradigm shift. Significant changes to basic assumptions and principles are occurring,

meaning new knowledge must be created, and an increasingly holistic understanding of the systems and value chains in place is needed.

Research on what exactly characterizes learning factories designed for both technical and conceptual knowledge creation is limited (Larsen et al., 2019). Many learning factories are focused on teaching technical competences in, e.g. lean, planning, manufacturing, assembly etc. (Abele et al., 2019). This learning happens primarily through transfer of knowledge from one party to another, i.e., from teacher to student, but also through knowledge creation, occurring as participants experiment and work together on open-ended problems.

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