SMART INDUSTRY – BETTER MANAGEMENT

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SMART INDUSTRY – BETTER MANAGEMENT

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INTRODUCTION

Tanya Bondarouk and Miguel R. Olivas-Luján

The age of Smart Industry has arrived! Definitions of Smart Industry are abundant (Habraken, this volume); however, most authors agree on the following characteristics. It involves future-proof industrial and product systems, which are smart and interconnected, and make use of Cyber Physical Systems, digitization, connectivity, and new manufacturing and product technologies (Kagermann, Helbig, Hellinger, & Wahlster, 2013). The history of and discourse around Smart Industry originated in Industry 4.0, the initiative that took off in Germany during the industrial trade fair Hannover Messe in 2011 (Pfeiffer, 2017). Following the trade fair 2011, the vision behind Industry 4.0 has spread to other countries under names such as 'Made in China 2025', 'Make in India', 'Advanced Manufacturing' (USA), Industrie 4.0 Österreich (Austria), Indústria 4.0 (Portugal), IPAR4.0 National Technology Initiative (Hungary), and Smart Industry (Netherlands), to name a few. Despite different labels, advocates of this initiative describe huge potentials for manufacturing industries. Among the promises, we can identify creating dynamic business and engineering processes, meeting individual customer requirements, facilitating optimized decision-making, and solving broader challenges like demographic change and resource efficiency (Habraken, 2020). In this volume, we have brought together high-quality articles that focus on innovative, evidence-based, cutting-edge research, case studies, new conceptualizations, and viewpoints on management in the age of Smart Industry.

Paraphrasing Huizinga et al. (2014), we emphasize the importance of a strategic vision of the future industry: a high degree of flexibility in production, in terms of product needs (specifications, quality, design), volume (what is needed), timing (when it is needed), resource efficiency and cost (what is required), being able to (fine-) tune to customer needs and make use of the entire supply chain for value creation. It is enabled by a network-centric approach, making use of the value of information, driven by Information Technologies and the latest available proven manufacturing techniques.

Another unique characteristic of this book is the combination of research conducted in divergent traditions of social sciences and engineering sciences. We need knowledge from all types of studies if we want to understand the complexity of recent developments in Smart Industry.

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Thus, Agata Leszkiewicz, Tina Hormann and Manfred Krafft discuss the impact of adoption of artificial intelligence (AI) on various stakeholders of a business-to-business organization. The cost-benefit approach allowed the authors to define the social value of AI as the combined value derived from AI adoption by a (B2B) organization with multiple stakeholders. The chapter explores further the social value of AI as the trade-off between (1) the benefits and improvements this technology brings for stakeholders and (2) the costs and concerns that arise from it. Specifically, we look at the impact of AI on (1) the internal stakeholders in the firm (e.g., executives, employees, etc.), (2) business customers, supply chain partners and competitors, and (3) society at large.

Klaas Stek takes us further in the discussion and his article claims that there is a serious gap between the intended learning outcomes in higher education and the needs of employees in Industry 4.0. His analysis shows that the history of the preceding industrial revolutions had the drawbacks of personality and character education; politicians have abused it to control societies in the nineteenth and twentieth centuries. The logic that soft skills are necessary to carry out hard skills calls for a shift towards a new type of citizenship that shapes the research question in the chapter: whether soft skills in education can lead to improved citizenship.

Sylwia Przytuła, Katarzyna Tracz-Krupa and Susane Rank continue the discussion about readiness for the impact of Smart Industry, but in the organizations, specifically – within and through the HRM function. Their chapter clarifies the state of opinion on expectations towards, and preparedness for, the impact of Industry 4.0 on human resources management and the implementation of various types of ambidexterity in these companies. By means of interviews with key HR informants from manufacturing companies operating in Germany and Poland, the authors have found that Industry 4.0 has a significant impact on HR practices. In international companies, various digital solutions in employee recruitment, development and performance have been implemented. There have also been mature examples of structural, contextual and sequential ambidexterity. Marie Molitor and Maarten Renkema investigate effective human-robot collaboration and present implications for Human Resource Management. Their research presents results of a vignette study that investigated factors affecting intention to collaborate with a robot.

Fabian Akkerman, Eduardo Lalla-Ruiz, Martijn Mes and Taco Spitters take us further on the Smart Industry road, to the field of a supply chain distribution and logistics strategy for which less-than-truckload shipments are consolidated into full-truckload shipments, also called cross-docking. The authors present results of the literature review on cross-docking literature, from 2015 up to 2020, that allows them to conclude about growing attention for Industry 4.0 concepts in cross-docking, especially for physical internet hubs (PI-hubs).

Ednilson Bernardes and Hervé Legenvre explored the nature and functioning of the inter-organizational governance mechanism underpinning an increasing number of Smart Industry initiatives. They also considered the nature and position of the technology within the broader set of technologies and the selected governance mechanisms and their relation to value capture.

The article by Devrim Murat Yazan, Guido van Capelleveen and Luca Fraccascia provides a conceptual framework about the current status and future development of smart decision-support tools for facilitating the circular transition of Smart Industry, focussing on the implementation of the industrial symbiosis practice. Based on the principles of a circular economy, the utility of such practices to close resource loops is analysed from a functional and operational perspective. For each phase of the life cycle – e.g., opportunity identification for symbiotic business, assessment of the symbiotic business and sustainable operations of the business – the role played by decision-support tools is described and embedding smartness in these tools is discussed.

Finally, the article written by Christian Versloot, Maria Iacob and Klaas Sikkel brings us to the companies that specialize in providing an analysis of the underground. Geophysical techniques such as Ground Penetrating Radar (GPR) are harnessed for this purpose. The authors present their work to amplify the analysing GPR data by means of Machine Learning (ML). In this work, harnessing the Action Design Research (ADR) design science methodology, an Intelligence Amplification (IA) system is designed for decision-making with respect to utility material type. It is driven by three novel classes of Convolutional Neural Networks (CNNs) trained for this purpose, which yield accuracies of 81.5% with outliers of 86%. The tool is grounded in the available literature on IA, ML and GPR and is embedded into a generic analysis process.

It is not difficult to notice that all nine chapters differ in terms of the research discourse and vocabulary, research methods in case of empirical studies, and application cases (types of industry). We have learnt a great deal from these chapters and engaging in the double-blind, peer-review process for all submitted manuscripts. To our knowledge, this is one of the first volumes that have combined manuscripts that describe one increasingly influential industry phenomenon in contemporary management – Smart Industry. We are convinced that this is the way to progress in science and practice: through integration of social and engineering research, to understand, cross-pollinate, and improve the discourse through approaches that are less familiar. The challenges brought about by the COVID-19 pandemic, particularly in the area of supply chain management, magnify the importance of such multi-disciplinary approaches into the future.

We are very thankful to all the authors, who joined us in this journey to explore the complexity of Smart Industry. Now, it is our readers' turn to contribute to this ongoing conversation!

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REFLECTIONS OF UNDERSTANDING SMART INDUSTRY

Milou Habraken

ABSTRACT

This chapter reflects on the understanding of the phenomenon known as Smart Industry, Industry 4.0, fourth industrial revolution, and many other labels. It does so by reflecting on the issue of terminology, as well as the existing diversity regarding the description of the phenomenon. The issue of meaning is addressed by assessing the results from Culot, Nassimbeni, Orzes, and Sartor (2020) and Habraken and Bondarouk (2019) which are, subsequently, used to develop a workable description. Findings from the two assessed studies raise the question of whether a workable construction of the phenomenon is to be understood as the key technologies or the distinctive developments? A question without a definitive answer, but I will present my view by taking inspiration from the manner in which the prior industrial revolutions are commonly understood. This leads to a, still multifaceted though, more focused understanding of the phenomenon. The insights, formulated proposition and developed model stemming from the reflection of terminology and meaning of the phenomenon helps move the current technology-related phenomenon forward. They assist with the establishment of well-documented papers. A critical aspect if we aim to understand how management will look like in the era of this phenomenon.

Keywords: Smart Industry/Industry 4.0; terminology; meaning; model; fourth industrial revolution; smart manufacturing

What started out as a German initiative to strengthen the competitiveness of the German manufacturing sector resulted in a global phenomenon which has received an increasing amount of attention over the past years; a development that has been documented both in words and numbers. But contradictory to its popularity, the understanding of the phenomenon is surrounded by ambiguity. For not only did the interest in the phenomenon

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grow, so did the number of labels and meanings related to the phenomenon. Given the impracticality behind this combination (i.e. popularity and ambiguity), the confusion and lack of conceptualization of the phenomenon has received attention by scholars. With a recent study being the systematic literature review by Culot et al. (2020), the authors assessed definitions for the phenomenon, that is Industry 4.0 and similar concepts, in academic as well as non-academic articles. In light of the findings from this systematic literature review, the proposition written in the dissertation by Habraken (2020, p. 136) and the importance of establishing a more stable foundation from which to work with regarding the current phenomenon, this chapter reflects on the understanding of the phenomenon from both a terminology and meaning perspective. By reflecting on noticeable issues that are at play, steps can be constructed that will help move the phenomenon forward. In other words, this chapter does not offer specifics when it comes to the question of management in the era of the current phenomenon. The combination of novelty and diversity surrounding the phenomenon makes how management will look like in this era a topic that requires time and, importantly, well-documented efforts. In contrast, this chapter offers insights that will assist with the creation of answers to the question of management in the era of the current phenomenon. It does so by reflecting on the notion of the label the fourth industrial revolution and the existing yet unnecessary diversity in labels which creates an integration challenge, both of which address terminology, and the multifacets of the phenomenon as well as the topic of workability which are both grouped under the understanding of meaning. But first the understanding of terminology is addressed.

UNDERSTANDING OF TERMINOLOGY

Made in China 2025, Make in India, Advanced Manufacturing, Smart Manufacturing, Factories of the Future, Industrial Internet, Industrie 4.0 (translations like Industry, Indústria & Pramonė 4.0), or… Smart Industry. They are all examples of, likely many more, labels that currently exist to highlight a phenomenon that is also often referred to with the term the fourth industrial revolution. Before turning to the apparent diversity, I first want to focus attention on the notion of the fourth industrial revolution.

Fourth Industrial Revolution

To start, let it be clear that the phenomenon in question can bring about fundamental changes (i.e. be disruptive). From this point of view, the terminology of a fourth industrial revolution is definitely appropriate. However, it is relevant to consider that a revolution is also tied to the concept of speed, as visible in understandings of the word 'revolution' – 'are *fast*, disruptive and destructive' (Blanchet, Rinn, Von Thaden, & De Thieulloy, 2014, p. 7) – and the word 'industrial revolution', 'a *rapid* major change in an economy…' ('Industrial Revolution', n.d.). When one takes this lens into account, the fit appears to become less suitable. The prior sentence includes the word 'appears' for, as Madsen (2019) points out, there is 'relatively little evidence on I4.0 adoption rates in different parts of the world' (p. 14). In addition, what is considered fast in this context is open to different interpretations. Consequently, a definite outcome regarding the speed of this phenomenon cannot be made. Nonetheless, available data do not hint at the phenomenon being a fast development.

For example, in 2016, two years after the introduction of Smart Industry in the Netherlands, only 15% of the respondents in a Dutch survey among entrepreneurs indicated to have heard of the term Smart Industry (Smetsers & Borst, 2017).[1] Within the same survey conducted in 2020, still 72% of the respondents stated to never have heard of the term or, having heard of it but not knowing what it is (Vegter, Witvliet, & Reinhartz, 2020). Though it is possible that companies have Smart Industry elements in place while being unfamiliar with the terminology, this is expected to be an exception rather than the rule; especially with the phenomenon being promoted at national and regional level as well as by platforms such as the Dutch Chamber of Commerce (KvK). The fact that respondents only represent small and medium sized enterprises (SME's), that is companies up to 50 employees, in addition cannot be used as a justification for the results since firms up to 50 employees account for 99% of all Dutch businesses in 2019, according to Statistics Netherlands (CBS) (2021). They make up the bulk of the economy and must therefore be considered when it comes to the speed of the revolution. The mention of barriers for adopting Smart Industry, like lack of time and investment budget, in the 2016 and 2020 survey further signals that the phenomenon does not have the speed associated with a revolution. The presence of barriers even transcends the Netherlands as can be understood from publications like Moktadir, Ali, Kusi-Sarpong, and Shaikh (2018) or Orzes, Rauch, Bednar, and Poklemba (2018). Lastly, results predate COVID-19, excluding it as an explaining factor.

To conclude, the phenomenon does not appear to be fast or rapid. Neither should that be a goal in and of itself. Technology needs to serve a purpose, and not be introduced because it is available. However, from a terminology perspective, the applicability of the label fourth industrial revolution can be questioned when adding speed to the equation. From solely a disruption standpoint, the term is understandable. As its predecessors, the term fourth industrial revolution indicates the presence of a major change. Whether we need a separate term to stress this fact, especially with the number four embedded in labels such as Industry 4.0, is another discussion.

Diversity of Labels

Having addressed the essential distinction in the interpretation of the word revolution, I turn to the existing diversity in labels used to denote the phenomenon. For some labels the overlap with the initial, German terminology Industrie 4.0 is relatively clear and interchangeability can therefore be easily assumed. Other labels are more unique and, as a result, give the impression that the label represents something different; in other words, not related to the Industrie 4.0 phenomenon. But based on the following evidence, the distinction signalled by the use of unique labels can be considered a pretence:

> You should not bring a German term like Industrie 4.0 to the Netherlands. We don't really like German labels, it must always sound a bit English, and if you give it an original name it seems as if you invented something new. As if you invented it yourself. Then of course it is very smart to call it Smart Industry. (A quote from a Dutch Smart Industry expert; from the study discussed in Habraken & Bondarouk, 2019)

> Implementing advanced manufacturing technology services/Industry 4.0… (Sentence on the website of the National Institute of Standards and Technology, that is part of the US Department of Commerce[2])

> In response to the recent global reindustrialization tide and Germany's high-tech strategy Industry 4.0, the State Council of China announced the Made-in-China 2025 Plan in May 2015 and Both Industry 4.0 and Made-in-China 2025 focus on the new round of industrial revolution and employ manufacturing digitization, CPS, IoT, and intelligent manufacturing. (Li, 2018, pp. 67–68)

> The analysis [a systematic literature review of academic studies providing a definition of Industry 4.0 and similar concepts] underlined how very few differences among definitions can actually be explained by the label used to describe the phenomenon. (Culot et al., 2020, p. 9)

The diversity with which we are faced with today thus stems from: 1. translations of the original German label into ones native language and a more international applicable, or English, label; 2. a countries desire to create their own label or brand to denote, the countries specific approach regarding, the phenomenon that arose in Germany, and; 3. creations by companies, General Electric for instance promotes the term Industrial Internet (Evans & Annunziata, 2012). These origins are also what make the movement towards the use of a single label complicated. Countries and companies cannot simply change a promotional label which they have heavily invested in. And as long as countries and companies use their labels, so will, in all probability, the academics and consultants embedded within those countries/companies. As Habraken (2020) pointed out, the use of a single label among scholars will therefore only be established if this topic is discussed. An achievement which, given the broadness of the phenomenon (i.e. scholars from a wide range of disciplines are involved), is a challenge in and of itself. As a result, a question that arises is whether the obtainment of one label is of enough importance that it justifies tackling this huge challenge? Or, can we work with the current unnecessary diversity while at the same time reduce expected issues as much as possible, such as a lesser awareness of scholars conducting research in this domain leading to reinventions of the wheel.

Though I am in favour of the establishment of a single label, it might be better to work with the situation that has emerged. Not just because of the complexity of the challenge, but also since striving for full awareness of all domain-specific knowledge is in general – thus probably also with a single label – a difficult task to achieve given today's knowledge generation and dissemination age. It, however, does not imply that we should abandon all attempts to improve awareness and integration. To assist this, existing developments like the presence of duplicate key words (i.e. the inclusion of several of the aforementioned labels as distinct key words) could be embraced and used to our advantage. For example, we could agree on counting a certain set of words as a single key word (e.g. to see inclusions like Industry 4.0, Smart Industry and Advanced Manufacturing as one entry). This would allow the retaining of multiple interchangeable labels while facilitating knowledge transfer across diverse labels, without interfering with the limitations, often placed on the available amount of key words.

UNDERSTANDING OF MEANING

As with the number of labels, diversity is also apparent regarding the description of the phenomenon in question. But the presence of various descriptions cannot be attributed solely to the existence of a multitude of labels. First, there are multiple definitions in existence, offered by both scholars and practitioners, with respect to one label. Take for instance the prevalent label Industry 4.0. In the paper by Culot et al. (2020), it is mentioned that 42 definitions of Industry 4.0 were found in the included academic sources and six definitions in the non-academic sources assessed. Bringing the number of descriptions for the label Industry 4.0 already to 48 based only on papers included in the systematic literature review by Culot et al. (2020). Second, Habraken (2020) showed that the label Smart Industry in the Netherlands has been described differently over time, by one source. Observations that in part are due to new insights, that is, descriptions changed with new knowledge. But another reason lies in the different facets, each containing various elements, that encompass the phenomenon. It, in other words, facilitates the emergence of variations. This presence of multiple facets also explains why the phenomenon is often coined as being 'broad' and 'overarching'.

In the next part, I will briefly elaborate on the different facets, using results from the systematic literature review by Culot et al. (2020) and the qualitative study pertaining to Smart Industry by Habraken and Bondarouk (2019). The inclusion of the latter paper stems from its analyses of the term Smart Industry which, despite the vast list of selected terms, was not considered by Culot et al. (2020). I am aware that this incites the question, what about all other related terms that were not incorporated? My intention with the addition was not to cover all existing labels, but rather arose from the use of the term Smart Industry in the title of this book. As a result, it was found to be a relevant inclusion to make.

Multiple Facets

In the paper by Culot et al. (2020), the notion of the multiple facets becomes evident by the fact that four coding categories were created, or needed, to refer to the constituting elements of the phenomenon: key enabling technologies, other enablers, distinctive characteristics, and possible outcomes. With *key enabling technologies*, the authors imply the main technological innovations supporting the change, or the technological drivers. Specifically the following 13 elements (not counting the unspecified element) – stated in order of popularity, with the number of observed occurrences indicated in brackets:

Internet of Things (84), cloud computing (81), machine learning and artificial intelligence (64), cyber-physical systems (63), simulation and modelling (63), big data analytics (63), interoperability and cybersecurity solutions (62), 3D printing (51), visualization technologies (47), advanced robotics (39), new materials (17), energy management solutions (16), and blockchain technology (11).

It is a category that is, in and of itself, broad since the phenomenon does not stem from a development in one domain but rather various fields. In other words, it is 'not about a single breakthrough invention but comprises several "tech ingredients"…' (Culot et al., 2020, p. 5). The category *other enablers* consists of the elements organizational enablers and business model innovation. Regarding the first, the following points are implied: organizational design should pursue higher inter- and intra-organization linkages, organizational structures should flatten out to accommodate distributed decision-making, and digital and strategic capabilities will be needed at all levels (Culot et al., 2020). These factors tie in with aspects that Habraken and Bondarouk (2019) classified under the heading preconditions (e.g. supporting infrastructure, people's ability to adapt and maintain value-adding capability, legislation-related issues). The element business model innovation, in contrast, was stated to be related to the increasing spread of smart products (i.e. products with integrated data-driven services or data-driven services that replace traditional product sales) and new forms of production such as 'home manufacturing' due to 3D printing, and offering activities via digital platforms (Culot et al., 2020). Based on this explanation, the element business model innovation appears to fit better under the category distinctive characteristics. The category *distinctive characteristics* is explained as containing descriptions of 'how to do Industry 4.0'. Its elements in a sense represent the transitions or developments generated by the key technologies. Examples are process integration, predictability, real-time information transparency, virtual representation of the real world, and autonomy (i.e. self-thinking and/or reacting systems). The distinctive characteristics are portrayed in a more abstract manner by Habraken and Bondarouk (2019), via their three technology-based developmental streams that each contains the notion of digitalization – the establishment of connections, the ability to make more use of the value of information and the availability of contemporary physical and non-physical assets. The category *possible outcomes* consists of possible impacts of the phenomenon. It overlaps with an extensive set of impacts found by Habraken and Bondarouk (2019). Finally, the results from Habraken and Bondarouk (2019) included the presence of intended rationales. It addresses the intention behind the phenomenon, which was retaining industries competitiveness and alerting industry of emerging opportunities.

The fact that multiple facets encompass the phenomenon is visually represented in Fig. 1. With 1A and 1B depicting the frameworks as developed by respectively Culot et al. (2020) and Habraken and Bondarouk (2019). Fig. 1C represents a model that combines insights from both frameworks.

Having addressed the different facets of the phenomenon, I will now turn to the topic of workability.

A Workable Phenomenon

The model presented in Fig. 1C cannot be considered a workable description. In other words, something cannot be part of a concept and at the same time facilitate, hinder or result from that concept. In that sense it is more reminiscent of a research field, depicting various directions of interest, than a concept. Removing the presumed interfering categories (rationales, conditions and outcomes), however, still leaves two potential categories. This raises the question of whether a workable construction of the phenomenon is to be understood as the key technologies or the distinctive developments? While there is no definitive answer to this question, I will present my view by taking inspiration from the manner in which the first, second and third industrial revolution are commonly understood. An assessment of the abundant, online industrial revolution diagrams and the mention of these revolutions in the papers by Davies (2015) and Drath and Horch (2014) shows that the main wordings are machination, mass production and automation, accompanied by the notion that these are driven by respectively steam and water power, electrification and the conveyor belt, and electronics and information technologies. Both categories thus also coexist in descriptions of these three industrial revolutions, but the brief reflection shows that emphasis is generally placed on the direction of the transitions

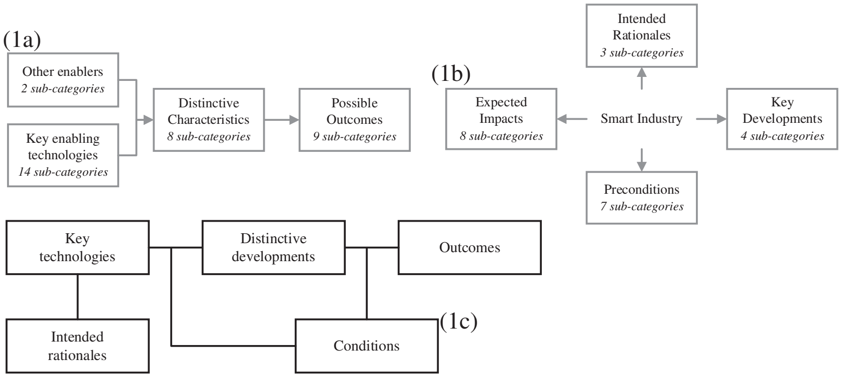

Fig. 1. Representing the Multiple Facets. 1A, is the framework inspired by Culot et al. (2020); 1B, is the framework by Habraken and Bondarouk (2019); and 1C, is the model developed based on the frameworks presented in 1A and 1B.

or the developments, rather than the underlying technological advancements. Following this line of reasoning, current phenomenon can then be understood as the distinctive developments. Therefore this category will be addressed in more detail below. However, with the phenomenon still unfolding, its content may not be limited to these elements. It thus covers the prominent transitions that can, to date, be attributed to the prior stated key technologies. As a result, especially the key technology 'energy management solutions' appears not to be represented. Though, it could be questioned whether this is an issue of time and more insights, or setting boundaries with respect to the key technologies tied to the phenomenon. 'Energy management solutions' addresses the sustainability theme, making it potentially more relevant for it to be positioned under the general topic of sustainability. The elements of the phenomenon in question covered here are:

Servitization

The notion of offering services in itself is not new, but what is visible is an increasing usage of services as a means of building revenue; whether it be in addition to, or as replacement of the original product/value proposition. In their article entitled 'What is servitization of manufacturing? A quick introduction', Emerald Publishing Limited (2020) presents five examples, and the following quotes offer two more, respectively from a manufacturer of adapted bicycles, and of winter maintenance vehicles.

> We developed a business model in which we will develop services as well as products. We are currently working on an app for reading relevant data from the e-bikes; with that information we can organise the service towards the customer in a smarter – preventive – way. (Financial/HRM director at manufacturer of adapted bicycles; in Link Magazine, 2016)

> From a hardware supplier we become a caretaker with integrated solutions. In doing so, we respond to the megatrends: solutions instead of products, availability instead of ownership. (Director at manufacturer of winter maintenance vehicles; in Link Magazine, 2017)

Platform Economy

As with servitization, the platform economy is not new. What makes it a noteworthy development is the fact that they are 'bigger, more virtual, more dynamic, and more intelligent than "platforms" of the past' (co-author of the book 'Platform Revolution'; in Manville, 2016). Recent innovations, thus, have led to a growth in and increased attention for the platform economy. The statement more intelligent, in the prior quote, indicates a connection with the next element (data usage), as explained with the following quotes:

> Platforms win, not just by facilitating such new interactions [e.g. joining more producers and customers], but also by aggregating and analysing the data of it all (Manville, 2016) and The explosion of data, and its use by platform businesses to keep learning is perhaps most significant. Uber, for example, is not just matching rides to travelers, but increasingly predicting and even structuring demand by algorithms that rebalance supply of available cars. (Co-author of the book 'Platform Revolution'; in Manville, 2016)

Data Usage

Combine the vast and varied amount of (real-time) data that can now be collected and the different (new) ways in which data can be processed, with the notion that done purposefully there is value to be gained from data and the core of this element becomes clear – data can and are used more frequently for various reasons. From monitoring, understanding and decision-making (take for instance the Covid-19 situation) to prediction, as shown via the following examples:

> A smart factory with machines that are packed with sensors that measure productivity. They keep track of everything: process values, alarms, vision control images, temperature, humidity, energy consumption, failure, malfunctions, logs, checklists, etc. … The ultramodern injection molding factory that K. is now building has been developed entirely according to the Industry 4.0 concept. A factory that constantly monitors the condition of the machines, predicts maintenance and generates the big data with which it can produce more efficiently. (Verpakkingsmanagement, 2017)

> The robotic system provides a flow of data as well as milk, [this data flow is used] to keep track of the best producers and the cows that may eventually have to be culled. 'We've got seven cows out of 113 that we're looking at', Jim Austin said, as he pointed to the red bars lighting up an office computer screen. (Boyle, 2016)

Another reason is traceability, for instance, to offer customers details about the path taken by products like food. A chapter in the book entitled 'Blockchain chicken farm: And other stories of tech in China's countryside' (Wang, 2020) presents a relevant case example. The improvement of services, for instance in the healthcare and tourism sector (Benjelloun, Lahcen, & Belfkih, 2015), is an additional reason that can be observed. The link between utilizing data and services is also evident in the above element of servitization since the manufacturer of winter maintenance vehicles is able to focus on availability instead of ownership by gaining insights into the deployment of their vehicles; 'the firm has equipped their grit and salt spreaders with a controller that offers up-to-date information, accessible through a web application, on performance aspects, such as spreading quantities, and on service aspects such as usage in hours or kilometres driven' (Habraken & Bondarouk, 2020, p. 7). Finally, a link with the next element can be made as 'autonomous' systems utilize data to function. To illustrate, autonomous mobile vehicles (AMV) are not restricted to fixed routes but navigate dynamically due to a blueprint of a location and live input of their surrounding (Fetch Robotics, 2018). To conclude, the element data usage can be seen as a standalone element leading to an increased focus on predicting, monitoring, assisted decision-making, etc. In addition, it ties to several of the other elements.

'Autonomous' Systems

A fourth development is the presence of 'independent' systems. The brackets around the word independent are included to highlight that systems are more autonomic than before, but often still require human involvement, for instance, to assist it with dealing with changes in the environment or human-made errors in the systems input. In other words, full autonomy is not really the case yet. Autonomous systems can range from being interpreted as autonomous devices like the above AMV and the milking robot from an earlier example (Boyle, 2016). But it can also be understood as people-light processes. An example is given with the quote from a supplier of sheet metal:

> To do this [people-light process from order to production], you must be able to recognise a customer's drawing, convert it into a quotation using software, then automatically have the right materials removed from the warehouse, have it processed, packaged, etc. (Van Ede, 2015)

The example highlights an autonomous process from customers to production. Firms could, however, extended it towards suppliers (e.g. autonomous ordering of parts) as well as decide to introduce a smaller scaled autonomous system.

Human-Robot Interaction

As Bartneck et al. (2020, p. 6) point out, 'the notion of human interaction with robots has been around as long as the notion of robots themselves'. What makes this development important now is that robots have moved beyond merely being a tool, to being an interaction partner in numerous ways. The AMV can be considered an example here as it interacts with people in order to not run into them. More examples of human-robot interaction applications are addressed by Bartneck et al. (2020, Chapter 2), with some of the discussed types being: service robots (e.g. tour guides, receptionist, delivery or security robots); robots for entertainment; robots in healthcare and therapy (e.g. for senior citizens or rehabilitation); collaborative robot (co-bot) arms; and remotely operated robots. An example of a remotely operated robot are drones, when interpreted in terms of moving sensors (i.e. scanning or mapping a terrain or conducting inspection work). But drones can also be classified as delivery robots as shown by the following headline from a news article by Palmer (2020) – 'Amazon wins FAA approval for Prime Air drone delivery fleet'.

Reconfiguration

As the word reconfiguration implies, this development is focused on the ability to rearrange settings, or the ease with which diverse outputs can be created. A well-known approach is additive manufacturing or 3D printing. This approach is featured in the quotes below from the manufacturer of adapted bicycles and a concrete factory:

> We see a great future for this [3D printing] because we are a producer with small series. We want to 3D print more and more products. We are also looking at collaborative robots. We have already done studies to see where we can deploy them. (Technical director at manufacturer of adapted bicycles; in Provincie Gelderland, 2019)

> 3D printing of concrete offers the new generation of architects a world of new possibilities. You can play with shapes, colours and structures and you are no longer bound to serial production of large volumes of the same product. A robot does not care whether it has to produce 10 or 100 different designs in a row. The construction world was primarily a mechanized industry, thanks to Smart Industry it is becoming a digital industry with many new possibilities. (Innovation manager of a concrete factory; in Boost, 2017)

What makes 3D printing relevant now, despite its origin in 1986, is the emergence of new applications both in method and in materials to print with (Ngo, Kashania, Imbalzanoa, Nguyen, & Hui, 2018). Besides a 3D printer, the prior mentioned co-bot arms also enable reconfiguration since they are 'able to change from one process to another with ease, making it possible to use one co-bot for multiple tasks…' (Shepherd, 2019); a statement evident in the above quote from the manufacturer of adapted bicycle. Finally, reconfiguration is reflected in the general quote from the supplier of sheet metal:

> In recent years machines have been introduced that can not only perform the operations automatically, but where you can also adjust an operation at the touch of a button. The changeover time is then zero. (Van Ede, 2015)

Separation

One interpretation of this element are developments related to reality. That is, the usage of digital currency, digital models, augmented reality (AR) and virtual reality (VR). Regarding digital currency and AR, the quote below offers an example from a clothing store. In addition, other AR and VR applications can, for instance, be found in respectively FDM (2020) and Mekni and Lemieux (2014).

> When you place a piece of clothing on the wooden box next to the mirror, 360-degree photos automatically appear on the mirror. By moving your finger over the photo, you can virtually rotate the article and view it from all sides. And the store also accepts payments in DigiByte. (Editorial Smart Industry, 2020)

Digital models entails the grown possibility of constructing virtual representations or digital models; better known as digital twins. This growth is due to the 'explosion of machine learning, wireless communication and cloud computing' (Lu, Liu, Wang, Huang, & Xu, 2020, p. 2). It is connected to the data usage element as digital twins rely on real-time data to depict what is currently happening (i.e. create a digital replica of a real-world 'thing'). In addition, according to Lu et al. (2020, p. 2) 'a digital twin can be used for monitoring, control, diagnostics, and prediction'. Separation in terms of reality is also visible in the creation of deep fakes. Linked to the data usage development, recent advancement have led to the creation of materials that are difficult to distinguish from reality. In the words of Kietzmann, Lee, McCarthy, and Kietzmann (2020, p. 135) 'Powered by the latest technological advances in artificial intelligence and machine learning, deep fakes offer automated procedures to create fake content that is harder and harder for human observers to detect. The possibilities to deceive are endless – including manipulated pictures, videos, and audio'. A second interpretation of this element is the introduction of assets which enable tasks to be performed away from their traditional location. To help explain what I mean, there is the following quote showcasing the presence of tablets on the shopfloor:

> In the old situation, the operators could see how the production was going on large screens. The machines were also equipped with all kinds of hmi-screens. In the new factory, most screens have disappeared and are replaced by tablets. With the help of those tablets, the operators can control everything and receive information about the status of the line. The processes and important functions can be found via icons on the tablet. If the compressed air icon turns red, the operator knows that something is wrong with the compressed air installation. If he inspects the machine and sees, for example, that there is an oil leak, he can take a picture with the tablet. The log is recorded instead of typed in and the service engineer immediately receives an SMS message and sees what the problem is. (Engineering consultant; in Verpakkingsmanagement, 2017)

Another example is the current piloting of smart grocery carts which brings the cash registration of groceries inside the store, as you can pay directly from the smart carts card reader, in contrast to a traditional, fixed cash registration point – see video by CityNews Toronto (2019) for a case example.

Though still being multifaceted, the distinctive developments present a more focused understanding of the phenomenon compared to Fig. 1C. It is viewed as expressing visible developments, from a business perspective, as a result of recent technological advancements. This understanding, however, does not take away from the complexity of working with the phenomenon. As shown in Fig. 2, the phenomenon comprises of elements that are being addressed and implemented independently. In other words, scholars may concentrate on one specific element (e.g. platform economy or human-robot interaction) and firms may just focus, for instance, on reconfiguration. But a combined view is of importance as well, since there are firms that have introduced aspects from various elements. Take for example the manufacturer of adapted bicycles, who focused on reconfiguration, offering services besides producing, and using data for prevention, or the farmer with an autonomous milking robot that simultaneously makes use of the data which this robot can generate, a step that is not strictly necessary when adopting a milking robot.

The above discussion will be used as input for the next, concluding heading.

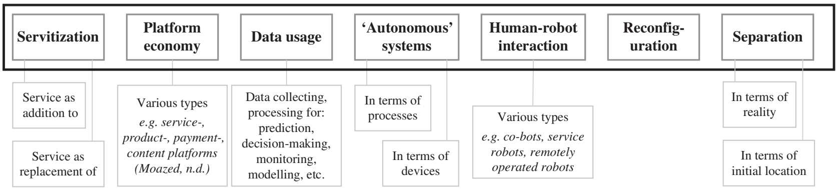

Fig. 2. Representing the Complexity. The bold line represents the phenomenon, the top row represents the seven developments that encompass the phenomenon, and the bottom row highlights the variety within a certain element.

CONCLUSIONS: MANAGEMENT IN THE ERA OF THIS PHENOMENON

With management defined as 'the act or art of managing: the conducting or supervising of something' ('Management', n.d., definition 1), it has a wide focus, covering aspects such as the management of people and work, external relations, data and the devices as well as systems themselves. Given the complexity depicted in Fig. 2, the effects of the phenomenon for each specific management direction will be heavily dependent on the particular context that is examined. Put differently, the phenomenon is tied to a number of technological breakthroughs or advancements, which have led to several (sub-) developments that can either be considered on their own or in various combinations; a fact that results in a set of multiple, unique expressions of the phenomenon in practice. Such unique expressions are unlikely to be captured by a single reflection of management in the current era, for each specific management direction. It is thus of importance to be aware of and clear about the particular expression of the phenomenon one deals with when assessing management-related questions, a notion facilitated by case-based research, where a single or several organizations take centre stage with respect to the raised question(s) of interest. In other words, the benefit of case studies is that it enables gaining insights into the expressions that exist, while assessing questions pertaining to the effect of a certain expression on various management directions and vice versa (i.e. expressions may effect management but it should also be kept in mind that existing management may influence the way in which the phenomenon is expressed in that context). A brief assessment of the use of case studies in existing literature on the phenomenon reveals that despite their relevance, case studies are not widely applied yet. That is, a literature enquiry using the most frequently used label 'Industry 4.0' for the period 2011 till present yielded, on 3 March 2021, 13,938 results in Scopus and 7,904 result in Web of Science. While a search for the keywords "Industry 4.0" AND "case study" for the same period and date provided 1,292 results in Scopus and 649 results in Web of Science, which is respectively 9.3% and 8.2% of the prior results. Both are a relatively low percentage, especially given that they stem from a generic search (i.e. it was not assessed if a case study was in fact conducted or, for instance, only proposed as a future research direction and the inclusion of a link with the topic management was not assessed). This low outcome could be due to a limited amount of empirical research towards the phenomenon in general. Nevertheless it leads me to recommend the use of case studies in future research on management in the era of this phenomenon. Over time, such research, supplemented by relevant existing case studies, will yield a better, more complete overview of the phenomenon in practice and a more comprehensive understanding of management in the era of this phenomenon.

I am aware that this is an abstract, future-dependent answer. However, we have to realise that we are dealing with a relatively new phenomenon, though coined in 2011, it did not take off till about five years ago (Habraken, 2020), that comprises of (at least) seven independent and interconnected developments which can be broken down into sub-components. This combination of novelty and diversity makes how management will look like in the era of this phenomenon, a topic that requires time and, importantly, well-documented efforts. Without the latter, it will be challenging to connect and collectively assess the conducted work in a few years' time. Fig. 2 and the earlier proposition related to the variety in labels (i.e. to count a specific set of labels as a single key word) are expected to assist with the establishment of well-documented papers by: facilitating the linking of papers with various but interchangeable labels for this phenomenon; creating a clearer understanding of the fact that there is no single expression of this phenomenon in practice; and helping with the establishment of unity in the manner in which the unique expressions of the phenomenon are documented in research articles.

NOTES

1. Members of the KvK entrepreneur panel who represent a diverse group with respect to gender, age, sector, and whether they are an independent entrepreneur or part of an SME.
2. Retrieved, Dec. 2020 from: https://www.nist.gov/mep/advanced-manufacturing-technology-servicesindustry-40.

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SMART BUSINESS AND THE SOCIAL VALUE OF AI

Agata Leszkiewicz, Tina Hormann and Manfred Krafft

ABSTRACT

Organizations across industries are increasingly using Artificial Intelligence (AI) systems to support their innovation processes, supply chains, marketing and sales and other business functions. Implementing AI, firms report efficiency gains from automation and enhanced decision-making thanks to more relevant, accurate and timely predictions. By exposing the benefits of digitizing everything, COVID-19 has only accelerated these processes. Recognizing the growing importance of AI and its pervasive impact, this chapter defines the "social value of AI" as the combined value derived from AI adoption by multiple stakeholders of an organization. To this end, we discuss the benefits and costs of AI for a business-to-business (B2B) firm and its internal, external and societal stakeholders. Being mindful of legal and ethical concerns, we expect the social value of AI to increase over time as the barriers for adoption go down, technology costs decrease, and more stakeholders capture the value from AI. We identify the contributions to the social value of AI, by highlighting the benefits of AI for different actors in the organization, business consumers, supply chain partners and society at large. This chapter also offers future research opportunities, as well as practical implications of the AI adoption by a variety of stakeholders.

Keywords: Artificial Intelligence; social value of AI; benefits of AI; AI risks; business-to-business; AI implementation

ARTIFICIAL INTELLIGENCE AND THE POST-COVID-19 RECOVERY

Digital technologies are rapidly changing the way businesses operate. There is an increased demand for partially or fully digital products and services; firms interact with customers and

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supply chain partners via digital channels; internal processes and operations such as production or office management also rely on digital technologies. The COVID-19 pandemic has accelerated these processes and underscored the benefits of 'digitizing everything'. The biggest organizational changes implemented during the crisis, for example, remote work and reduction in the on-site workforce, will prevail in the post-pandemic recovery, which makes investments in new technologies of strategic importance for businesses.

This chapter is focused on Artificial Intelligence (AI), which was named as the number one technology to help businesses recover and improve after the COVID-19 crisis (McKinsey, 2020b). Looking at the big picture, AI is argued to contribute to economic and societal welfare as well. For example, AI image analysis software CAD4COVID, developed by Delft Imaging, is analysing thousands of chest X-rays from COVID-19 patients and used for diagnostics in 120 hospitals worldwide.[1] Furthermore, it is estimated that AI can add 1.4% of annual GDP growth for the European economy until 2030 (McKinsey, 2020a). This is reflected in the EU's billion euro investments with the ambition '… to lead globally in the development and uptake of human-centric, trustworthy, secure and sustainable AI technologies' (European Commission, 2021, p. 3).

Defining the Social Value of AI

The purpose of this chapter is to discuss the impact of AI adoption on various stakeholders of a business-to-business (B2B) organization. To this end, we adopt a cost-benefit approach and define *the social value of AI* as *the combined value derived from AI adoption by a B2B organization by multiple stakeholders*. More specifically, the social value of AI can be understood as the trade-off between (1) the *benefits and improvements* this technology brings for stakeholders and (2) the *costs and concerns* that arise from it. Specifically, we look at the impact of AI on (1) the internal stakeholders in the firm, i.e. the executives and employees, (2) business customers, supply chain partners and competitors, and (3) society at large.

Our definition of the social value of AI is rooted in the theory of value creation, which recognizes that 'value created by organizations […] may not be wholly captured by them but, instead, may spill over into society as a whole' (Lepak, Smith, & Taylor, 2007). Social value of AI as a central concept in this chapter, emphasizes the overall anticipated impact of AI on many stakeholders of an organization. While the focus of this chapter is the AI adoption by a B2B firm, our definition allows that the social value of AI be created by any type of organization and captured by its stakeholders.

AI in Business-to-Business Relationships

The B2B literature has noted the pervasive impact of digital technologies on relationships in business networks (see e.g. Hofacker, Golgeci, Pillai, & Gligor, 2020; Pagani & Pardo, 2017). Focussing on AI technology specifically, it has been shown to contribute to improved decision-making and overall firm performance (Bag, Gupta, Kumar, & Sivarajah, 2021) thanks to the ability to generate insights and knowledge from a variety of digital data sources such as for example social media information. Multiple studies have also discussed how AI can support buyer-seller exchanges in the sales process (Luo, Tong, Fang, & Qu, 2019; Paschen, Wilson, & Ferreira, 2020), contract negotiations (Schulze-Horn, Hueren, Scheffler, & Schiele, 2020), or throughout the purchasing process (Schiele & Torn, 2020). Gligor, Pillai, and Golgeci (2021) have recently discussed the potential dark side effects of AI on B2B relationships, such as exacerbated power asymmetries or reinforced organizational inertia. We extend this literature by considering how AI impacts the internal stakeholders and society at large, not only customers and supply chain partners.

Ethical Considerations Arising from Digital Technologies

This research builds on the developments in business ethics and sustainability literature, which have recently considered the digital domain. Lobschat et al. (2021) defined a new concept of Corporate Digital Responsibility (CDR), arguing that companies need to assess the impact of digital technologies on business partners in the value chain, individual users of data and technology (customers, managers, employees technology developers), public institutions and non-governmental organizations. Elsewhere, López Jiménez, Dittmar, and Vargas Portillo (2021) theorized that on top of the (minimal) legal requirements, firms will voluntarily subscribe and commit to a stricter, industry-specific code of conduct about the digital activities. Finally, Kumar and Ramachandran (2020) discuss the stakeholder well-being as an outcome of digital transformation, arguing that firms can pursue stakeholder focus together with the adoption of technology and analytics.

The contribution of this chapter lies in the discussion of the social value of AI, which extends the above studies in several ways. First, unlike previous studies, we focus on the impact of one specific technology, the AI, and the implication of automation and algorithmic decision-making. Second, Lobschat et al. (2021) and López Jiménez, Dittmar, and Vargas Portillo (2021) have emphasized the importance of the internal processes and corporate self-regulation about digital technologies, and we complement those studies with a more detailed discussion about the pervasive impact of AI on internal and external stakeholders of a B2B company. While Kumar and Ramachandran (2020) discuss multiple stakeholders and focus on the growth strategies that are realized by the focal firm, we contribute with an interdisciplinary review of the impact of AI on the organization, its environment and society.

The chapter is organized in the following way. We first discuss AI and related technologies, and discuss its main advantages and disadvantages. Second, we identify different groups of stakeholders that a B2B company should consider when developing AI. Next, we discuss the value contributions to the social value of AI, by showing how different stakeholders can benefit from this technology. We close this chapter with a short discussion and implications for managers.

ARTIFICIAL INTELLIGENCE AND ITS ADVANTAGES AND DISADVANTAGES

Overview of AI and Related Technologies

We use the definition of AI proposed by Kaplan and Haenlein (2019), formulated as 'a system's ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation'. A system is understood here as interconnected computers, interfaces, robots, sensors, or any smart devices, governed algorithmically to execute specific actions. AI understood in this narrow sense uses machine learning (ML) algorithms – predetermined rules to achieve prescribed goals based on input data. For example, in predictive analytics, ML analyses vast amounts of historical data to predict the probability of future unknown events. AI is different from other analytics technologies because it evolves and becomes more effective and efficient, thanks to the ability to autonomously learn from past data, from new data sources, as well as from the system's responses via the feedback loop. For a non-technical review of AI technology see e.g. Agrawal, Gans, and Goldfarb (2018).

The development of AI is closely related to the developments of digital technologies, such as IoT, blockchain, machine-to-machine communications (sensors), robotics, cloud computing, big data, ML and deep learning. For example, used in the Smart Industry, IoT and sensors generate volumes and a variety of data, which are continuously tracked and monitored to optimize production lines with AI. Cloud computing and big data facilitate automation and real-time implementation of algorithmic decision-making. ML is prevalent in everyday life, for example, computer vision is used for face recognition, and natural language processing with voice recognition are used by chatbots and voice assistants. In recent years there has been a discussion about the ability of AI to mimic and surpass human intelligence and creativity (see e.g. Huang & Rust, 2018; Ng, 2016); however, so-called *strong AI* does not exist yet. We focus here on a narrow definition of AI, and the associated implications of automation and algorithmic decision-making.

Benefits of AI

Social value of AI as a new concept takes into account the benefits and improvements this technology brings for a variety of stakeholders, as well as the costs and concerns associated with this technology. Looking at the benefits, we focus on two aspects of AI: (1) AI can perform tasks faster and with fewer errors than humans, which leads to efficiency gains; (2) AI's ability to analyse vast amounts of data, which leads to better, more timely predictions and enhanced decision-making (i.e., higher effectiveness). Therefore, AI enables automation and predictive analytics making, which have powerful implications for stakeholders of a B2B company.

AI Risks and How to Mitigate Them?

The concept of the social value of AI also takes into account the costs and risks associated with this technology. First, the technology is costly to implement and requires significant financial investments for firms, including public subsidies (European Commission, 2021; McKinsey, 2020a). Second, the diffusion of AI within organizations is kerbed by necessary organizational changes, adjustment costs, data vulnerability (cybersecurity), and the lack of skilled staff (Brynjolfsson, Rock, & Syverson, 2017).

There are also concerns about the fairness of the algorithms underlying AI, therefore developers and organizations should monitor the quality of training and input data, create algorithms that are fair and appropriate, and evaluate the outcomes for potential bias. Furthermore, AI algorithms need to be explainable: transparent and understandable for decision-makers to allow for inspection. Although algorithmic decision-making in principle implies that AI systems can be autonomous, in order to perform efficiently and ethically correctly, there must be a human in the loop. For a discussion of algorithms from an ethical perspective, see for example Martin (2019).

Using lessons learnt from GDPR and California privacy law, companies also anticipate the costs of compliance with stricter AI regulations.[2] For example, the Artificial Intelligence Act in the European Union or the Canadian Algorithmic Impact Assessment are the legislative initiatives regulating the use of AI.[3] While this legislation represents the minimal legal requirements, firms additionally self-regulate to mitigate undesirable AI risks and voluntarily commit to a stricter code of conduct (López Jiménez, Dittmar, & Vargas

Portillo, 2021). Signalling the higher standards can lead to an improved brand image, but the non-compliance could imply a damaged credibility and consumer pushback.

Finally, there is an important discussion about the development of AI and its negative implications for individuals, such as customer privacy concerns, algorithmic bias, the psychological and emotional drivers of AI resistance, or human-machine interactions. While important in the B2C context, they are less relevant for a B2B company and therefore outside the scope of this research. For a recent discussion on privacy in consumer marketing, we refer the interested reader to the research of Krafft et al. (2021), who developed a framework to understand how both individuals and firms derive value from the data exchange. Algorithmic bias has been covered recently by Lambrecht and Tucker (2020). The work of Puntoni, Reczek, Giesler, and Botti (2020) explains how individuals experience AI, and algorithm resistance is covered for example by Huang and Rust (2018), and Leung, Paolacci, and Puntoni (2018) provide an analytical model of AI job replacement.

Social Value of AI Is Expected to Increase

Being mindful of the above concerns about AI, we believe that the social value of AI will increase over time. First of all, while capital investment remains a major barrier for the AI diffusion, the information technology costs are declining and we observe the overall growth in computing power. Secondly, the anticipated tightening of laws and regulations about the use of AI can, on the one hand, increase the financial cost for firms, but on the other hand, will decrease the AI risk and concerns for the users and society at large. Overall, we expect the latter effect to dominate because the majority of companies are already actively self-regulating to mitigate AI risks, and there are brand reputation benefits for the voluntary code-of-conduct about the use of AI (López Jiménez, Dittmar, & Vargas Portillo, 2021; McKinsey, 2020a). Thirdly, over time the AI algorithms become better and more efficient thanks to their learning capacity, which increases the AI value. Furthermore, we expect that the AI skills gap, a major obstacle for AI diffusion at the moment, will slowly close, given the emergence of dedicated programs at academic institutions. Finally, as AI becomes more pervasive in industries and societies, more and more stakeholders will reap their benefits, thus increasing the social value of AI.

KEY STAKEHOLDERS IN B2B

Building on stakeholder theory, we aim to understand the pervasive impact of AI on various actors in the value chain of a B2B company. Stakeholder theory proposes that successful companies need to take into account all the 'publics' that have an influence on the firm. Therefore, the focal firm must consider its position in a business ecosystem, maintain relationships with stakeholder groups, understand their role in value co-creation as well as their interests (see e.g. Hult, Mena, Ferrell, & Ferrell, 2011; Hillebrand, Driessen, & Koll, 2015). This is relevant because B2B relationships are an increasingly complex network of co-existing and codependent relationships between organizations: suppliers, business customers, distribution partners in the global value chain and competitors (Hofacker et al., 2020; Pagani & Pardo, 2017). Stakeholder theory is also relevant for AI diffusion, currently driven by joint investments in public-private partnership (ppp) initiatives. For example, the EU's Coordinated Plan on Artificial Intelligence (European Commission, 2021) emphasizes the joint role of businesses, SMEs, start-ups as well as policymakers, academic institutions, and NGOs in the responsible development of AI.

We analyse three levels of stakeholders that the focal firm needs to consider so that the development of AI takes place with regard to the well-being of individuals, customers and society. As such, the focal firm can contribute to the social value of AI across three levels: (1) the internal environment level, represented by the organization itself, with top management and employees (including salespeople) as the key stakeholders, (2) the immediate environment, represented by the immediate actors in the value chain, with whom the focal firm has direct interactions: customers, supply chain partners and competitors, (3) the remote environment (macroenvironment) where the focal organization has only an indirect influence. Nevertheless, the focal firm needs to take into account the influence of external stakeholders on its strategy and operations. These stakeholder groups are the government, public and academic institutions, NGOs, industry associations and technology ecosystems.

Key Stakeholders within the Organization

Executives Seek Efficiency Gains Associated with AI

According to the aforementioned McKinsey Report (2020a), the development and implementation of AI technology have become now a strategic priority among the companies leading in digital transformation. Executives recognize that adopting AI can generate business value, through increased revenues and cost reductions.

Employees Might Resist Work Automation

The proliferation of AI means that well-structured, routine and repetitive tasks are automated and managed by algorithms; for a recent review of developments in digital technologies in the workplace see e.g. Bondarouk, Parr, and Furtmueller (2017). In Amazon warehouses, the algorithms can determine the tasks and how they should be executed by the workers, and they also continuously track performance (van Rijmenam, 2020). However, job automation and algorithmization of tasks may lead to frustration, feeling of scrutiny, reduced interactions between employees, as well as lower employee engagement because 'following the script' reduces creativity and independence (Kellogg, Valentine, & Christin, 2020). Furthermore, employees might resist AI fear of being replaced by a technology that can perform their job tasks faster and with fewer errors. On the other hand, automation of routine tasks frees employee capacity to solve more creative, complex tasks, increasing employee engagement and overall firm performance (Kumar & Pansari, 2016).

How Is AI Used in Sales Organizations?

We consider salespeople as one specific group of employees affected by the adoption of AI in a B2B organization. AI is already assisting humans in marketing and sales tasks at all stages of the B2B funnel; for a detailed review see e.g. Agnihotri (2020) or Paschen et al. (2020). For example, in the prospecting phase AI algorithms analyse large volume of data to build better prospect profiles and to qualify leads (Meire, Ballings, & Van den Poel, 2017). In the (pre-)approach phase ML can improve the targeting and retargeting of digital advertising (Järvinen & Taiminen, 2016), and natural language processing is used by conversational sales chatbots to interact with prospects (Luo et al., 2019); ML algorithms are used in automatic dynamic pricing systems to help close the deals (Leung, Luk, Choy, Lam, & Lee, 2019); as well as automating the workflows, services, customer relationship management post-sales (Chatterjee, Rana, Tamilmani, & Sharma, 2021; Libai et al., 2020). Finally, AI has the potential to play an important role in the on-the-job training of salespeople. In this context, Luo, Qin, Fang, and Qu (2021) have demonstrated through a series of experiments that using an AI coach (vs. a human coach) leads to improved salesperson sales rates.

External Stakeholders: Business Customers and Supply Chain Partners

Consider an example of a bicycle manufacturing industry, which since the beginning of COVID-19 pandemic has seen an exploding consumer demand. While other industries begin to recover, the majority of bicycle manufacturers have been affected by a lockdown of a production site from a key supplier, Shimano, which holds 65% of the market for high-end breaks and gears.[4] This single event contributed to the continued global bike shortage as the manufacturers report now average lead times of about 400 days – a number comparable to producing a luxury car.

As seen from this example, business relationships are nowadays very dynamic and complex. Digital technologies and AI facilitate the connectedness of this global marketplace (Hofacker et al., 2020; Pagani & Pardo, 2017), by connecting partners directly, and effectively blurring the boundaries between buyers and suppliers. Adopting AI within a firm will impact the stakeholder groups that lie immediately within the firm's value chain: the business customers and the downstream and upstream supply chain. Furthermore, those external stakeholders may encourage the firm's decision to adopt AI. To realize efficiency from process automation, AI systems require a good alignment of buyers and suppliers in the network, integration of data and real-time data sharing with business partners to generate valuable insights. Through collaboration the focal firm and its business partners can extract more value from AI.

Business Customers

For a focal B2B company, important buyers constitute end-users or manufacturers whom a focal firm supplies with materials and subcomponents required in the production process. A company adopting AI can leverage big data about consumers and markets to better manage business relationships, and cost-effectively personalize products and services. Predictive customer lifetime value (CLV) models and value-based segmentation will be more accurate and better, taking into account not only the transaction but also social media information. This results in better customer development but also more effective loyalty programs and incentives (Libai et al., 2020), and a higher engagement between B2B firms (Chatterjee et al., 2021).

Suppliers and Supply Chain Partners

A focal B2B firm also needs strong relationships with upstream and downstream supply chain partners such as their own suppliers, distribution partners and retailers, and companies that provide products and services to support their operations. Recall the example of the bicycle manufacturing industry: when a key supplier experiences production shortages, manufacturers can benefit from being a preferred customer and prioritized deliveries. In this context, AI systems are used in B2B companies to automate procurement processes and gain better insights about suppliers and sourcing opportunities. New and publicly available data sources such as social media information, industry reports, or global news events can be used to provide additional information about supplier opportunities. Schiele and Torn (2020) consider how AI systems can be incorporated in procurement at all the stages of the purchasing process. For example, AI-based virtual interactive chatbots can facilitate suppliers in creating proposals, which then are being analysed and preselected using text mining. AI algorithms can facilitate the execution of complex negotiations, which in B2B involve many parties, multiple decision criteria (e.g. delivery times, guarantees, prices, quantities) as well as quality and budget constraints. This is typically a hard optimization problem and AI systems can explore unobvious solutions to reach an acceptable outcome for all parties involved (Schulze-Horn et al., 2020).

Looking at the downstream operations B2B firms cooperate with distribution partners and retailers to deliver their goods to end-users. In logistics, AI and ML use the RFID and blockchain to track materials, components, and products throughout the value chain to optimize and automate the schedule of deliveries (Tsolakis, Zissis, Papaefthimiou, & Korfiatis, 2021). Operations in large logistics hubs, such as for example Port of Rotterdam, rely on autonomous navigation and Automated Guided Vehicles, and use AI analytics for optimization and container management.[5] COVID-19 pandemic has exposed the vulnerabilities of the global supply chains, disrupting for example the bike manufacturing industry. Dubey, Bryde, Blome, Roubaud, and Giannakis (2021) show that in unpredictable events like COVID-19, companies within a strong alliance are able to take advantage of AI analytics and improve operational and financial performance.

Competitors

There is an active discussion on how AI will affect the competition and the markets, because algorithms can induce mechanisms promoting the competition and hindering it. Looking at algorithmic pricing, research has found that, on the one hand, AI can lead to lower prices thanks to better forecasting, but on the other hand, algorithms can also learn to play collusive strategies (Miklós-Thal & Tucker, 2019). Varian (2019) considers how first mover advantages are created thanks to returns to scale (economies of scale, indirect network effects and learning-by-doing effect) in the industries using AI. While imitation from late movers is possible thanks to public data sources, open source AI algorithms and cheap cloud computing infrastructure, Varian (2019) identifies the lack of expertise as the major obstacle for AI diffusion.

Furthermore, as a result of digitization 'firms are compelled to compete with their partners and collaborate with their competitors' (Hofacker et al., 2020, p. 1163). Therefore, competition and value co-creation emerge as two phenomena that are integral to the analysis of B2B relationships. Focussing on AI adoption, it has been linked with improved competitive advantage and increase in relative power of a focal firm (Chatterjee et al., 2021), but it can also hinder interorganizational trust (Gligor et al., 2021).

Macro Perspective: Societal Stakeholders and Other Interest Groups

Apart from internal stakeholders and supply chain partners, there are actors in the distant environment of the firm who will be affected by the firm's AI adoption. Those actors will also influence the firm's decision about AI development.

Governmental bodies, public administration institutions, and NGOs shape the legal environment about the use of AI to protect individual and consumer rights. Furthermore, governmental actors and policymakers have an interest in AI development, foreseeing potential for economic growth and societal improvements. They offer public funding opportunities to stimulate AI development, balancing economic gains and responsible AI use. For example, the European Commission has set forth an aligned AI policy priority and investments for AI R&D with the aim of '… seizing the benefits and promoting the development of human-centric, sustainable, secure, inclusive and trustworthy artificial intelligence (AI)' (European Commission, 2021, p. 2).

Industry associations and accreditation bodies give representation for small and medium-sized businesses to influence AI policies. Furthermore, industry associations are an ecosystem through which businesses learn, share knowledge and experience about AI solutions, improving the diffusion of AI. Industry associations may promote their own standards about AI, writing a code of conduct which complements the legislation. For example, recently a Data Pro Code was proposed by the association of the Dutch ICT sector, NL Digital. Companies who voluntarily subscribe to these strict regulations signal a commitment to responsible AI, which can enhance brand image. Violating the code could lead to the damaged credibility and consumer pushback (López Jiménez, Dittmar, & Vargas Portillo, 2021).

AI incubator ecosystems arise from the geographical convergence of high technology start-ups, academic institutions, enterprises, and governmental actors. Thanks to the access to human resources, capital and infrastructure, there are collaboration opportunities and synergies for the actors. Within this ecosystem, high technology start-ups are a source of AI innovations (Garbuio & Lin, 2019). Successful start-ups attract talent and capital and give back to the community ('pay it forward mentality'). Big multinational enterprises present in the incubators further attract talent, provide financial support for ppp innovation, the infrastructure and scale up opportunities. They are also interested in investing and acquiring AI start-ups to stay innovative and ahead of the competition. For example, the technology consulting giant Accenture recently announced a strategic investment in Pipeline, a start-up that 'uses artificial intelligence (AI) technology to increase financial performance by closing the gender equity gap'.[6] The academic institutions in the AI ecosystems educate AI talent, provide training for start-ups and enterprises, and are a source of AI innovation via spin-offs. Public administration actors, discussed in detail above, provide infrastructure and support for the entire ecosystem and act as investors to stimulate local AI research.

CONTRIBUTIONS TO THE SOCIAL VALUE OF AI

The *social value of AI* is defined as the total value of AI for different groups of stakeholders: the actors within the organization, business customers and supply chain partners, and society at large. It consists of AI value contributions from each actor, which we discuss in detail in this section.

Firm-Related Outcomes of AI Adoption: How Is AI Value Generated within the Firm?

Increased Operational Productivity and Process Efficiency

Executives report that implementing AI in the organization improves operational efficiency: (1) through cost and time savings brought by automation, and (2) increased revenues, thanks to better products and services (see e.g. Brock & von Wangenheim, 2019; McKinsey, 2020a). Recently, Brynjolfsson, Jin, and McElheran (2021) demonstrated that adopting AI-based predictive analytics leads to up to an average 3% increase in productivity (equivalent to yearly revenue gains of $918,000) when comparing AI adopters vs. non-adopters in the US manufacturing industry. Elsewhere, Huang, Wang, and Huang (2020) find that AI is linked with better financial performance and market value, but not with improved labour productivity of Fortune 1,000 companies.

More Informed Decision-Making

AI and big data implementation has been linked to better firm performance because they help improve products and services (Brock & von Wangenheim, 2019); they also lead to better marketing decisions about the prices, channel management, product-service design, and development (Suoniemi, Meyer-Waarden, Munzel, Zablah, & Straub, 2020). AI is also a knowledge management enabler which helps companies integrate information about the customers, users, and the market to support decisions leading to enhanced firm performance (Bag et al., 2021). Therefore, the adoption of AI-based digital technologies has the potential to bring higher effectiveness due to improved decisions, higher productivity and better use of (human) resources.

Innovation and Diversification

There is varied evidence about the impact of AI on firms' innovation activity. Research has found the positive relation between AI and incremental innovation (Brock & von Wangenheim, 2019), because the technology can improve a firm's position in existing sectors through improved product-services for consumers. Furthermore, companies that possess dynamic capabilities related to technology, data and skills (Mikalef, Boura, Lekakos, & Krogstie, 2019) use AI for radical innovation. Comparing different digital technologies, AI together with big data, robotics, and 3-D have been associated with the highest potential for enabling radical innovation. On the other hand, common digital technologies (like emails, videoconferencing) have a negative effect on innovation because reduced interaction hinders creativity (Usai et al., 2021).

Improving Work Quality and Employee Engagement

AI can enable automation of well-structured, repetitive and tedious tasks, which are executed faster and with fewer errors compared to the work done by human employees, thus improving the overall labour quality and consistency. Furthermore, AI enables human-machine interactions, such as with customer service chatbot, which can be as effective and productive as human employees (Luo et al., 2019). As a result, AI is freeing the capacity for employees to engage in less structured but more creative tasks, which has been linked to employee engagement (Kumar & Pansari, 2016).

AI Creates Value for Business Customers and Supply Chain Partners

Efficiency Gains in B2B Exchanges

Embedding cloud-based AI solutions throughout the B2B buying process means that buyer-seller interactions and transactions can be automated and done remotely. This leads to overall lower transaction costs, benefiting all actors in the B2B exchanges. There are also time and effort savings for both purchasing and sales functions, where tedious and complex tasks such as text analysis of RFI or RFP documents can be outsourced to AI (Schiele & Torn, 2020). In supply chains, predictive analytics allows more accurate forecasting and demand prediction, improving the efficiency of the supply through reduced levels of excess inventory, lower product return rates, and minimizing delays (Dubey et al., 2021).

Customized Smart Products and Services

AI together with other digital technologies is an enabler for hyperpersonalization thanks to their ability to connect the physical and virtual infrastructure. For example, manufacturers increasingly share production infrastructure and resources; with the remote access, they can configure, control and monitor the machine operations, while the production lines switch automatically (aka. flexible manufacturing). Buyers have a remote access to configure smart products and services according to their required specifications, and can create prototypes, for example with the use of VR technology (Kostis & Ritala, 2020). In purchasing and sales, chatbots allow for personalized and real-time communications in RFI processes and sales transactions, while automated negotiation systems and pricing systems use ML methods to factor in supplier-specific information (Schulze-Horn et al., 2020).

Improved Customer Relationship Management and Customer Engagement

Adopting AI systems and ML in customer relationship management (CRM), firms can enhance their relationships with potential and existing customers. In customer acquisition, AI integrates different data sources, such as user-generated content or Google search data about emerging market trends and new customer opportunities, which can help firms expand their prospect base. Automating lead generation and qualification process contributes to lowering the overall customer acquisition costs. AI can also help expand the relationships with current customers through upselling and cross-selling techniques, higher order frequency and longer relationship duration. Predictive analytics can improve the accuracy of CLV, which will help firms identify and target high-value (prospects) customers with (acquisition) retention tactics, thereby optimizing the (acquisition) retention budgets and prevent customer churn of high-value customers (Libai et al., 2020). Finally, the use of conversational agents and automated, personalized communications can lead to higher customer engagement (Chatterjee et al., 2021).

Enhanced Relationships with Suppliers

The adoption of AI can improve the company's relationship strategy with potential and existing suppliers and partners. Matching systems with big data capability broaden the base of potential suppliers for the buying firms and help to identify better sourcing opportunities which otherwise could be overlooked (Allal-Chérif, Simón-Moya, & Ballester, 2021). In supplier relationship management systems, AI methods are used to monitor and evaluate supplier performance and supplier satisfaction. This improves the focal firm's supplier orientation and induces supplier development so that suppliers are ready to better serve the needs of the buying firm (Gu, Zhou, Cao, & Adams, 2021). Finally, the use of conversational agents has also been linked to increased supplier engagement.

AI Creates Value for the Societal Stakeholders

In 2015 the United Nations wrote an agenda for a better and more sustainable future, containing 17 Sustainable Development Goals (SDGs).[7] AI is already used by the policymakers and governments in many countries to help achieve those goals. For example, governments optimally direct resources and subsidies at a local, decentralized level (ElMassah & Mohieldin, 2020), and even identify individual households at risk of over-indebtedness and poverty (Boto Ferreira et al., 2021). In this section, we discuss the benefits that AI technology can generate for society at large. We focus specifically on AI impact on the environment (SDG #6, #7, #13), on employment opportunities (SDG #8), and on health and well-being (SDG #3).

Reduced Environmental Impact

In industries with big environmental impact, for example manufacturing, the capabilities of AI and ML allow producers to pursue industrial sustainability: to realize business goals while minimizing waste and environmental impact. Circular economy is a closely associated concept: the idea that thanks to smart (re)use, recycling of materials in production, distribution, and consumption we can improve environmental quality (Ren et al., 2019). AI automation and the developments in robotics improve the operational efficiency in logistics, and help lower the total global warming effect of CO_2 emissions (Tsolakis et al., 2021). Finally, Google has used AI to anticipate temperature changes in its data centres and adjust air conditioning settings, which led to 15% reduction in their overall energy consumption.[8]

Taking a marketing perspective, Hermann (2021) discusses how AI and data science can be used to promote sustainable consumption. For example, internet search and social media information can uncover psychometric and behavioural patterns of environmentally conscious consumers and nudge them towards the ecological products with targeted advertisements. Amazon recommender systems could be programmed to promote sustainable alternatives and ecological products.

New Opportunities in the Labour Market

There is an active discussion about the impact of AI and automated predictions on the creation and disappearance of jobs. Without a doubt AI can perform many tasks faster and with fewer errors than a human agent, and it already exhibits traits of intuitive and empathetic intelligence allowing human-machine interactions even in service settings (Huang & Rust, 2018). In labour-intensive industries, AI may lead to a rise in poverty and isolation; iflow-wage earners are replaced by AI. On the other hand, AI offers new opportunities. Thanks to improvements in automated predictions, AI reduces uncertainty faced by organizations, so decision-makers can address new, previously impossible or too costly scenarios. Therefore, thanks to AI, new decisions are required and new tasks are created (Agrawal, Gans, & Goldfarb, 2019). Furthermore, AI has created a huge demand for skilled staff, which is currently one of the main challenges faced by organizations implementing AI (Brock & von Wangenheim, 2019).

Improved Health and Well-Being

There is a huge potential for AI to improve the overall quality of life, health and well-being. In healthcare organizations, AI and big data analytics have been associated with improved quality of care, higher patient satisfaction and lower readmission rates, contingent on existing BDA capabilities and skilled personnel (Wang, Kung, Gupta, & Ozdemir, 2019). Applications of AI in medicine include affordable personalized health and e-health services (Oderanti, Li, Cubric, & Shi, 2021), or social robots that help overcome loneliness and assist in active ageing (Odekerken-Schröder, Mele, Russo-Spena, Mahr, & Ruggiero, 2020). However, public acceptance of AI in healthcare is still limited and customers may resist medical advice if it is provided by AI (Longoni, Bonezzi, & Morewedge, 2019). Therefore healthcare providers must overcome customer scepticism and trust barriers to realize the full potential of AI in healthcare.

DISCUSSION

Taking a cost-benefit approach we have defined a new concept of the social value of Artificial Intelligence, which is the combined value of AI for all stakeholders. To this end, we look at different actors relevant for a B2B firm and discuss the advantages and disadvantages of AI diffusion, which constitute the value contributions to the overall social value of AI. Our analysis has focused mainly on the benefits of AI. While we have acknowledged the concerns about AI, we do not treat them in detail, since they have been extensively discussed in the extant literature. We are cautiously optimistic about the value-creating impact of AI diffusion for different stakeholders, and we theorize that the social value of AI will continue to increase, because over time the benefits of this technology will outweigh the concerns about it.

Conclusions and Implications for Science and Practice

From an academic perspective, this research contributes to the discussion of CSR and business ethics considerations arising in the digital age. Building on the stakeholder theory and B2B literature, the purpose of this research was to initiate an interdisciplinary discussion about the pervasive impact of AI on internal and external actors relevant for a B2B company, as well as society at large.

Future research can use the concept of the social value of AI as a starting point and extend it in several ways. First, there is interest in measuring the impact of AI adoption on stakeholders to find causal evidence of improvements that AI can bring for stakeholders. Second, it is important to study AI adoption together with the relevant moderating factors – understanding the differentiating effect of AI deployment across industries, SMEs vs. multinationals, firms with strong data governance, or those developing AI skills through employee training. Finally, it is important to further investigate the concerns arising from AI from a legal and ethical perspective to provide guidance for policy-makers. We have treated this aspect as static, but as AI becomes prevalent, new and unanticipated ethical and moral dilemmas may arise. We acknowledge this as a limitation that can be addressed by future research.

This study offers insights for the business practice about the AI adoption and consequences thereof. We first highlight general obstacles for AI adoption and how they can be mitigated: from ethical issues around automation and predictive analytics, to firm's lack of data capabilities and employee pushback. Second, we identify a wide array of stakeholders and discuss how their interests are (mis)aligned with the interests of a focal firm deploying AI. Interestingly, a B2B firm can collaborate with stakeholders when considering AI adoption. For example, AI incubators can help with access to technology (via start-ups), funding (via local governments and public administration institutions) and training opportunities (via academic institutions).

We have also discussed the initial empirical evidence indicating that AI adoption leads to organization-wide efficiency gains and financial benefits when the firm has IT capital, skilled employees or automated production workflows. Therefore, firms implementing AI need to audit whether they possess the complementary assets to capitalize on the technology. Finally, we conclude that firms implementing AI have a potential to generate the social value of AI. We have provided ample real-world examples of how AI is applied to achieve sustainable development goals. In light of the increased importance of sustainability efforts, we believe that firms implementing AI ethically, responsibly and with regard to individual and societal well-being can strengthen their own brands and reinforce existing CSR efforts.

NOTES

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PERSONALITY DEVELOPMENT IN HIGHER EDUCATION IN THE ERA OF INDUSTRY 4.0: COMPARING EDUCATIONAL PRACTICES AND PHILOSOPHIES IN INDUSTRY 1.0 AND INDUSTRY 4.0

Klaas Stek

ABSTRACT

Industry 4.0 or the Fourth Industrial Revolution is characterized by robotic process automation and machine-to-machine communications. Since computers, machines, and robots share information and knowledge more swiftly and effectively than humans, the question is what human beings' role could be in the era of the Internet-of-Thing. The answer would be beneficial to institutions for higher education to anticipate. The literature reveals a gap between the intended learning outcomes in higher education institutions and the needs of employers in Industry 4.0. Evidence is shown that higher education mainly focused on knowledge (know-what) and theory-based (know-why) intended learning outcomes. However, competent professionals require knowledge (know-what), understanding of the theory (know-why), professional (know-how) and interpersonal skills (know-how and know-who), and need intrapersonal traits such as creativeness, persistence, a result-driven attitude et cetera. Therefore, intended learning outcomes in higher education should also develop interpersonal skills and intrapersonal characteristics. Yet, personality development is a personal effort vital for contemporary challenges. The history of the preceding industrial revolutions showed the drawbacks of personality and character education; politicians have abused it to control societies in the 19th and 20th centuries. In the discussion section, the institutions for higher education

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are alerted that the societal challenges of the twenty-first century could lead to a form of personality education that is not in the student's interest and would violate Isaiah Berlin's philosophical concept of 'positive freedom'.

Keywords: Competencies; higher education; Industry 1.0 and 4.0; personal development; personal freedom; soft skills

INTRODUCTION – IS SOFT SKILLS EDUCATION IN THE FIRST INDUSTRIAL REVOLUTION A LESSON FOR THE FOURTH INDUSTRIAL REVOLUTION?

The Fourth Industrial Revolution or *Industry 4.0* is the subject of discourse on its implication on individuals and the requirements for their personal development. The term *Industry 4.0* (or *Industrie 4.0*) was first introduced at the *Hannover Messe* (Hannover Fair) in Germany in 2011 (Kagermann, Wahlster, & Helbig, 2013). The World Economic Forum (WEF), in cooperation with The Boston Consulting Group, combined the digital challenges of Industry 4.0 (Schwab, 2016) with future job environment requirements to shift towards Industry 4.0 (WEF, 2015).

WEF (2015) formulated a range of 16 crucial skills, which students should possess. This twenty-first century skill-set consists of six cognitive skills that WEF calls *Foundational Literacies – how students apply cores skills to everyday tasks*: *literacy/ability to read and write, numeracy, scientific literacy, ICT literacy, financial literacy, and cultural and civic literacy* (WEF, 2015, p. 3). WEF (2015) further proposes three interpersonal skills: *communication, collaboration and leadership* and seven character traits or virtues, which also can be defined as intrapersonal traits: *critical thinking/problem-solving, creativity, curiosity, initiative, persistence, adaptability, and social and cultural awareness* (WEF, 2015, p. 3). WEF groups these in slightly different compositions as *Competencies – how students approach complex challenges* and *Character Qualities – how students approach their changing environment* (WEF, 2015, p. 3).

WEF underlined that *To thrive in the twenty-first century, students need more than traditional academic learning. They must be adept at collaboration, communication and problem solving, which are some of the skills developed through social and emotional learning (SEL). Coupled with mastery of traditional skills, social and emotional proficiency will equip students to succeed in the swiftly evolving digital economy* (WEF, 2016, p. 4). In these ideas, the statement of the European education ministers resounds in which they issued in 2009.

In their statement, the European education ministers rejected the traditional, classical, frontal, teacher-centred learning where the lecturer has an active role in 'transferring' primarily cognitive skills with frontal education. Instead, they promoted a student-centred learning approach, where students take the active role in their learning: *Student-centred learning (…) will help students develop the competences they need in a changing labour market and will empower them to become active and responsible citizens in the future* (Leuven/Louvain-la-Neuve Declaration, 2009, p. 1). The European institutions for higher education have taken and received a crucial role: *Higher education should be based at all levels on the state of the art research and development thus fostering innovation and creativity in society* (Leuven/Louvain-la-Neuve Declaration, 2009, p. 4).

Moreover, academia and higher education promote and endorse the shift towards student-centred methods via the European Association of Institutions in Higher Education

(EURASHE) and the European University Association (EUA). EURASHE, EUA and the European ministers of education co-developed the Standards and Guidelines for Quality Assurance in the European Higher Education Area (ESG Report, 2015). The ESG Report states that: *Institutions should ensure that the programmes are delivered in a way that encourages students to take an active role in creating the learning process and that the assessment of students reflects this approach (...) Student-centred learning and teaching plays an important role in stimulating students' motivation, self-reflection and engagement in the learning process* (ESG Report, 2015, p. 12).

Most of the 16 twenty-first century skills proposed by WEF consist of interpersonal skills (three items) and intrapersonal characteristics (seven items). This chapter follows the definition of Delamare-Le Deist and Winterton (2005), who distinguished between, on the one hand, interpersonal skills and intrapersonal characteristics and, on the other hand, knowledge and professional skills; a competent professional possesses the right mix of both. These have an essential role in applying knowledge and cognitive skills in daily practice. Interpersonal skills and intrapersonal characteristics are referred to as 'soft skills' (Laker & Powell, 2011). Hence, 10 of the 16 twenty-first century skills can be seen as 'soft skills'.

Hence, soft skills are crucial. They are even more important than cognitive and professional skills or 'hard skills' for a professional (Ahmed, Fernando Capretz, Bouktif, & Campbell, 2012). The presence of soft skills is an excellent forecaster to success in life, and an absence appears to be causing the ending of a labour relationship rather than a lack of cognitive skills (Ahmed et al., 2012; Heckman & Kautz, 2012; Zunk & Sadei, 2015). Stek and Schiele (2021) provided quantitative evidence that soft skills are necessary conditions to carry out hard skills, meaning that the absence of soft skills is problematic for carrying out professional tasks.

WEF underlines that soft skills will become increasingly vital for the workforce and to *equip students to succeed in the swiftly evolving digital economy* (WEF, 2016, p. 4) and to *empower them to become active and responsible citizens in the future* (Leuven/Louvain-la-Neuve Declaration, 2009, p. 1). Lecturers in higher (business) education should formalize intended learning outcomes for soft skills and introduce learning objectives that cover the context of future requirements caused by the challenges of sustainability and the Internet of Things (e.g. Bals, Schulze, Kelly, & Stek, 2019; Stek, 2021a; Stek & Schiele, 2021).

Remarkably, academic courses and tracks have been evaluated for not or almost not learning and developing soft skills (Birou, Lutz, & Zsidisin, 2016; Hoidn, 2017; Wong, Grant, Allan, & Jasiuvian, 2014). Although institutions for higher education need to anticipate the challenges of the twenty-first century, Fawcett and Rutner (2014) have found that higher education is *not evolving at the pace and in the way expected by professionals* (Fawcett & Rutner, 2014, p. 181). In job advertisements, 50% of job requirements the employers demand are soft skills (Stek, Zunk, Koch, & Schiele, 2021). Employers notably value intrapersonal abilities, but they seldom explicitly emerge in academic curricula (Hoidn, 2017).

Thus, in higher education courses, a significant role is given to the transfer of knowledge and theory, and in parallel, these courses are not equipped or primarily focused on developing soft skills. Higher education failed to formalize soft skills learning objectives. Their challenge is to offer students soft skills to prepare them into another mode of citizenship, *active* and *responsible*.

Concluding, the logic that soft skills are necessary to carry out hard skills is confirmed in the literature (e.g. Stek & Schiele, 2021). The shift towards a new era demands a new type of citizenship. However, it is unclear whether soft skills development can create better, more *active* or *responsible* citizens. Therefore this research deepens the following research question:

RQ1a: can soft skills development in education lead to improved citizenship?

RQ1b: if so, how must soft skills development be applied to improve citizenship?

The twenty-first century skills are associated with Industry 4.0, which challenges the workforce with further digitalization and, in parallel, sustainability issues. The question arises whether in modern history shifts have been detected in which competence requirements changed significantly and another form of citizenship was required. Currently, the Fourth Industrial Revolution takes place. In the early nineteenth century, during the First Industrial Revolution, a similar discourse took place. It was led by the Prussian educator Wilhelm von Humboldt (1767–1835), who promoted *Bildung,* the educational ideal of developing personal skills, traits and virtues for better citizenship, instead of preparing students for vocational purposes (Schaffar & Uljens, 2015).

This leads to the following research questions:

RQ2a: how did educators prepare their learners with soft skills education during the First Industrial Revolution?

RQ2b: which lessons can be drawn from educational insights and practices during the First Industrial Revolution?

Therefore, this chapter presents a study that focuses on the late-eighteenth and nineteenth century attention for soft skills development and describes the educational and philosophical insights in Western Europe. The recent call for improved citizenship resounds from that era, and the backgrounds, insights and lessons learned are described in the remainder of this chapter. This chapter alerts that soft skills education or personal skills development is prone to political points of view. Personal skills development should be a personal effort to develop according to the free will of the learner instead of being imposed on developing specific thoughts and attitudes that do not serve the individual learner but a political aim. Since imposed, constrained, political-induced 'personal development' obstructs conscious self-development, a paragraph deepens the concepts of liberty.

EDUCATIONAL INSIGHTS FROM THE FIRST INDUSTRIAL REVOLUTION

Von Humboldt and the Bildung Ideal – Inspired by the Ancient Greek Philosophy

Von Humboldt distinguishes between two philosophical education streams, referred to with the Germanic terms *Bildung* and *Ausbildung,* commonly used in Anglophone literature. *Bildung* refers to the personality development and self-cultivation ideal, and it has often been linked to the Humboldtian model of higher education (Bruford, 1975), meaning that this approach intends to create graduates with developed abilities to be formed for a career or life and not only for a particular (first) job (Schaffar & Uljens, 2015).

Ausbildung, in contrast, is related to acquiring the skills needed for a specific profession. It could thus be described as 'vocational training', that is *Ausbildung* takes a professional profile approach of teaching (cognitive) knowledge and (practical) skills and aims to create graduates ready to enter a specific job function at the labour market. The German physics Nobel price winner Werner Heisenberg (1901–1976) defined the difference between *Bildung* and *Ausbildung*: 'Bildung ist das, was übrig bleibt, wenn man alles vergessen hat, was man gelernt hat' or *Bildung is that what is left over when all is forgotten what one has learned* (own translation; Heisenberg, 1973, p. 105).

The changing timeframe of the early nineteenth century in which Von Humboldt conceptualized the *Bildung* idea is reflected in the letter he wrote in 1809 to the Prussian king: *People obviously cannot be good craftworkers, merchants, soldiers or businessmen unless, regardless of their occupation, they are good, upstanding and – according to their condition – well-informed human beings and citizens. If this basis is laid through schooling, vocational skills are easily acquired later on, and a person is always free to move from one occupation to another, as so often happens in life* (Günther, 1988, p. 132). Thus, citizens 'often' changed jobs two centuries ago and needed to be trained as good, upstanding, well-informed citizens.

Central to *Bildung* is that individuals develop personal skills and traits. The purpose of *Bildung* does not lie outside the individual: it is not about preparing to perform specific functions or tasks in society. *Bildung* is a process without a fixed end goal, a continuous development of capabilities. Therefore, *Bildung* is never completed: it presupposes lifelong, ongoing and interacting working with the outside world on one's personal development, that is life-long learning (De Hert, Kinneging, & Colette, 2015).

In 1789, Von Humboldt advocated a reorientation of political thinking inspired by the French philosopher Jean-Jacques Rousseau (1712–1778): *When will man finally cease to regard the outward consequences of action with greater esteem than the inward spiritual flame of mind from which they flow; when will someone appear who will be for legislation what Rousseau was for education, who will withdraw the point of vantage from the outward physical results to the inward cultivation* (Bildung) *of men?* (Sorkin, 1983, p. 58). *Bildung* is here translated as *cultivation*.

Von Humboldt distinguished *civilization, culture,* and *Bildung* (or *cultivation*) as follows: *Civilization is the humanization of peoples in their outward institutions and customs and the inner attitude pertaining thereto. Culture adds science and art to this refinement of the social order. But when we speak in our language of cultivation* (Bildung), *we mean by this something at the same time higher and more inward, namely the disposition that, from the knowledge and feeling of the entire mental and moral endeavour, pours out harmoniously upon temperament and character* (Von Humboldt, 1999, pp. 34–35).

Inspired by Greek philosophy, Von Humboldt compared the ancient Greek city-state's political constitution with the nineteenth century Prussian state. In the ancient Greek city-states, the direct influence on private lives was minimal. However, the influence was indirectly applied by expanding politics into personal life through education to generate loyal citizens (Sorkin, 1983). The ancient Greek education *sought to mold the individual in the hard and inflexible matrix of a dominant society* (Meyer, 1939, p. 1).

In line with Von Humboldt's ideas, this political fashioning of private life must have had a harmful effect, because by manipulating human's *inneres Dasein* (or: 'inmost being'), it must have irrevocably distorted the inhabitants of the ancient Greek city-states (Sorkin, 1983, p. 60). Paradoxically, the opposite occurred, Von Humboldt notes, since the city-states endorsed happiness via the development of virtues, it promoted harmonious, individual development. In an attempt to in aiming to develop *kraftvolle* (i.e. temperate and energetic) citizens, the city-state gave *higher impulse to their whole spirit and character* (Sorkin, 1983, p. 60).

Von Humboldt states that the promotion of individual virtues in the ancient Greek city-states could be copied into the Prussian state *for the sake of since its aim is too eudaemonistic,* that is the ethical theory promoting happiness and personal well-being as highest goals (Sorkin, 1983). *By attending to man's well-being and his property, his ease and comfort, the modern state suppresses man's energies; it thwarts man's personal growth in favor of obtaining a productive and obedient citizen. The modern state must, therefore, be* *restricted to a negative function, providing merely the outward conditions of freedom for individual development* (Sorkin, 1983, p. 60).

Or as Von Humboldt noted: *The State must wholly refrain from every attempt to operate directly or indirectly on the morals and character of the nation otherwise than as such a policy may become inevitable as a natural consequence of its other absolutely necessary measures; and that everything calculated to promote such a design, and particularly all special supervision of education, religion, sumptuary laws, etc., lies wholly outside the limits of its legitimate activity* (Von Humboldt, 1854, p. 113).

Understanding German (i.e. Prussian) society and its development and response to the modernisation process in the eighteenth century is needed to grasp the *Bildung* ideal (Alves, 2019). Von Humboldt (1767–1835) lived in a 'Germany' that consisted of a *patchwork of small autonomous principalities, marked by a rigid social stratification and by the small despotism that left no room for individual initiative and stifled cultural creation* (Alves, 2019, p. 7).

However, after the Seven Years War (1756–1763), *Prussia emerged as a European power* (Alves, 2019, p. 7). *In this modernizing society, where the development of sciences and techniques and the increasing division of labour lead to an increasing specialization of knowledge, new forms of integration and social distinction were necessary* (Alves, 2019, p. 7).

From 1770 to 1815, *Bildung* was seen in Germany *as a cosmopolitan and universalist ideal that was associated with the ideas of individual autonomy and self-determination and with the image of an integral individual endowed with an aesthetically harmonious personality* (Alves, 2019, p. 9). This educational view reflected the ideals of genuine and objective understanding instead of external reasons and utilitarian purposes. After Napoleon defeated Prussia in 1807, the *Bildung* ideal found a favourable opportunity to realize a series of reforms (Alves, 2019).

Influenced by the liberalism ideal of civil equality, in Prussia, actions were taken. For instance, peasants were liberated from servitude. The Prussian government asked Von Humboldt and the neo-humanists to reform the Prussian educational system according to their ideal of humanity (Humanitätsideal). The pedagogy of the Swiss pedagogue Johan Heinrich Pestalozzi (1746–1827) was adopted at primary schools, which took into account the child's needs and specificities. Gymnasia were instituted based on the ideal of harmonious individuality and the study of the Greek classics.

The current Von Humbolt University in Berlin was founded in 1810 based upon freedom of research and teaching. It served as an example for the re-organization of all the other German universities. The educational philosophy was not to adjust the student to the world and to train professional skills and knowledge, *but to awaken the inner forces, creativity, and critical judgment to transform the world and to realize within itself the ideal of humanity* (Alves, 2019, p. 10).

Blanqui, the Inventor of the Term 'Industrial Revolution'

In nineteenth century Prussia, the *Bildung* approach developed students' minds and character into cultivated and precisely 'competent' citizens. In parallel, in nineteenth century France, similar thoughts were expressed by the liberal economist Jérôme-Adolphe Blanqui (1798–1854) on 'management' education. He included the coverage of *the moral lesson of freedom, leaving room for the apparently useless (…) as well as the strictly utilitarian* (Deslandes, 2019, p. 8).

Blanqui was focused on the developments in British industry and education during the First Industrial Revolution. He spoke English, followed the British press and often travelled in the United Kingdom. *He urged his audience not to shrink from debating and thinking about the big questions facing contemporary France* (Deslandes, 2019, p. 6). At his time, Blanqui lauded British education. Throughout Britain, political economy was lectured, while it was lectured almost nowhere in France. Additional, *the UK boasted a network of around 60 mechanics institutions offering evening classes, which aimed to explain the technical workings of industry to a wider audience* (Deslandes, 2019, p. 6).

The nineteenth century political economists studied the circumstances under which consumption or production was organized in nations, the relationships between public good and private interest, wealth production and human well-being, the proper distribution of the social product, and the state's role in intervening in the economy (Satz, 2012). Sally (1994, p. 166) underlines that nineteenth century enterprises had an 'atomistic' character, compared 'to a late twentieth century multinational', and urges that both cannot be easily compared. Moreover, the inception of the business administration discipline is often associated with Frederick Taylor's Scientific Management in the early twentieth century. Therefore, in the early nineteenth century, the business administration discipline as such is not *en vogue*. Production and the role of privately owned companies in nations were subject of political economy. The thoughts that were expressed by Blanqui on 'management' education have to be regarded in that context.

Interestingly, Blanqui (1837) is the inventor of the term 'Industrial Revolution' and praised the UK's inventions, the steam engine's invention and the spinning machine. These inventions overturned old trading systems by generating similarly material products and unprecedented social issues. *It looked like England had discovered new mines and had suddenly been enriched with unexpected treasures,* while *the French Revolution was doing its large social experiments on a volcano* (own translation; Blanqui, 1837, p. 166). And: However, barely hatched from the brains of these two men of genius, Watt and Arkwright, the *industrial revolution* took possession of England.[1,2] At the end of the eighteenth century, a single piece of cotton was not consumed in Europe, which did not come to us from India, and 25 years later, England sent it to the very country from which it had so far pulled all similar products. The river, says J.-B. Say, went back up to its source (own translation; Blanqui, 1837, p. 167).[3]

Scotland – Mill Inspired by Von Humboldt

Whereas Von Humbolt in Prussia was inspired by the ideals of freedom of the French Revolution and Blanqui in France by the British Industrial Revolution, the Scottish, liberal economist, John Stuart Mill (1806–1873) was inspired by Von Humboldt's work *Ideen zu einem Versuch, die Gränzen der Wirksamkeit des Staates zu bestimmen* (Von Humboldt, 1851). Von Humboldt wrote this work already in 1791. Since of difficulties with the Berlin censorship, Von Humboldt decided to withdraw the manuscript. However, individual sections were published in 1792 in the 'Berlinische Monatsschrift' and Schiller's *Neuer Thalia.* Eventually, the book was published in full posthumously in 1851, shortly after the revolution year 1848. At that time, state power was on the rise in Europe (see: preface of Von Humboldt, 1854).

In his inaugural speech at the University of St. Andrews, Scotland, in February 1867, inspired by Von Humboldt, Mill expressed the Anglo-Saxon character-education ideal: *At least there is a tolerably general agreement about what an* (sic!) *University is not. It is not a place of professional education. Universities are not intended to teach the knowledge required to fit men for some special mode of gaining their livelihood. Their object is not to make skilful lawyers, or physicians, or engineers, but capable and cultivated human beings* (Mill, 1867, p. 4).

The Enlightenment inspired von Humboldt's thoughts. In the summer of 1789, when he visited Paris, Von Humboldt witnessed the French Revolution (see the preface of Von Humboldt, 1999). Inspired by the French revolutionary 'Liberté', Von Humboldt's message of freedom fitted the atmosphere after 1848 and was therefore not limited to Prussia. His book *Ideen zu einem Versuch, die Gränzen der Wirksamkeit des Staates zu bestimmen* (Von Humboldt, 1851) was translated in English, entitled *Sphere and Duties of Government* (The Limits of State Action) (Von Humboldt, 1854). Mill took up Von Humboldt's ideas and quoted Von Humboldt at the beginning of his book entitled *On Liberty*: *The grand, leading principle, towards which every argument unfolded in these pages directly converges, is the absolute and essential importance of human development in its richest diversity* (Mill, 1859, p. 4).

Mill builds up his case for individual freedom from a development perspective. Freedom is crucial for civilization and development. Instruments for this development are free speech, experimenting with different life forms, and the clash of ideas to become better citizens and society. Mill reasons that freedom aims to serve development. Mill adds a subtle shift in meaning to the Humboldtian 'development concept' (De Hert et al., 2015).

This shift is best illustrated with Mill's metaphor of a tree: *Human nature is not a machine to be built after a model and set to do exactly the work prescribed for it, but a tree, which requires to grow and develop itself on all sides, according to the tendency of the inward forces which make it a living thing* (Mill, 1859, p. 107).

The comparison to a tree has two crucial implications. First, the development lies in humans' nature and slowing down that development would be unnatural. Second, Mill reasons further than Von Humboldt that individual development's objective is to realize human nature (De Hert et al., 2015).

Criticism on Governmental Misuse of the Bildung Ideal

As introduced in the Prussian nineteenth century school system by Von Humboldt, the *Bildung* education led to criticism in the second half of the nineteenth century, philosophically articulated by philosopher Friedrich Nietzsche (1844–1900) (Sanderse, 2019).

Von Humboldt's ideal of *Bildung* referred to personality development and self-cultivation (Bruford, 1975) and was initially *intended as a progressive and cosmopolitan project, but was used by German governments in the nineteenth century to fashion the nation-state* (Sanderse, 2019, p. 399). Indeed, the *Bildung* underwent *an important change in the semantic structure of the ideal of self-cultivation occurs after the Restoration period (1815–1848)* (Alves, 2019, p. 10). During the Restoration, Von Humboldt's measures were used to expand the state's influence on the school system to control society and curb political expression against the government (Alves, 2019).

Alves (2019) notes that in 1819, the so-called Carlsbad decrees constrained the press, association and expression freedoms in reaction to nationalist and socialist activism, particularly within student associations (Burschenschaften). As opposed to Von Humboldt, the Prussian reformers never gave up state dominance over the educational system, which controlled all its aspects: internal organization, curriculum, finance, examinations and teachers. It facilitated the school system to be moulded by later Prussian nationalism (Alves, 2019).

In the 1870s, Nietzsche led the criticism against *Bildung* philosophically; he *criticized the German system of public education for having relinquished the Bildung ideal, having replaced it with preparing students to serve the German nation station and war machine* (Sanderse, 2019, p. 406).

Von Humboldt greatly influenced Nietzsche's thoughts regarding *Bildung* (Zauli, 2019): *It is clear from innumerable references in Nietzsche's works that the idea of 'Bildung' was one of his principal preoccupations at all stages in his life* (Bruford, 1975, p. 164). In Nietzsche's work, the word *Bildung* refers to the academic training of a particular individual. However, Humboldt's definition is *closely linked to the question of language, which he considers as the organ of inner being or even this being itself* (Zauli, 2019, p. 126).

The *Bildung* ideal of the early nineteenth century had, according to Nietzsche, alienated from the initial idea of experimenting *with classical ideas to spur a people's cultural development* and *called people that pride themselves of their high German culture, Bildungfilister* (Sanderse, 2019, p. 408). Here, the German word *Filister* or *Philister* should be translated or interpreted as a name for a narrow-minded *petite-bourgeoisie* member.

Nietzsche's criticism focused on education, being under the control of the *national-economic dogma*, meaning that schooling was aimed to increase knowledge and culture, leading to more production and consumption, more money, and subsequent happiness, and eventually an increased competitive advantage related to other nations (Sanderse, 2019).

According to Nietzsche, the *Bildung* ideal was falsely employed for 'utility' and 'gain' to turn students into 'currency' to let them 'circulate' in the national economy (Sanderse, 2019). Thus, Nietzsche's criticism of *Bildung* was that it was used as a vehicle to fashion the German nation-state and alerted that *Bildung* (or every other form of character education) is susceptible to governmental influence.

The Concept of Liberty and Personality Education

After Nietzsche launched his criticism in 1872, some examples of governmental misuse of the *Bildung* ideal or character education can be pointed out. Lansing (2010) explicitly describes the continuation of the *Bildung* activities under the twentieth century totalitarian regimes in Germany in his book entitled *From Nazism to Communism: German schoolteachers under two dictatorships.*

These authoritarian and totalitarian regimes intended to influence and shape (young) people, violating the liberty concept Von Humboldt and Mill proposed. Von Humboldt argues that it is not a task for governments to promote citizens' development but maintain order and safety and guarantee the freedom of conscience. Imposed *Bildung* would obstruct conscious self-development. A government that aims to develop society will reap conformity and dependence if that society is not prepared to create, as illustrated with the abovementioned German examples by Lansing (2010). The government must, therefore, exercise restraint and allow citizens to develop as they like. Von Humboldt pleaded for a relatively small, neutral and tolerant government as a precondition to developing citizens and society (De Hert et al., 2015).

However, if, according to Mill, development is the goal of man and society, inevitably, the question arises whether forms of development are a task of the government to promote these actively. Indeed, Mill distinguishes higher and lower order activities and clarifies that pursuing higher forms is preferable, both for the individual and society. Unlike Von Humboldt, Mill is convinced that the government can at least support individuals' self-development process. In his work, the *Principles of Political Economy,* Mill states that the government can start through targeted policy. Mill has a more positive view of the state than Von Humboldt, who mainly pleaded to increase the individuals' free space. Mill sees more room to manoeuvre for the public sector. However, Mill does not see a role for governments to provide education. It should be left for private initiatives (De Hert et al., 2015). Here, as Isaiah Berlin (1958) proposed, the issue of positive and negative freedom comes to the forefront. In the next section, the context of the two liberties is briefly described.

Liberalism and Two Conceptions of Liberty: Positive and Negative Freedom

The concept of liberalism first emerged in the early decades of the nineteenth century. The term then referred to those who, after the French Revolution, promoted the freedom ideal. In 1812, the term was first used to refer to a specific political group, the Spanish *Liberales*. In the same decade, the term became common parlance in France and Great Britain as a collective term for political movements defending rights to extend citizens' freedoms. Remarkably enough, the Swiss and French philosopher, politician and essayist Benjamin Constant (1767–1830) used the term *Liberalism* already in 1797, as a description from his middle position, between the extremes (De Hert et al., 2015; Vincent, 2000).

Freedom is the core value for Constant. He emphasized that a part of human existence is necessarily individual and independent, which needs to stay out of the government's reach. The government's power has to be delineated and limited based on a constitution and institutions established for that purpose, transparent laws and procedures, independent courts, the separation of powers, direct elections of authorities, and a responsive policy (De Hert et al., 2015).

In 1819, Constant distinguished two conceptions of freedom: the *ancients* and the *moderns.* Modern freedoms are mainly private: privacy and individual freedom are modern concepts. It concerns freedoms such as expression, property, choice of profession and residence, association, religion, right to vote and the right not to arbitrary deprivation of liberty or be subject to abuse. Ancient liberty was lying in the possibility of participation and representation in politics (De Hert et al., 2015).

With the distinction of the two liberties, Constant is the founder of modern freedom (De Hert et al., 2015) that inspired, amongst others, Mill (Lachs, 1992) and the British political philosopher Isaiah Berlin (1909–1997), who further developed the idea of two freedoms. In 1958, Berlin presented before the University of Oxford his inaugural lecture *Two Concepts of Liberty,* the negative and the positive concept. In the negative view, individuals are more unrestricted when the space in which an individual can act unhindered by others is larger:

> 'The negative concept: I am said to be free to the degree to which no human being interferes with my activity. This is the classical sense of liberty in which the great English philosophers, Hobbes, Locke, Bentham, Paine, and indeed Mill, used it' (Berlin, 1958, p. 14). 'Another characteristic of this "negative" conception of liberty is that it is compatible with autocracy, or at any rate the absence of self-government. Liberty, in this sense, is concerned with the area of control, not with its source'. (Berlin, 1958, pp. 9–10)

In the positive concept, the individual is free only when being the master of oneself. When the individual cannot use positive freedom because of poverty or ignorance and cannot master itself, there is no positive freedom and, consequently, no negative freedom. *The 'positive' sense of the word 'liberty' derives from the wish on the part of the individual to be his own master* (Berlin, 1958, p. 14). *For the positive sense of liberty is an answer to the question: By whom am I governed? Who is to say what I am and what I am not to be or do?* (Berlin, 1958, pp. 10–11).

Berlin warns that the positive concept can easily be misused by those who reason about what is right for others and dictate how to live. One could argue that those involved would be misusing their negative freedom because of ignorance and social circumstances and would not be the master of themselves (i.e. positive freedom). Berlin concludes that, at best, the positive conception of freedom leads to paternalism and, in the worst case, to despotism (De Hert et al., 2015).

In conclusion, the concept of maximum negative freedom would conflict with the categorical imperatives of Kant and consequently with the negative freedom of other subjects. Nonetheless, Von Humboldt and Mill served as participants in the discourse on liberties and pleaded for maximum negative freedom. Von Humboldt warned that imposed *Bildung* would obstruct conscious self-development, and for Mill, negative freedom aims to serve the individuals' development. As elaborated, Rousseau, Von Humboldt and Mill, placed development and learning in the context of (negative) freedom.

CONCLUSION – FREEDOM IS CRUCIAL FOR PERSONAL DEVELOPMENT

In the above sections, links between the First and Fourth Industrial Revolution could be detected. In both era's employees or citizens increasingly require personal skills and traits that educators need to address. Differences are made apparent. The early nineteenth century differs from the current timeframe. First, business administration was not yet developed as a discipline two centuries ago. Moreover, the geopolitical, philosophical and societal landscapes are deviating.

Interestingly, in both era's the call for personal development, 'improved' citizenship and the role of higher education is heard, which regards the research question *RQ2a* (*how did educators prepare their learners with soft skills education during the First Industrial Revolution?* The common ground of the described approaches of educators in Scotland, France and Prussia lies in the freedom of personal development.

Mill states that the universities' *object is not to make skilful lawyers, or physicians, or engineers, but capable and cultivated human beings* (Mill, 1867, p. 4). Von Humboldt adds: *(…) when we speak in our language of cultivation* (Bildung), *we mean by this something at the same time higher and more inward, namely the disposition that, from the knowledge and feeling of the entire mental and moral endeavour, pours out harmoniously upon temperament and character* (Von Humboldt, 1999, pp. 34–35). For Blanqui, *management studies could in no way be reduced to an accumulation of technical capacities, however necessary they may have been. In his view, proper management education was an exercise, which enabled future economic decision-makers to develop the crosscutting know-how and skills needed to reformulate problems and identify solutions in complex organisational situations* (Deslandes, 2019, p. 8).

In the early nineteenth century, the idea of freedom to develop as a person was promoted by Von Humboldt, inspired by Rousseau. Von Humboldt was in Paris on 14 July 1789, when the storming of the Bastille took place. Blanqui was Von Humboldt's contemporary and had similar ideas on the liberty of personal development. Constant provided the distinction of two concepts liberty, and as the founder of modern freedom (De Hert et al., 2015), he inspired Mill (Lachs, 1992). Moreover, Mill was inspired by Von Humbolt.

Therefore, the answer to research question *RQ2a* lies in leaving room for personal development. Crucial for Blanqui was to include the coverage of *the moral lesson of freedom, leaving room for the apparently useless (…)* (Deslandes, 2019, p. 8). In line with that, Mill adds that freedom is crucial for civilization and development, including free speech, experiments with different life forms and opposing ideas to become better citizens and society. Mill reasons that freedom aims to serve development (De Hert et al., 2015). Or, as Von Humboldt noted: *The State must wholly refrain from every attempt to operate directly or indirectly on the morals and character of the nation* (Von Humboldt, 1854, p. 113).

The answer to the research question *RQ2b* (*which lessons can be drawn from educational insights and practices during the First Industrial Revolution?*) is addressed by Deslandes (2019), who points at the Fourth Industrial Revolution's challenges and sees comparisons with the First Industrial Revolution. Based upon the ideas that Adolphe Blanqui's formed during the First Industrial Revolution, Deslandes (2019) emphasizes that management schools currently should offer students the political, technical, artistic, philosophical and literary contemporary context to understand the future better: *The large proportion of top managers with a background in humanities serves as a reminder that certain intangible qualities cannot be understood strictly in terms of organisational utility: personal identity, interpersonal skills, shared cultural values, and even the 'economic' intelligence we carry more or less unconsciously* (Deslandes, 2019, p. 8). Hence, managers need a broad education.

The first two research questions, *RQ1a* (*can soft skills development in education lead to improved citizenship?*) and *RQ1b* (*if so, how must soft skills development be applied to improve citizenship?*), are difficult to answer based on the above historical overview. The Bildung experiment was abused to fashion the German nation-state in the nineteenth century and by dictatorial regimes that scourged Germany in the twentieth century, which is an answer to *RQ2b* and can be classified as negative 'lessons learned', although Von Humbolt had predicted the outcome before. Therefore on the first two research questions will be elaborated in the discussion section.

DISCUSSION ON PROMOTING PERSONAL DEVELOPMENT IN HIGHER EDUCATION

European politicians stated that higher education has to empower students *to become active and responsible citizens in the future* (Leuven/Louvain-la-Neuve Declaration, 2009, p. 1). The historical overview revealed the warnings that personal development requires freedom and showed examples that infringements obstruct development.

Berlin (1958) has defined the two concepts of liberty. The negative freedom is regarding the space than the source of freedom. Negative freedom is the personal freedom not to be obstructed by others. Positive freedom limits the negative freedom and is instead a source and gives the person the freedom to choose who can limit it.

When applying the two concepts of liberties, as explained by Berlin (1958), the Leuven/Louvain-la-Neuve Declaration (2009, p. 1) is an example of limiting positive freedom when stating that students need *to become active and responsible citizens in the future*, which leads in the best case to paternalism and the worst case to despotism (De Hert et al., 2015).

The question arises of what the European ministers meant with these wordings. What are active and responsible citizens in their eyes? Sanderse (2019, p. 411) warns that the *history of the Bildung idea offers an all too potent reminder of the fact that such ideals are vulnerable within a strong education system that focuses on turning young people into 'currency', to use Nietzsche's phrase,* although the *Bildung* ideal is often initiated with the best intentions.

Concluding, the role of the state of politicians in promoting personal development is suspect. Personal development does not belong to politics. Mill thinks that the government can foster personal development and has a more positive view on state interference than Von Humboldt, who defended the individuals' free space (De Hert et al., 2015).

The possible answer to the first research question might be found in the apparent discipline: pedagogy. Rousseau's philosophies are associated with the abovementioned Swiss pedagogue Pestalozzi, whose pedagogy was adopted by Von Humboldt to operationalize *Bildung* (Alves, 2019; Meyer, 1939). Moreover, Rousseau inspired many others such as the Italian pedagogue, medical doctor Maria Montessori (1870–1952), the German pedagogue Friedrich Fröbel (1782–1852), the Dutch teacher and educational innovator Jan Ligthart (1859–1916), the co-founder of the progressive education movement, the Swiss educator Adolphe Ferrière (1879–1960) and the influential US-educational philosopher John Dewey (1859–1952) (Meyer, 1939).

The Swiss psychologist Jean Piaget (1896–1980) and Russian psychologist Lev Vygotsky (1896–1934) have positively influenced the educational discourse in the twentieth century, and their respective constructivist and behaviourist approaches are compared multiple times in the literature (DeVries, 2000). Vygotsky focused on researching children's development; the child is a dependent individual who cannot live in isolation and cannot live without interaction with the social world (DeVries, 2000). Jean Piaget mainly emphasized the interaction of the child with the physical world. Vygotsky presented the behaviourist idea that *the pupil is a reacting apparatus* and *the whole composition of the instrumental act can, without exception, be reduced to a system of stimulus-response connections* (DeVries, 2000, p. 188). The similarities between Vygotsky and Piaget are that *social factors play a central role in child development; internalization is not a process of copying material from the environment but is a transformative process;* and *what develops is the individual* (DeVries, 2000, pp. 190–192).

In the 1990s, Biggs (1996, p. 347) introduced *Constructive alignment* in which two ways of thinking are combined: *the first derives from constructivist learning theory and the second from the instructional design literature.* Central in constructivism is creating the meaning of the learner's activities, impacting the teaching and assessment methods. The *Instruction design* underlines the alignment between a course's learning objectives and the student's performance assessment methods.

Biggs (1996, p. 347) combines both ways to *Constructive alignment*. Constructivism is applied as the instructional design framework to create curriculum objectives *in terms of performances that represent a suitably high cognitive level, in deciding teaching/learning activities judged to elicit those performances, and to assess and summatively report student performance* (Biggs, 1996, p. 347). De Houwer, Barnes-Holmes, and Moors (2013, p. 633) defined learning as *ontogenetic adaption,* that is *as changes in the behavior of an organism that are the result of regularities in the environment of that organism.*

In conclusion, the common ground in the individual educational theory is that learning is a unique reconstruction in each individual's mind within the (social) context. Through Berlin's (1958) lens, the philosophical explanation for individuals' educational development would ensure positive freedom to prevent governmental paternalism.

In the introduction, the construct of competence is defined. A distinction is made, which is here Delamare-Le Deist and Winterton (2005) and Campion et al. (2011) presented in the triangle (1) knowledge (and theory), (2) (professional and interpersonal) skills and (3) intrapersonal traits and attitudes. Biggs' (1996) Constructive alignment also represents a triangle and urges educators to align (1) intended learning outcomes, (2) didactical approaches and (3) assessment methods.

Since learning knowledge and theory, professional and interpersonal skills, and intrapersonal traits differ in intended learning outcomes, so the didactics and assessments methods must be aligned. Personal development, as proposed by Von Humboldt, Blanqui and Mill, is here categorized as *(3) intrapersonal traits and attitudes.* Intrapersonal traits and attitudes have their origin in ways of thinking.

In the literature, there is a discourse on 'thinking'-learning objectives, like 'creative thinking', 'critical thinking', 'strategic thinking', et cetera. Willingham (2008) leads the discourse and warns: *If you remind a student to 'look at an issue from multiple perspectives' often enough, he will learn that he ought to do so, but if he doesn't know much about an issue, he can't think about it from multiple perspectives* (Willingham, 2008, p. 21). The plea of Willingham (2008) for specific thinking is to provide it in a context, which would be in line with Delamare-Le Deist and Winterton's (2005) definition that competent professionals possess a construct of three elements, knowledge, skills, abilities and other characteristics. It is also aligned with constructive alignment, as proposed by Biggs (2011).

In an experimental education project in a master course at a polytechnical university, Stek (2021b) illustrates formalizing intended learning outcomes regarding interpersonal traits and characteristics and the Constructive alignment with the didactics and assessment. Stek (2021b) introduced intended learning outcomes for knowledge, professional and interpersonal skills and intrapersonal traits.

In the challenge-based course, the students are confronted with a real-life case study provided by practitioners, who have to be interviewed. The students were provided (online) frontal instruction lectures and a Massive Open Online Course on knowledge and theory. Additionally, several workshops were provided, such as workshops on ethical behaviour and sound leadership, consultancy skills, creativity and inventiveness skills and negotiation skills. Thus, the students were immersed with knowledge, theory, experiences, stories and workshops of several practitioners to solve a case study.

The experimental setting of the course was in measuring the self-assessed levels of interpersonal skills and intrapersonal traits. Two-third of the 36 self-assessed soft skills levels could be improved by the course that is part of a business administration track. Notably, the intrapersonal trait 'strategic thinking' could be improved most significantly. The course offered a complex challenge-based case study that left room for the student's personal development and fostered creativity and inventiveness, aligning with a modern interpretation of the described nineteenth century educators.

European ministers stated that 'Student-centred learning (…) will help students develop the competences they need in a changing labour market and will empower them to become active and responsible citizens in the future' (Leuven/Louvain-la-Neuve Declaration, 2009, p. 1). However, apart from the question what 'active and responsible citizens' are the research questions, RQ1a (can soft skills development in education lead to improved citizenship?) and RQ1b (if so, how must soft skills development be applied to improve citizenship?) are hard to answer. The answers to the second pair of research questions revealed that personal freedom is a prerequisite for personal development.

NOTES

1. James Watt (1736–1812) presented an improved version of Thomas Newcomen's steam engine in 1776.
2. Sir Richard Arkwright (1732–1792) in 1769 patented a spinning frame that was initially water powered and later steam powered.

3. Jean-Baptiste Say (1767–1832) was a French liberal economist that is known of Say's law, that says that the production creates the demand and is the source of the demand. Moreover, Say was Blanqui's lecturer.

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AMBIDEXTERITY AS THE RESPONSE OF SMART INDUSTRY 4.0 – TOWARDS BETTER HR PRACTICES

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ABSTRACT

Due to the global labor market challenges, international companies react and adjust fast to these circumstances by implementing digital solutions into all business processes. Organizational ambidexterity is seen as the response of digital transformation and it can be divided into structural, contextual, and sequential dimensions. In this context, organizations representing the smart industry will need employees with specific competencies which let them meet technological challenges.

This chapter aims to clarify the state of opinion on expectations towards, and preparedness for, the impact of Industry 4.0 on human resources management and the implementation of various types of ambidexterity in these companies. We have conducted interviews with key HR informants from manufacturing companies operating in Germany and Poland. We have found that Industry 4.0 has a significant impact on HR practices. In both international companies, various digital solutions in employee recruitment, development, and performance, have been implemented. There have also been mature examples in both companies of structural, contextual, and sequential ambidexterity.

Keywords: Ambidexterity; smart industry; HR management; digitalization; HR challenges; Industry 4.0

INTRODUCTION

The fourth industrial revolution is known as Industry 4.0 in most German-speaking countries. Different terms for this concept can be found in other countries, such as

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Smart Industry in the Netherlands or the Industrial Internet in the United States of America. Industry 4.0 is the production of goods and services with the help of technical components such as Big Data, Cyber-physical systems, the Internet of Things, social components like attractive workplace conditions and production components such as smart factories to increase the competitiveness of a country (Bulte, 2018). 50% of German companies are planning industrial networks, while 20% have already transitioned to the smart factory of Industry 4.0 which means that machines, people and production resources are in interaction (Bayraktar & Ataç, 2019). In Poland, digitalization of business process and automation in various sectors is in its infancy. The Polish industry is between reality 3.0 and 4.0. Specific solutions are introduced 'locally'. A comprehensive approach is rare when the introduction of culture 4.0 simultaneously covers various levels and areas of the company's operations (Polski Przemysł 4.0, 2018).

Thus, in a time of rapid, dynamic and unexpected social, economic and political changes affecting the global labour market (Przytuła, 2018), the companies must react and adjust fast to such challenges as Industry 4.0 which brings increasing automation and digitalization into management. Automation is the second most important strategic priority: 36% of companies plan to increase automation over the next 12 months through leveraging cloud computing and 13% by investing in RPA – Robotic Process Automation (Deloitte, 2016). The HAYS (2018) forecasts prove that nearly half (47%) of existing jobs are bound to be performed by machines within the next 25 years. Additionally, it is estimated that approximately 57% of jobs are at risk of automation in highly developed countries, while in the EU market it is about 54%. Digitalization is changing the organizational and functional structure of each company. This term means an ever-increasing use of technology and corresponding substantial changes in numerous domains of business and society. This notion is also true for human resource management (HRM) (Strohmeier, 2020). In this context, ambidexterity can be seen as a solution for digital transformation.

'Ambidexterity' comes from Latin and means 'both (hands) right', in other words being equally adept in the use of both hands. It is a concept that often comes up when companies restructure themselves to embrace digital transformation. Studies have shown, however, that organizations have to continuously reconfigure their activities to meet changing demands in their internal and external environments (Raisch & Birkinshaw, 2008).

Organizational ambidexterity refers to the ability of an organization to both explore and exploit-to compete in mature technologies and markets where efficiency, control and incremental improvement are prized and also its competing in new technologies and markets where flexibility, autonomy and experimentation are needed (O'Reilly III & Tushman, 2013). Exploitation is associated with activities such as 'refinement, efficiency, selection and implementation', whereas exploration refers to notions such as 'search, variation, experimentation and discovery'. Exploitation and exploration therefore require fundamentally different organizational structures, strategies and contexts (Raisch & Birkinshaw, 2008). In this context of digital transformation in companies, ambidexterity is considered as a modern organizational concept managing current strategical requirements as such innovation for new digital solutions vs. efficiency in existing processes in fast developing smart factories as Garaus et al. (2016) pointed. According to Andriopoulos and Lewis (2010), Schnellbacher and Heidenreich (2020) and Uotila (2018) the organizational ambidexterity long-term success depends on the ability to explore new opportunities and to exploit existing capabilities. A lot of research has been done on Industry 4.0 from a technical point of view, but there has been little research done on what it is meant for the workforce or society as a whole (Habraken & Bondarouk, 2017). According to Habraken et al. (2018), HRM research mainly focuses on how the HR function can acquire digital competencies or make use of technology in HR domains, such as using new technologies for administration (e-HRM), recruitment (video interviews, CV scanning systems), training (virtual reality glasses, or serious gaming) or performance appraisal (continuous feedback apps). However, the impact of technology on the future of work and consequently the role of HR is much broader and may lead to downsizing, restructuring the content of jobs, teams, or departments, decreased quality of work, working conditions, or employment relations. Also, a growing body of literature suggests organizational ambidexterity is influenced by companies' HRM practices (Malik, Sinha, Pereira, & Rowley, 2019) especially concerning individual knowledge and organizational capabilities. Schnellbächer and Heidenreich (2020) showed that ambidextrous knowledge offering (exploration) leads to higher performance in settings where radical innovations are required; in contrast, ambidextrous knowledge seeking (exploitation) leads to increase in performance where settings required incremental innovation.

Fourné, Rosenbusch, Heyden, and Jansen (2019) revealed in their meta-analysis that high technology companies benefit from a special type of ambidexterity, that is structural one, which is discussed in the next section. Therefore, there is necessity for smart factories focusing on ambidexterity to balance the need of innovation vs. efficiency. Two transformation paths are under consideration for companies: organizational vs. individual ones (Mom, Chang, Cholakova, & Jansen, 2018). The central issue is how to transform the 'context' for ambidexterity in companies by changing their capabilities, that is organizational structure, culture, IT, processes/routines, leadership or employee competencies and behaviour. For building an ambidextrous organization, Stelzl, Röglinger, and Wyrtki (2020) identified these capability areas. These areas could be applied for running a situational analysis and defining the maturity level as a starting point for the transformation journey on the organizational level. For the employee level, Rosing, Frese, and Bausch (2011) argued that the leadership behaviour for implementing ambidexterity requires 'two complementary sets of leadership behavior that foster exploration and exploitation in individuals and teams: opening and closing leadership behavior'. Zacher, Robinson, and Rosing (2016) showed in a field study that opening leadership impacts exploration behaviour of employees, whereas closing leadership influences their exploitation behaviour. Therefore, the HR is in charge of assessing the maturity level of ambidexterity and guiding through this transformation on organizational vs. individual levels.

This requires, for instance, redefining the new role of HR to be fully engaged in running 'old processes', but facing new, digital and technological challenges.

Kang and Snell (2009) propose that each component of intellectual capital (human, social and organizational) resides in both approaches of ambidexterity, creating unique configurations that are set to align the objectives and purposes of the organization. In ambidextrous organizations, this allows to seek co-existence of explorative and exploitative approaches and the management of several layers of intellectual capital. These processes require proper handling and effective interventions. Several researchers have highlighted the importance of HRM in assessing, developing, monitoring and influencing an organization's intellectual capital, Kang and Snell (2009) provide several configurations of how HRM can enable this in ambidextrous companies by promoting the practice areas of development (e.g. training, job rotation), employee relations (e.g. advancement, career planning) and performance systems (e.g. job design, performance appraisals) to achieve both stability and continuity.

From an organizational point of view as Garaus et al. (2016) stressed the necessity for an integrated, ambidextrous HRM system which focuses on the exploration path, on *employment practices* and on the exploitation path, on *work practices* ending up in collaboration, knowledge integration and learning. The authors provide evidence that these practices do not need to be distinct or even conflicting, to accommodate ambidexterity, and argue that practices should be evolved in an integrated fashion to allow both approaches to connect and ensure the ability of the company to integrate knowledge.

Similarly, Malik et al. (2019) illustrate how efficiency can be achieved by simultaneously adapting HRM practices seeking both continuity and adaptation. In doing so, HRM ensures that the intellectual capital can be re-aligned or re-configured through various practices at different levels to accommodate the explorative *and* exploitative requirements of the company simultaneously, especially in the context of global competition.

Thus, we focused on the direct impact of Industry 4.0 on the HR function (recruitment, performance, talent management, development) through the lenses of the ambidexterity concept (Schnellbächer & Heidenreich, 2020) because the mandate of HRM is to guide and support organizational and individual transformation (Garaus et al., 2016; Stelzl et al., 2020).

BEST PRACTICES FOR AN AMBIDEXTROUS ORGANIZATION

Smart companies (companies with Industry 4.0, German term, see Pfeiffer, 2017) apply digitalization by implementing artificial intelligence (AI) for their business products and solutions. For the management, this means to think twice about optimizing established business processes with automation, artificial intelligence as well as creating new, disruptive innovation for new digital products in the digital age. On the one hand, digitalization helps to increase the process efficiency of these established business processes and core business competencies developed in an existing pattern. On the other hand, innovation is created by applying digitalization or even AI to invent new products and services via disruption (O'Reilly III & Tushman, 2013).

What solution could we think of to integrate both aspects in working processes? This dual pattern of management in the current digital age is an important key aspect to add business value by applying organizational ambidexterity (O'Reilly III & Tushman, 2013). Ambidexterity focuses on both aspects of exploration (process efficiency) and exploitation (innovation) either within the teams along the business process or by defining separate teams for exploration and exploitation (structural ambidexterity). This creates a management perspective for driving digital transformation within the company. O'Reilly III and Tushman (2013) differentiate between three patterns of ambidexterity: structural, contextual and sequential.

First, applying the most common pattern, structural ambidexterity means separating exploration and exploitation into independent business units. Beyond the business units for existing processes, an innovation hub is created to explore new disruptive business ideas in flexible units. Then, there is evidence of a positive impact on company's performance (Jansen, 2005). His study revealed that the structural differentiation on ambidexterity is mediated through informal senior team and cross-functional interfaces (Jansen, Tempelaar, van den Bosch, & Volberda, 2009). Fourné et al. (2019) emphasize this type for high technology companies. Second, contextual ambidexterity balances exploration and exploitation by making team members capable of creating a potential for efficiencies and be innovative at the same time, for example through simultaneous activities in one organizational unit. The success factors for implementing contextual ambidexterity pointed out by Birkinshaw and Gibson (2004) are the social support of the management and the high-performance organizational context with high achievement motivation of the staff.

Third, sequential ambidexterity covers a temporal sequence of exploration and exploitation (e.g. one follows the other) which is applied in the new digital business opportunities. Less evidence for the increasing impact on performance was given (He & Wong, 2004), but Chou, Yang, and Chiu (2017) showed that sequential ambidexterity, as a temporal switching capability, is positively related to new product performance. The type of business strategy and absorptive capacity moderated the impact of the sequential ambidexterity on new product performance.

The added value of different ambidexterity patterns depends on the organizational context in the light of industry 4.0 (see Pfeiffer, 2017). Based on the best practices in the literature of the subject, we illustrated this with three company cases from Germany. The first business example from 'Munich Re' goes for the structural pattern, the second case from 'Trumpf' focuses on the contextual pattern of ambidexterity, whereas the final example of the 'BMW' company presents sequential ambidexterity.

'Munich Re' as an Example of Structural Ambidexterity

This re-insurance company with 40,000 employees and 52 billion Euro revenue in 2019 was founded in 1880. Dietl (Dietl, 2020) described in his article the case study of why the re-insurance company Munich Re has chosen structural ambidexterity: *Munich Re offers insurances for catastrophes which are very rare, risk calculation is the essential mandate of everyday work which might limit creative thinking and innovatio*n. The innovation for new products was limited because of some structural and cultural barriers. Therefore, the top management decided to set up cross-functional teams with up to 300 employees who were upskilled in agile working methods to understand customer demands. They worked in a very dynamic environment within an innovation hub close to the board. This structural ambidexterity ensures service excellence in existing business processes in the large corporation and resulted in a new organizational entity Munich Re Ventures, a new digital unit in a startup setting, and special technological units for the Internet of Things. Finally, a new spin-off stands for focusing on a niche, evaluating market opportunities, fast iterative processes ('build, measure and learn') and customer-centric focus. Beyond these structural changes, Dietl (2020) summarized the following success factors for more innovation at Munich Re: top management focus, freedom for disruptive innovation, long-term resource allocation and budget for innovation even in times of revenue losses because of COVID-19. The final management lessons learned are to acquire skilled employees, establish a culture for innovation and passion to experiment although the outcome is not yet predictable.

'Trumpf' as an Example of Contextual Ambidexterity

The Trumpf company for machine tools, laser technology and electronics for industrial applications was founded in 1923 (Trumpf, 2021). The company is a market and technology leader in machine tools and lasers for industrial manufacturing. Software solutions pave the way to the Smart Factory. Hönl (2021) pointed that contextual ambidexterity has the advantage over structural ambidexterity to integrate the old and the new business perspective (*traditional mechanical engineering practices vs. artificial intelligence*) in heterogeneous, cross-functional teams in parallel for maximizing customer benefits. He also explained this type of ambidexterity as a dynamic, iterative, so-called agile development; the new role of 'product owner' within an agile team focuses on managing the technical content side and feasibility, while agile managers (former line manager) create the appropriate organizational framework, essentially by making it adaptable and facilitating continuous learning and collaboration across boundaries in the light of contextual ambidexterity. In Hönl's interview (2021), Duwe argued that new capabilities need to be combined with existing knowledge; therefore training on these capabilities is essential. Finally, Duwe (2018) summarized that this contextual ambidexterity is a key success factor for digital transformation, thus leadership behaviour should encourage thinking in both patterns in parallel. In consequence, the current business leaders apply contextual ambidexterity by flexibly switching their and their employees' mindset and capabilities between exploration and exploitation in the business processes, enabling the necessary frame for new work behaviour, tools and collaboration for their teams and employees, as in agile project management. The lesson learned from this case is to increase capabilities by developing skilled employees in interdisciplinary fields combined with an agile approach.

'BMW' as an Example of Sequential Ambidexterity

Bayerische Motoren Werke AG, commonly referred to as BMW, is a German multinational corporation that produces luxury vehicles and motorcycles. The company was founded in 1916 as a manufacturer of aircraft engines. Birkinshaw, Zimmermann, and Raisch (2016) identified BMW as an example of sequential ambidexterity: 'BMW's successful sequential alternation is its culture that encourages employees to critically reflect on their strengths; in the phase between 2006 and 2010, when front-line managers were working hard to optimize BMW's continuous profitable growth in its established model range, top executives began to meet with customers, industry experts, and researchers to discuss the future of mobility'. This is a good example of how different internal stakeholders dealt with sequential ambidexterity. Birkinshaw et al. (2016) summarized: 'During exploitative phases, front-line managers rely primarily on seizing capabilities, whereas top executives emphasize their sensing capabilities to identify the right moment and prepare the organization for the shift towards an exploratory focus. Conversely, during explorative phases, front-line managers primarily deploy their sensing capabilities, while top executives emphasize seizing capabilities, to prepare the organization for a shift back to exploitation'. In a nutshell, BMW realized the sequential pattern less within a team focus and more with many stakeholder groups on different organizational levels.

Overall, Luger, Raisch, and Schimmer (2018) criticized that ambidexterity is not the only best fitting solution for any strategical movement because this focus could result in defensive activities by the management if dynamic, transforming external forces in the environment are not taken into account. Luger et al. (2018) favours a continuum of exploration-exploitation with balanced resource allocations; in the long-term run, companies should focus on 'capability-building processes (to balance exploration and exploitation) and capability-shifting processes (to adapt this balance to the changing requirements)'. In a current cross-country comparison, Bustinza et al. (2020) revealed in the product service industry that sequential exploitation-exploration pathway maximizes company performance, but the optimal tested pattern consistent across all the world regions (except Japan) is the contextual ambidexterity impacting company performance. In contrast, Clauss et al. (2020) showed in a survey-based study in German mid-sized engineering companies how ambidexterity, exploration and exploitation affect the self-assessed competitive advantage. They favoured an exploration strategy of innovation processes with radically new knowledge, products and services, linking this with strategic agility as only exploitation has not increased competitive advantage, whereas an ambidextrous strategy on its own could negatively impact the competitive advantage.

However, our best practices focused more on structural ambidexterity which is an excellent entry point for the first implementation of ambidexterity on organizational structural level. Next, on the individual level, the leader and employee behaviour requires a transformation step in the direction of sequential or contextual ambidexterity accompanied by agile working methods. These agile working methods push the radical innovation like it was revealed by Clauss et al. (2020) and Trumpf (2021).

To conclude, we argue that a hybrid integrative pattern of contextual and structural ambidexterity with flexible staffing and job rotation between organizational units, temporary project teams, is worth considering for a smart industry. Relying only on structural ambidexterity with an independent innovation hub is not enough.

If organizational ambidexterity is implemented, there is a crucial issue of capability in terms of either allocating the resources to flexible business demands or developing employee capabilities progressing on the ambidexterity maturity level (Stelzl et al., 2020). HRM practices need to be flexible for both patterns of working along a continuum (Luger et al., 2018). Furthermore, HRM practices should extend their traditional services with add-ons for supporting the flexible explorative working style. In a nutshell, several HR practices are highlighted to stress the necessity for HRM adaptations due to digital transformation (Buisson, Gastaldi, Geffroy, Lonceint, & Krohmer, 2021; Seeck & Diehl, 2017; Shipton, Sparrow, Budhwar, & Brown, 2017). This research field is developing right now, so our discussion is more an outlook rather than a complete summary. Beyond this focus, HRM practices have to foster further current challenges for digital transformation within their companies. Hansen, Güttel, and Swart (2017) linked the ambidexterity theory with the HRM strategy and system in order to evaluate, within a company, which HR system is needed based on current strategic requirements (i.e. degrees of flexibility vs. innovation) and argued that four different HR systems (1–4) are required within the same company: (1) compliance vs. (2) productivity-based systems for exploitation needs or (3) collaborative vs. (4) commitment-based HR systems for exploration enhancement. Balancing ambidexterity in business, HR systems should apply the above solutions.

CHALLENGES FOR HRM

There is a price to be paid in building HRM systems to serve and help the enactment of ambidextrous organizations, and the number of challenges to companies that seek ambidexterity are well known. Because ambidextrous organizations require parallel actions that may often deem incompatible, much time and resources are required to build the kind of HRM practices that can be effectively integrated to achieve company continuity and development simultaneously. In addition, HRM professionals should be endowed with a specific attitude and mindset that will allow them to boldly depart from typical traditional approaches or even remain inculcated in one approach. Therefore, preparation and the right frame of mind is required (Buisson et al., 2021). Moreover, an HRM system in an ambidextrous environment implies additional complexity, and with complexity come more uncertainties to deal with. Therefore, HRM professionals need to design and implement HRM systems to support work that requires dual capabilities, to allow the company to achieve ambidexterity (Ferraris, Erhardt, & Bresciani, 2019). Finally management support is required to enable a sense of involvement and participation that is required for employees to explore new ways of behaving while maintaining efficiency at work (Prieto-Pastor & Martin-Perez, 2015). Human resource professionals are concerned with overseeing the HR of organizations, which, through Industry 4.0, will be affected by technological tools and innovative technology (Jesuthasan, 2017). Technological disruption, robotics and automation threaten to replace low-skilled, routine jobs (Naudé, 2019). The increase in technological capability will not only cause an increase in unemployment but will also change the nature of work and the workforce because of the underlying trends in technology that accelerate job automation (Dhanpat, Buthelezi, Joe, Maphela, & Shongwe, 2020).

Many scholars have examined various challenges of human resources management regarding organizational ambidexterity, including leadership (Cunha, Fortes, Gomes, Rego, & Rodrigues, 2019; Jansen et al., 2009; Nemanich & Vera, 2009), top management characteristics (Lubatkin, Simsek, Ling, & Veiga, 2006; Simsek, 2009; Smith & Tushman, 2005; Venugopal, Krishnan, Kumar, & Upadhyayula, 2019), employee motivation (Ahammad, Glaister, & Junni, 2019) and organizational culture (Wang & Rafiq, 2014). In a situation of ambidexterity, companies need to successfully combine different activities over time and space, and this brings enormous challenges for HRM, particularly in the matters of competency management (Buisson et al., 2021). Following Pfeifer's (Pfeiffer, 2017) argumentation, there is a global work reorganization for new capabilities of the workforces, either upskilling or downsizing employees, depending on the specific job families. O'Reilly III & Tushman (2013) argued to focus on dynamic capabilities and relocating these organizational capabilities by covering all three types of ambidexterity: 'Leaders must be able to orchestrate the allocation of resources between the routine and new business domains'. There has also been substantial, though insufficient, research on human resource development as a challenge for HRM in the context of ambidexterity and smart industry. Specifically, vast research exists in examining exploratory and exploitative learning (Dixon, Meyer, & Day, 2007; Kostopoulos & Bozionelos, 2011). Thus, our attention is focused on re-training and new competencies required in an ambidextrous organization. These result from digitalization of various processes in an organization. On the one hand, digital technologies are employed to support operational HR practices, such as recruitment or compensation. On the other hand, the operational application of digital technologies implies a 'liberation' of HR professionals from the operational burden, and makes them focus on value-added strategic activities of HRM (Strohmeier, 2020). Implementation of Industry 4.0 will pose new challenges for re-training. This, in particular, includes the need to equip employees with certain competencies that are crucial in the current labor market.

In the strategic document *European Digital Competence Framework for Citizens* (Vuorikari, Punie, Carretero, & Van den Brande, 2016), the European Union underlines the importance of digital competencies with key components, such as information and data literacy to articulate information needs, to locate and retrieve digital data, information and content; communication and collaboration to interact through digital technologies while being aware of cultural and generational diversity; digital content creation to create and edit digital content; safety to protect devices, content, personal data and privacy in digital environments; physical and psychological health protection to be aware of digital technologies for social well-being and social inclusion; and the last one, problem-solving to identify the needs and problems and to solve conceptual problems and problem situations in digital environments (Vuorikari, Punie, Carretero, & Van den Brande, 2016).

Other researchers go a step further, indicating the need to strengthen cognitive competence, social and emotional adaptability, and resilience (Agrawal, De Smet, Lacroix, & Reich, 2020) that goes in line with the literature and report review made by Przytuła, Strzelec, and Krysińska-Kościańska (2020). It is about finding employees with the most needed competences of the future labour market expectations, which can be achieved through re-skilling or re-training in the process of Continuous Professional Development (CPD). Industry 4.0 transforms jobs and competencies profiles as a result of two trends. First, traditional manufacturing processes characterized by a very clear division of labour will now be embedded in a new organizational and operational structure where they will be supplemented by decision-taking, coordination, control and support service functions. Second, it will be crucial to organize and coordinate the interactions between virtual and real machines, plant control systems and production management systems (Kagermann, Wahlster, & Helbig, 2013). Organizational ambidexterity will expect the organization to explore on the one hand and exploit on the other, in a turbulently changing environment. In this context, Industry 4.0 and organizational ambidexterity will require fundamental changes to the way that professionals are to be trained and the competencies they are to be provided with. In this vein, the introduction of HR Data Analytics as part of the key competence indeed requires rethinking of the skill repertoire as both technical and human considerations come into play (Eubanks, 2019; Rasmussen & Ulrich, 2015) and, above all, an appreciation of HR Data Analytics is placed within a broader strategic perspective (Falletta & Combs, 2020). The HR function can contribute to business results (Habraken et al., 2018; Habraken & Bondarouk, 2017; Jorgensen & Becker, 2017; Strohmeier, 2020), but to achieve this, HR specialists should understand and interpret financial data, have skills and knowledge helping them to translate reality into technological language, have a good command of the dynamics in the sector in which the company operates (Bayraktar & Ataç, 2019).

TOWARDS BETTER HR PRACTICES – EXAMPLES FROM COMPANIES OPERATING IN GERMANY AND POLAND

Patel, Messersmith, and Lepak (2013) emphasize that 'although the ability to achieve ambidexterity arises out of the human resource base itself, it is likely to be supported by the system of HRM practices employed by an organization'. To contribute to HR business practice, we looked at HR practices where smart solutions can be simultaneously applied while balancing between exploitation and exploration. We provided examples of ambidextrous approaches in companies operating in Germany and Poland based on interviews with key HR informants. As a result of their personal skills or position in an organization, key informants are able to provide more information and a deeper insight into what is going on around them. By definition, they all had formal roles which exposed them to information about the strategic and operational issues in company (Marshall, 1996). The first respondent is the Head of Global Talent Management at Schott AG with its headquarters in Germany. The company manufactures glass in production sites in 34 countries. The Schott corporation employs 16,500 people worldwide, including 5,900 in Germany. The global approach is focused on applying digitalization and AI in the management process, including HR practices.

The second respondent is an HR Manager for Production Operations of 3M Poland, which is a technological and production company that is a branch of the international 3M concern. 3M operates in 4 areas: Safety and Industrial, Transportation and Electronics, Health Care and Consumer Products. The company has subsidiaries in 70 countries with more than 90,000 employees worldwide. Using science and acting in accordance with the principles of sustainable development, 3M creates innovative solutions that improve the quality of life and safety standards in the workplace, reduce the risk of infection, support the treatment process, increase the comfort of living at home, and are even used in the space industry. Every year, the company invests ca. 5.9% of its sales in research and development (R&D), as a result of which approximately 1,000 new products are created annually. The company policy is focused on innovation and sustainability as its core values, and these are also reflected in the HR practices.

The interview questions were as follows:

(1) What are the general challenges businesses are facing in the era of Industry 4.0?
(2) What is the example of structural ambidexterity in your company/in HR?
(3) Are there any down-top initiatives taken by your employees, in a collective effort with no written rules or routines that develop your organization? (as an example of contextual ambidexterity)
(4) Did your company change its business model to better realign to environmental challenges? (as an example of sequential ambidexterity)
(5) What are the most required employee competencies because of Industry 4.0?
(6) How do you use digitalization in HRM processes?

HR Learning Results from the Interviews

Below we present the HR business practices in both companies concerning each research question.

Ad.1. What are the general challenges businesses are facing in the era of Industry 4.0?

The key *business challenges* for *Schott AG* are digitalization and introduction of innovations in IT and R&D. The respondent pointed out: *We have a clear and structured roadmap for digitalization and Industry 4.0 in our company […] We believe that the two enablers for our business strategy 2026 are digitalization and best teams. Digitalization is covered by 3 hubs (operation technology (OT) hub, IT hub and R&D hub) with new roles of Artificial Intelligence scientists.*

In *3M*, the key challenges in the era of Industry 4.0 are in employees' competencies, skills shift towards virtuality, AI, digital affinity and redefinition of current job profiles, as mentioned by our interviewee: *In working with augmented reality, artificial intelligence or remote system controls, digital affinity, and competencies to operate in this new reality, are a must.*

Ad.2. What is the example of structural and contextual ambidexterity in your company?

Ad.3. Are there any down-top initiatives taken by your employees, in a collective effort with no written rules or routines that develop your organization?

Both structural and contextual ambidexterity was identified in Schott's business model. According to our HR key informant: *As an example of structural ambidexterity in our company, I would point to three units, e.g., OT, IT and R&D. Founding these innovation hubs confirms the structural ambidexterity, and they are structured as follows: (1)*

Operations technology (OT) based at HQ in Mainz directly reports to our board. The OT focuses on Industry 4.0 and digitalization with different business units globally. (2) The IT hub is within the IT department. (3) R&D is a small team of scientists working with AI and big data.

In *Schott AG*, a combined approach of digitalization with a lean management champion network serves as the best practice for implementing contextual ambidexterity on a global basis. Our respondent pointed to down-top initiatives taken by Schott AG employees in a collective effort with no written rules or routines: *Yes, we implemented previous initiatives taken by employees who serve as change agents in a network of lean champions as bottom-up support in each production site. This combined approach of Lean Management and digitalization by the OT hub is the best practice for contextual ambidexterity.*

Similarly to Schott AG, also in 3M Poland both examples of organizational ambidexterity – structural and contextual – were identified. The structural ambidexterity exists in the form of an innovation hub and cross-functional units like information technology (IT), operations technology (OT) and R&D which are coordinated by highly educated experts and science advocates. The interviewee explained that: *3M introduced a program framework which required arranging multidisciplinary, cross-functional teams. The traditional definitions of IT and OT, as an example, needed to be explored and revised to allow these two groups to create synergy. On top of that, we bring together expertise related to machine design, automation, manufacturing technology, research, and development needed to build the new ecosystem [….]. We have established a group of science advocates who engage the next generations to pursue their careers in STEM fields.*

As regards contextual ambidexterity, the improvement in communication and exchange of information is a major bottom-up initiative that leads to employee engagement, motivation and proactivity. According to our respondent: *Our major goal of bottom-up ideas is to create a culture of open exchange of ideas, walking the talk, getting inspiration for smaller and larger improvements. We created such platforms to exchange information: (1) Continuous improvements – is enhanced by rotating leaders of daily production meetings, visualization of the problems and actions by linear process coaching, problem-solving worksheets; (2) Safety and Health – aims at engaging all levels of employees in proactive preventive thinking to report potential incidents. (3) See and Act program (GROW) where leaders of all levels talk to employees to engage and motivate them by showing interest and having* a *personal conversation.*

Ad.4. Did your company change its business model? (as an example of sequential ambidexterity).

There were some initiatives taken by these companies to better realign to environmental challenges as an example of *sequential ambidexterity*. In *Schott AG*, the key informant said: *Yes, due to a new business strategy, we defined business goals for alignment to sustainability by getting climate-/CO-neutral in 2026 at our core business; glass production is very energy-intensive.*

The response of *3M* to current environmental challenges is clearly stated in the strategic plans and, according to the interviewee: *The switch to renewable energy is part of 3M's strategy focused on climate protection with efforts to innovate in order to cut emissions from industry and reduce our environmental footprints. Thanks to the application of scientific and technological knowledge, as well as the constant introduction of innovative products and solutions, 3M has been regularly reducing carbon dioxide emissions since 2000. Actions taken today are to result in the achievement of total (100%) carbon neutrality by 2050. 3M* *has also committed to reducing water consumption at its production facilities around the world over the next decade – by 10% by 2022, by 20% by 2025, and by 25% by 2030. We're currently working on 100% transition to LED lighting, which will soon save 17 million kWh of energy.*

Ad.5. What are the most required employee competencies because of Industry 4.0?

As regards the research question concerning *the most required employee competencies* in the view of Industry 4.0, *Schott AG* relies on digital competencies of new employees: *In our company, we expect employees to learn new digital competencies described within the EU framework we applied, however, I don't remember all the competencies in detail, the EU digital competency framework is the basis for our learning journey and paths.* Digital competencies of the employees in production sites are a core element of career development:

> Everybody got a map for his/her learning journey with stickers, which was implemented by the local HR managers, as our HR network from headquarters to regional to local HR managers, works very well. We implemented a framework for digital competencies which is the basis for the learning journey and paths.

In *3M*, we found a more advanced and mature approach to employee competencies. The respondent said that: *In 3M, we have experts in all of those fields, most of them highly educated with Ph.D. degrees and years of experience in the industry, labs and universities* and the most required competencies are STEM skills – technical skills, such as IT, mathematics and engineering to operate advanced machines and systems. According to our key respondent: *New competencies of the employees are needed for 3M and these include STEM and digital competencies that the company develops via courses on Data science, digitalization or Machine Learning, engaging Industry 4.0 solutions, such as virtual reality (VR).* 3M company is focused on employees' analytical skills, but simultaneously supports those who are willing to learn and reshape their skills and competencies flexibly: *What is very important is the openness to learn and grow. We are developing programs for both production and non-production employees that help unblock the past and shift towards the future, show how the growth mindset positively impacts individuals and the organization.*

Ad.6. How do you use digitalization in HRM processes?

In relation *to the last research question* for *Schott AG*, HRM focuses on the digitalization of its processes, such as HR software implementation, and partly contributes to contextual ambidexterity by fostering innovation, such as digital learning programs, online assessment centres, or leadership coaching within the talent management process, as was pointed by our key informant: *Our talent management process was adapted to digital elements, for example tools for potential analysis, such as an assessment center or coaching in e-tools and e-coaching. We created small learning units instead of long-lasting training programs for the talents. Our talents are self-responsible for choosing their learning units on urgent demand.*

Performance management was simplified to contribute to organizational ambidexterity in business: *We streamlined our previous complex performance management system by simplifying the performance talks to several feedback talks every 3 months during a business year and focusing on two simple questions: What do you contribute and how do you contribute?*

In *3M*, there is a great emphasis on digitalization of HR processes with particular attention to recruitment: *In recruitment, to be closer to potential candidates, we use social media, especially LinkedIn that connects professionals and Facebook to build employer branding and attract potential candidates. We also use an Automated Tracking System to monitor the applications and manage candidates' data. Additionally, as we continuously* *invest in Industry 4.0, we recruit employees with experience in programming Programmable Logic Controllers, Visual Basic and SQL, mechatronics, robotics, data analysis, experience in implementation of historians, ability to work with the Internet of Things (IOT).*

> As an example of an ambidextrous recruitment process, we have recently created new roles related to the implementation of Industry 4.0 projects, directly related to machine-learning – Digital Shop Floor for Data Engineer positions. To assess the skills, we have engaged our current employees with AI, IT, machine learning expertise, e.g. R&D employees from Poland and abroad.

To promote analytical skills, 3M offers various internal development courses for employees: *In HR Development, we use virtual training for manufacturing employees via virtual training center for warehouse operations with the use of simulation and 3D. In the area of data science, one of the courses we offer is Machine Learning – this internal training is run by a 3M employee teaching at the Minnesota University, and is about searching for and using interdependencies in big data sets. Applications, such as Netflix, YouTube, Siri, use machine learning. The course is addressed to all those who can use data science in their work.*

CONCLUSIONS

We conclude that the essential mandate for HRM in the twenty-first century is to deliver modern HRM frameworks for supporting the management and employees in routine and innovative work environments. In this digital age, HRM should help by implementing a flexible working culture, dynamic workforce capabilities and working tools in a smart factory; for HR professionals in companies stick to the so-called New Work concept (Bergmann, 2019). Facing the business challenges in the digital age (big data, global connectivity, AI), the HR management increases the maturity level for ambidextrous approaches: structural, contextual or sequential ones (Stelzl et al., 2020).

For the purposes of this chapter, we interviewed HR key informants representing two corporations (based in Germany and Poland) that are using digital and innovative solutions as a response to Industry 4.0. The respondents identified similar challenges in their businesses: sustainability (getting climate/CO-neutral), digitalization and innovation, AI, and new interdisciplinary competencies of employees 4.0 which were also pointed by Buisson et al. (2021) and Bulte (2018). In both companies, we identified examples of structural ambidexterity, such as innovation hub, IT, OT and R&D units which create synergy and add value to the whole organization. The interdisciplinary teams of highly qualified experts from machine designs, automation, manufacturing technology and AI cooperate on the verge of industry, business and science.

We also asked about any down-top initiatives taken by employees in both companies, understood as collective efforts with no written rules or routines that contribute to the development of these organizations. The respondents pointed to various solutions, such as a network of change agents in all corporate units, platforms for exchanging information, implementation of lean management (linking digitalization with existing change initiatives), engagement of all levels of employees in proactive, preventive thinking to follow the Kaizen method. These are examples of contextual ambidexterity and according to Mom et al. (2018), the *bottom-up* practices are mediated by individual behaviour (self-efficacy and intrinsic motivation) and influence organizational ambidexterity outcomes. Also regarding contextual ambidexterity, Simsek et al. (2009) argued that organizations need to focus on multiple levels: individual, group and organizational. Individuals must allocate their efforts to manage the dual learning modes of exploration and exploitation in a way that they seek help and support from their managers (Nemanich & Vera, 2009). According to Zacher et al. (2016) ambidextrous leadership behaviour enables the new required employee behaviour. Sequential ambidexterity was described as changes introduced in the business model due to new environmental challenges. The practices in both companies are still *in statu nascendi* and mostly focus on sustainability, green electricity and the achievement of carbon neutrality within the next decade.

Regarding the *most required competencies of Industry* 4.0, both Schott AG and 3M valued digital competencies, virtuality, STEM education, analytical skills, openness to learn and grow, creativity and flexibility. These requirements are in line with 'The Accreditation Board for Engineering and Technology (ABET)' which recommends the following 'must-have abilities' of successful professionals: apply STEM knowledge, analyze and interpret data; identify, formulate and solve engineering problems; understand the impact of engineering solutions in global, economic, environmental and societal contexts; use the techniques, skills and modern engineering tools necessary for engineering practice (ABET, 2021). Similarly, Hernandez de Menendez et al. (2020) concluded that there is a vast literature that reviews the competencies needed in Industry 4.0. However, the common ones could be considered those related to the ability to use and interact with Industry 4.0 technologies, data analysis, technical knowledge and the need for personal skills (Hernandez-de-Menendez, Morales-Menendez, Escobar, & McGovern, 2020).

Concerning *HR practices* that are supported by digital solutions in both companies, the interviewees pointed to recruitment, performance management and development of employees – mostly affected by automation and digital tools. Companies that implement Industry 4.0 need to understand that their employees must continually acquire new skills. This can be achieved by offering frequent training and education programmes to employees or by hiring external talent with the needed abilities (Hernandez-de-Menendez et al., 2020). Overall, for our key informants, organizational ambidexterity seems to be a valid concept combining their efforts on efficiency with innovation goals operationalized in business units and in a daily teamwork confirmed by empirical studies on ambidexterity's impact on business performance by considering different contextual settings (Junni, Riikkka, Taras, & Tarba, 2013). Because of the imperative of new digital technologies (big data, global connectivity, AI), a new HR operating model is necessary. Rehse, Agarwal, Rodt, and Twesten (2019) suggest updating current HR services by implementing AI as core elements. Flores, Xu, and Lu (2020) call for new structural interactions among employees, additional qualities to human capital and different ways to identify the competencies for the workforce.

To conclude, HR managers are required to support their business units with implementing the digital transformation together with organizational ambidexterity, and simultaneously the HR teams are required to plan and implement their own HRM digital transformation for their core HR processes (e.g. employee recruitment and development, HR analytics). HR professionals might push forward their own digital and AI innovations by applying contextual ambidexterity within the HR teams in this disruptive and digital twenty-first century.

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CROSS-DOCKING: CURRENT RESEARCH VERSUS INDUSTRY PRACTICE AND INDUSTRY 4.0 ADOPTION

Fabian Akkerman, Eduardo Lalla-Ruiz, Martijn Mes and Taco Spitters

ABSTRACT

Cross-docking is a supply chain distribution and logistics strategy for which less-than-truckload shipments are consolidated into full-truckload shipments. Goods are stored up to a maximum of 24 hours in a cross-docking terminal. In this chapter, we build on the literature review by Ladier and Alpan (2016), who reviewed cross-docking research and conducted interviews with cross-docking managers to find research gaps and provide recommendations for future research. We conduct a systematic literature review, following the framework by Ladier and Alpan (2016), on cross-docking literature from 2015 up to 2020. We focus on papers that consider the intersection of research and industry, e.g., case studies or studies presenting real-world data. We investigate whether the research has changed according to the recommendations of Ladier and Alpan (2016). Additionally, we examine the adoption of Industry 4.0 practices in cross-docking research, e.g., related to features of the physical internet, the Internet of Things and cyber-physical systems in cross-docking methodologies or case studies. We conclude that only small adaptations have been done based on the recommendations of Ladier and Alpan (2016), but we see growing attention for Industry 4.0 concepts in cross-docking, especially for physical internet hubs.

Keywords: Cross-docking; materials handling; Industry 4.0; physical internet; systematic literature review; supply chain distribution

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INTRODUCTION

Cross-docking is a supply chain distribution and logistics strategy for minimizing long-term storage of products and parts, maximizing fleet utilization and minimizing trucks dispatches. Over the past decades, the domain has gained attention from a variety of industries, e.g., retail, automotive, perishable goods and pharmaceutics (van Belle, Valckenaers, & Cattrysse, 2012). At cross-docking terminals, cargo is typically stored for less than 24 hours. The process at the terminals consists of unloading, sorting and temporarily storing the goods of inbound trucks from suppliers, after which the goods are moved across the terminal where they are loaded on outbound trucks to be dispatched further down the supply chain.

Developments in cross-docking systems have generated competitive advantages. The market of supply chain management is becoming increasingly competitive, making it crucial to optimize logistics costs and throughput of products to stay competitive, as observed in industries such as retail chains, e.g., Walmart (Chen, Fan, & Tang, 2009), and mailing companies, e.g., UPS (Forger, 1995). Logistics-related activities are one of the main cost drivers for many industries (Gue, 2014; Wang, Ranganathan Jagannathan, Zuo, & Murray, 2017). Furthermore, the environmental impact becomes more important; for every voluntary disclosure of an additional 1000 metric carbon emissions, the value of a company deteriorates by $212,000 on average (Matsumura, Prakash, & Vera-Muñoz, 2014). Solution methods for cross-docking that quantify and minimize carbon footprints are under development (Çolak et al., 2020; Nathanail, Terzakis, & Zerzis, 2020). Hence, due to the nature of low inventory levels and higher utilization of trucks, cross-docking has found an increasing amount of attention in the domain of (green) supply chain management (Dadhich, Genovese, Kumar, & Acquaye, 2015).

There is a wide range of literature on quantitative methods to optimize various decision levels of cross-docking problems, e.g., truck scheduling (Berghman, Briand, Leus, & Lopez, 2015; Bodnar, de Koster, & Azadeh, 2015; Shakeri, Low, Turner, & Lee, 2012), vehicle routing (Ahmadizar, Zeynivand, & Arkat, 2015; Dondo & Cerdá, 2015), truck-to-door assignment (Guemri, Nduwayo, Todosijević, Hanafi, & Glover, 2019) and the shape of cross-docking terminals (Bartholdi & Gue, 2004). Due to the computational complexity of cross-docking problems, the majority of the proposed optimization models use simplifications. Often, such models do not match industry requirements, and reviews suggest an absence of implementation focus on cross-docking literature (Ladier & Alpan, 2016).

To compare what industry practices are commonly used in the literature, Ladier and Alpan (2016) conducted a review study divided into two parts: state-of-the-art literature research on quantitative solution approaches to operational cross-docking problems, and on-site research with interviews at eight cross-docking terminals. The authors constructed a framework for comparing cross-docking research with industry practice. A significant share of the quantitative studies use modelling constraints and performance measures that do not adequately reflect real-world industry practice (Ladier & Alpan, 2016). Ladier and Alpan (2016) recommended connecting future research and industry practice by changing modelling settings and performance indicators.

We aim to build on the study performed by Ladier and Alpan (2016). The survey and state-of-the-art review described above was performed in a non-systematic way. The methodology followed in that work involved that selected articles had to be written in English and include well-defined keywords, e.g., cross-dock, cross-docking, transhipment, etc. The authors limited the resulting works to the operational level, resulting in 142 papers up to the year 2015. Since then, numerous new studies have been conducted within the cross-docking domain. Hence, it is interesting to find indications if there is more presence of the practical modelling settings that were recommended for future work. Since 2016, three new literature reviews have been conducted on cross-docking. Buakum and Wisittipanich (2019) conducted a literature review on the period of 2001–2017, exclusively on what type of meta-heuristic solutions are proposed to cross-docking operational problems. The systematic literature review conducted by Ardakani and Fei (2020) extracts information about processes uncertainty for cross-docking planning. Theophilus, Dulebenets, Pasha, Abioye, and Kavoosi (2019) conducted a state-of-the-art review on the timeframe of 2016–2018 regarding the truck scheduling problem. No studies have been conducted on the intersection of research and industry practice. Thus, in this chapter, we conduct a systematic literature review in which we select papers that consider industry practice, e.g., case-based studies or studies presenting real-world data. This allows us to study whether the gap between research and industry practice has narrowed since 2016.

Furthermore, we focus on developments in academia and industry with regards to Industry 4.0. The term Industry 4.0 was coined by Kagermann and Wahlster (2011). The term is used for a new revolution in industry, after the first revolution moving from hand labour to machines (1760–1840), the second revolution in faster transport and communication using rail and telegraph (1871–1914) and the third revolution (late twentieth century) in computers and automation. The fourth revolution entails the interconnection of machines, transparency of information, the assistance of machines in human labour and autonomous decision-making of machines (Lu, 2017). Our review examines the degree to which Industry 4.0 has been adopted in academic research and the cross-docking industry.

We compare the studies obtained from our review with the state-of-the-art literature before 2015, using the same elements of the classification framework by Ladier and Alpan (2016), i.e., cross-docking settings, business process level and performance indicators. Indications of change or absence of change are used to recommend starting points for future reviews and future implementation-oriented studies. Unlike Ladier and Alpan (2016), we follow a systematic literature review primarily focused on the literature published in the period 2015–2020 and do not conduct interviews with cross-docking managers. Thus, the contributions of this chapter are (1) the summary of new works on cross-docking in the period 2015–2020, (2) the review of changes in literature since 2016, (3) the review of Industry 4.0 adoption in cross-docking research and (4) recommendations for future research in cross-docking and Industry 4.0.

The remainder of this chapter is structured as follows. First, cross-docking in the Industry 4.0 era is further explained in Section 'Cross-Docking in the Industry 4.0 Era'. Next, the methodology for the systematic literature review is explained in Section 'Methodology'. In Section 'Results', the outcomes of the systematic literature review are presented. Finally, we discuss our findings in Section 'Discussion', conduct a complementary literature review of Industry 4.0 in cross-docking in Section 'Extended Search on Industry 4.0 in Cross-Docking' and draw conclusions in Section 'Conclusion'.

CROSS-DOCKING IN THE INDUSTRY 4.0 ERA

Cross-docking is typically defined as the process of consolidating less-than-truckload (LTL) shipments with the same destination to full truckloads (FTL), with the additional trait that products are stored up to a maximum of 24 hours (Boysen & Fliedner, 2010). The processes at cross-docking terminals generally constitute unloading of inbound trucks, checking, sorting, temporary storage, transhipment across the terminal and loading into outbound trucks. We give an overview of cross-docking decisions in Section 'Cross-Docking Research and Industry Practice'. Next, we introduce Industry 4.0 and its potential for cross-docking in Section 'Industry 4.0 Components in Manufacturing and Logistics'.

Cross-Docking Research and Industry Practice

Cross-docking allows consolidation of many LTL shipments into fewer FTL trucks, transporting the variety of products or parts in a network of consumers, warehouses and producers. Furthermore, the trait of 24-hour maximum storage time enables a feasible production and transportation strategy for industries with perishable products, e.g., food or pharmaceutical industries.

Successfully implementing cross-docking operation strategies into an organization requires changes to business model and operations (Stephan & Boysen, 2011), e.g., finding the operational gains of cross-docking, analyzing network integration suitability and evaluating possible negative effects, e.g., delayed delivery times on customer satisfaction and double-handling costs. Successful implementation of cross-docking into a company's supply chain seeks to eliminate and reduce redundant operations, e.g., storage and movement of products (Enderer, Contardo, & Contreras, 2017). Since the 1980s, several cross-docking studies were done, following the industry trend. Only after 2004, cross-docking started to receive significant attention in the scientific literature (van Belle et al., 2012; Ladier & Alpan, 2016). Over the past three decades, numerous studies have been conducted on the feasibility and benefits of implementing cross-docking for various industries, e.g., the pharmaceutical branch (Ponikierska & Sopniewski, 2017), automotive industry (Witt, 1998), food industries (Vasiljevic, Stepanovic, & Manojlovic, 2013), retail (Benrqya, 2019; Buijs, Danhof, & Wortmann, 2016) and online retail (Cattani, Souza, & Ye, 2014).

To benefit from incorporating cross-docking operations in supply chains, it is recommended to adopt a more holistic approach to supply chain management than traditional warehousing (Vogt, 2010). Employing cross-docking operations implies almost eliminating the storage buffer in a distribution network. The local cross-docking operation efficiency is interdependent with distribution activities across the supply chain network. Planning across the entire supply chain is crucial, and the models that include uncertainty are indispensable for coping with disturbances in the supply chain network (Ardakani & Fei, 2020).

Introducing cross-docking terminals allows for a reduction in the number of trips for the truck fleet (Buijs, Vis, & Carlo, 2014). Initially, each of the suppliers producing unique products would often directly ship LTL batches of their product to each of the costumers or a long-term storage warehouse. These customers are sometimes located in high-traffic city hubs or other types of urban areas for industries like retail or foods. Last-mile delivery often takes a significant time (Nathanail et al., 2020). By introducing the intermediate stop at a cross-docking terminal, all suppliers deliver shipments less frequently, and the products are consolidated in FTL trucks according to the specific customer demands. Fig. 1 illustrates the difference between classical direct transport (left) and transport using cross-docking (right). Additionally, the decisions for cross-dock location and vehicle routing are indicated.

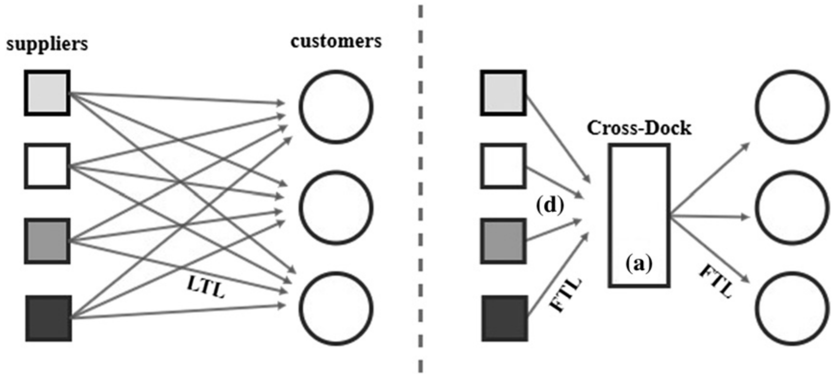


Fig. 1. Schematic Representation of a Classical Supply Chain and a Cross-Docking Supply Chain; the Meaning of the Cross-Docking Decision Levels: (a) Cross-Dock Location Selection and (d) Vehicle Routing Decision.

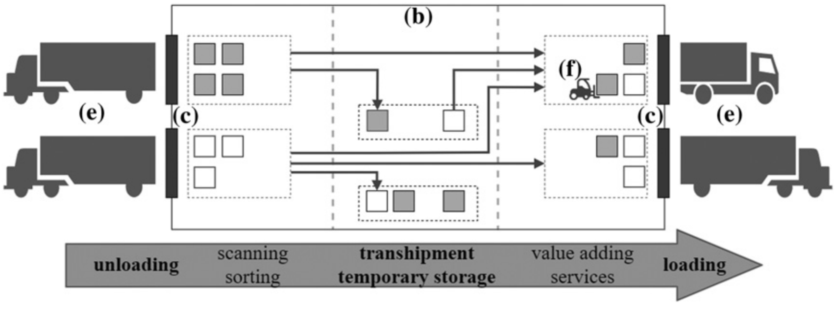


Fig. 2. Schematic Representation of an I-Shaped Cross-Dock, Decision Levels: (b) Design and Terminal Layout, (c) Door Policy and Assignment, (e) Truck Scheduling and (f) Internal Resource Scheduling.

Truck scheduling and internal procedures vary per industry. Fig. 2 illustrates a general structure of a cross-docking terminal. The letters in Figs. 1 and 2 represent the decision-making levels for the cross-docking distribution strategy.

Typically, cross-docking problems have been classified into three levels of decision-making: strategic, tactical and operational. We utilize a rephrased definition of the three levels applied to cross-docking as introduced by van Belle et al. (2012).

Strategic decisions in this context deal with the location and layout of cross-docking terminals. Location planning is centred around the decisions regarding the structure of the distribution network and the locations of cross-docking terminals. The design and layout of the terminal concern the physical characteristics, i.e., shape and the number of doors. Building shapes are often indicated by a letter, e.g., I, X, L or T. A comparison of the various building design choices of a cross-docking terminal can be found in Bartholdi and Gue (2004). Furthermore, for optimal building selection and cost-to-quality real-estate acquisition, there are models in development that take a company's specific needs and variables into account (Baglio, Perotti, Dallari, & Garagiola, 2019).

Tactical decisions concern the design of cross-docking networks. This involves deciding how goods flow through a network that contains more than one cross-docking centre. We refer to the works of Lim, Miao, Rodrigues, and Xu (2005), Chen, Guo, Lim, and Rodrigues (2006), or Ma, Miao, Lim, and Rodrigues (2011) as examples of tactical cross-docking works.

Concerning operational planning, the problems at this level relate to vehicle routing, truck scheduling, door assignment and internal resource scheduling. The vehicle routing problem considers combining distribution policies into the network, e.g., direct shipments or milk runs, by flexibly deciding per supplier whether to stop at a cross-docking terminal. We refer to a review of the VRP literature and a case study for multiple cross-docking terminal routing conducted by Nasiri, Rahbari, Werner, and Karimi (2018). Truck scheduling involves decisions regarding the schedule of what trucks are (un)loaded at which dock doors. The door assignment decisions regard the assignment and service of inbound or outbound destinations to specific dock doors. The types of door policies have been classified as follows: exclusive door assignment based on the destination, assignment based on the type of product (e.g., fresh, cooled storage) or based on the type of truck (Stephan & Boysen, 2011). Moreover, classical practices have commonly addressed exclusive door services, where typically inbound trucks can only dock on one side of the terminal and the outbound trucks on the opposite side. A flexible approach of mixed service doors allows both inbound and outbound trucks to be docked at any door. A recent example of research on mixed service doors with promising results has been conducted by Bodnar et al. (2017). Lastly, internal resource scheduling relates to decisions regarding the multiple resource coordination problems in the (un)loading, scanning, transhipment, consolidation and possible value-adding processes inside the terminal. For an example of research on workforce planning integration with internal transport planning for (un) loading, we refer to the work of Tadumadze, Boysen, Emde, and Weidinger (2019). Considering the rich family of cross-docking problems based on the planning level, in this chapter, we limit the collection of cross-docking related works to those addressing internal resource and truck scheduling operations. Regarding the latter, the first classification of truck scheduling is provided by Boysen and Fliedner (2010). Since then, the naming of the various types of truck scheduling in the related literature is found to be inconsistent, where different terms refer to the same type of problem or a general one such as cross-docking scheduling when referring to a specific type of cross-docking scheduling problem (Ladier & Alpan, 2016). Consequently, we use the classification provided by Ladier and Alpan (2016):

- Truck-to-door assignment: It aims at determining which door each truck is assigned to. Truck-to-door problems are scheduling problems where time is explicitly considered.
- Truck-to-door sequencing: This type of cross-docking problem considers the order of trucks and their assignment to doors to minimize the average distance the cargo is transported inside the terminal.
- Truck-to-door sequencing and scheduling: These problems focus on the temporal dimension and do not consider which door each truck is assigned to as long as the maximum number of doors is not exceeded. The distinction between both problems is that sequencing only involves the order in which the trucks are processed, while scheduling explicitly considers the arrival/departure times.

For a more in-depth nuance between the types of truck scheduling, the reader is referred to the work of Ladier and Alpan (2016). Moreover, each of the aforementioned problems is dependent on one another in some way, and it is possible to create various syntheses of various levels of decision-making per unique industry. Extensive research has been done on the synchronization of the different decision levels (Buijs et al., 2014; Enderer et al., 2017; Luo, Yang, & Wang, 2019).

Industry 4.0 Components in Manufacturing and Logistics

In this section, we introduce the general concept of Industry 4.0 and list its different components relevant to cross-docking. After an extensive literature search and classification, Nazarov and Klarin (2020) define Industry 4.0 as 'the integration of networking capabilities to machines and devices that allows seamless collaboration between the digital and the physical ecosystems for increased efficiencies in the organizational value chains that transform industries and the society for an increased level of productivity and efficiency'. Wagire, Rathore, and Jain (2020) conduct a systematic review and construct a taxonomy of Industry 4.0 research. They found 13 distinct research themes that are clustered in a taxonomy of five principal research areas: Industry 4.0 realization strategies, standards and reference architectures, smart factories, real-time data management and new business models. Ivanov, Tang, Dolgui, Battini, and Das (2021) conducted surveys among researchers to examine the current standing of Industry 4.0 research in Operations Management. They found the following technological aspects of Industry 4.0 in Operations Management: (1) cyber-physical systems/embedded systems, (2) Internet of Things (IoT), (3) 3D printing/additive manufacturing, (4) automated guided vehicles, (5) mobile robots, (6) augmented reality, (7) big data and analytics, (8) artificial intelligence, (9) track-and-trace systems, (10) machine-to-machine communication, (11) cloud services, (12) smart products, (13) blockchain and (14) RFID. The systematic literature reviews in Hofmann and Rüsch (2017) and Garay-Rondero, Martínez-Flores, Smith, Morales, and Aldrette-Malacara (2019) recognize the same Industry 4.0 technology components in (digital) supply chain management and logistics research. Based on the aforementioned surveys and literature review, we synthesize the technological components of Industry 4.0 that are potentially relevant to cross-docking, as summarized in Table 1.

Cyber-physical systems integrate computation with physical processes (Lee & Seshia, 2011). It integrates computing, communication, and storage with monitoring and control of entities in the physical world (Sha, Gopalakrishnan, Liu, & Wang, 2008). Inside these cyber-physical systems, a network of machines can be connected using the IoT, which is a concept that entails the connectivity of machines (e.g., 3D printers and AGVs), smart

Table 1. Synthesis of Industry 4.0 Technological Components for Cross-Docking.

Industry 4.0 Technology for Cross-Docking	Description
Cyber-physical systems/embedded systems	Integration of physical processes and computation
Internet of things/distributed control	Connectivity of machines via the internet
AGVs/mobile robots	Automated movement or transportation on a pre-defined path
Artificial intelligence/big data and analytics	The use of modern computing for better analysis and decision-making
Track-and-trace systems/RFID/smart sensors	Tracking of physical entities using sensors
Machine-to-machine communication/ networked automation	Direct communication between automated machines

Source: Based on Hofmann and Rüsch (2017), Garay-Rondero et al. (2019), and Ivanov et al. (2021).

sensors, software (e.g., artificial intelligence algorithms for decision-making) and other embedded systems (Kumar, Tiwari, & Zymbler, 2019). Examples of (potential) adoption of Industry 4.0 in manufacturing and logistics are: (1) the full connectivity of suppliers, (2) logistics and suppliers in a single platform, (3) position-based routing of interconnected vehicles to prevent congestion, (4) fill-level information directly communicated to suppliers using smart sensors, (5) full control of a supply chain using RFID sensors (Hofmann & Rüsch, 2017) and (6) the use of sensors to predict maintenance of manufacturing machines (Lee, Bagheri, & Kao, 2015). In this systematic literature review, we examine the adoption of Industry 4.0 topics (Table 1) in scientific studies about cross-docking.

METHODOLOGY

To find out what cross-docking models have been implemented into practice over the recent five years, we conduct a systematic literature review on studies testing and applying quantitative approaches to cross-docking operational decision levels. This study differs from other recent review studies in the cross-docking domain by explicitly focussing on papers that consider industry practice, e.g., a practical case or incorporating real-world data. The purpose of the study is to extend the comparison framework between industry practices and optimization literature from Ladier and Alpan (2016), with a focus on real-world settings. In addition, we study the degree to which Industry 4.0 concepts have been adopted in research and practice.

As indicated in Kitchenham and Charters (2007), we develop a review protocol to guide the identification, selection and extraction process of collected studies. In doing so, we followed the guidelines within the PRISMA method (Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2009) and also considering the COCHRANE handbook (Higgins et al., 2019). For our systematic literature review, five phases are formulated: (1) definition of the review scope and formulation of review questions, (2) determination of search terms, (3) formulation of exclusion and inclusion criteria, (4) analysis and (5) synthesis of findings. In Section 'Phase 1: Scope and Review Questions', the review questions are explained. Next, in Section 'Phase 2: Search Terms', we elaborate on the search terms and finally, we detail the inclusion and exclusion criteria in Section 'Phase 3: Inclusion and Exclusion Criteria'.

Phase 1: Scope and Review Questions

To systematically assess the eligibility of each paper for inclusion, we formulate review questions. First, we address the industry practice with the review question: 'To what extent does the paper consider industry practice?' Next, we consider the level of decision-making that is considered (i.e., strategic, tactical or operational) with the question: 'What planning level is the work at hand addressing?' The solution method proposed is investigated using the review question: 'What solution method is proposed?' Finally, we consider the three questions related to the type of information that needs to be extracted after inclusion: 'What are the performance indicators utilized?', 'What were the cross-docking settings utilized in the solution method?' and 'On what data was the solution method tested?'

Phase 2: Search Terms

The online databases considered for this study were *Scopus* and *Web of Science*. Only reports written in English are eligible for inclusion. The considered timeframe for publications is from 2015 to May 2020, and all source types are eligible for inclusion. After piloting several search queries, we settle on the terms '*cross-dock**' *OR* '*crossdock**' *OR* '*cross dock**'. These conditions result in 704 studies. At first glance, we find a significant number of publications in the search pool on a biochemical process by the name of cross-docking, a binding mechanism for receptors of proteins and ligands. The selection is then filtered to exclude all the research from the biochemistry domain on the cross-docking process using the search term *AND NOT* ('*ligand**' *OR* '*protein**'), which reduces the number of studies from 704 to 536. We compare the occurrence of cross-docking keywords of the search pool before and after the search exclusion and find that the number of hits on cross-docking specific keywords (e.g., trucks and logistics) remains unchanged, i.e., no literature is mistakenly excluded. The mentioned search criteria are illustrated in Table 2. After duplication removal, 337 records remain for the screening phase.

Phase 3: Inclusion and Exclusion Criteria

To enhance the reproducibility and robustness of our review, we formulate and present the protocol for including studies in the final selection (Denyer & Tranfield, 2009; Higgins et al., 2019). We first screen the title, abstract and keywords, and in a second phase we read all full papers. After the first screening phase, 55 studies of 337 remain for in-depth screening. Table 3 shows the inclusion and exclusion criteria used.

After the first phase, we read all papers and use the same criteria for exclusion. Specific focus lies on the industry practice that is considered. We exclude a paper when it does not have a case study, on-site study, real-world comparison or real-world data. We also exclude papers that do not use a quantitative solution approach or do not target an

Table 2. Search Criteria used in this Systematic Literature Review.

Search terms for titles, abstracts and keywords	('cross-dock*' OR 'crossdock*' OR 'cross dock*')
Filter	AND NOT ('ligand*' OR 'protein*')
Timeframe	Jan 2015–May 2020
Language	English
Source type	All
Document type	All
Publication status	All

Table 3. Criteria for Inclusion and Exclusion.

Inclusion Criteria	Exclusion Criteria
Practical case presented	Theoretical case without real data
Quantitative solution method	The cross-docking concept is not the main object of study
Targets truck scheduling or internal resource operational decision levels	Domain level too wide
Published between 2015 and May 2020	Duplicate studies
	Non-English written papers

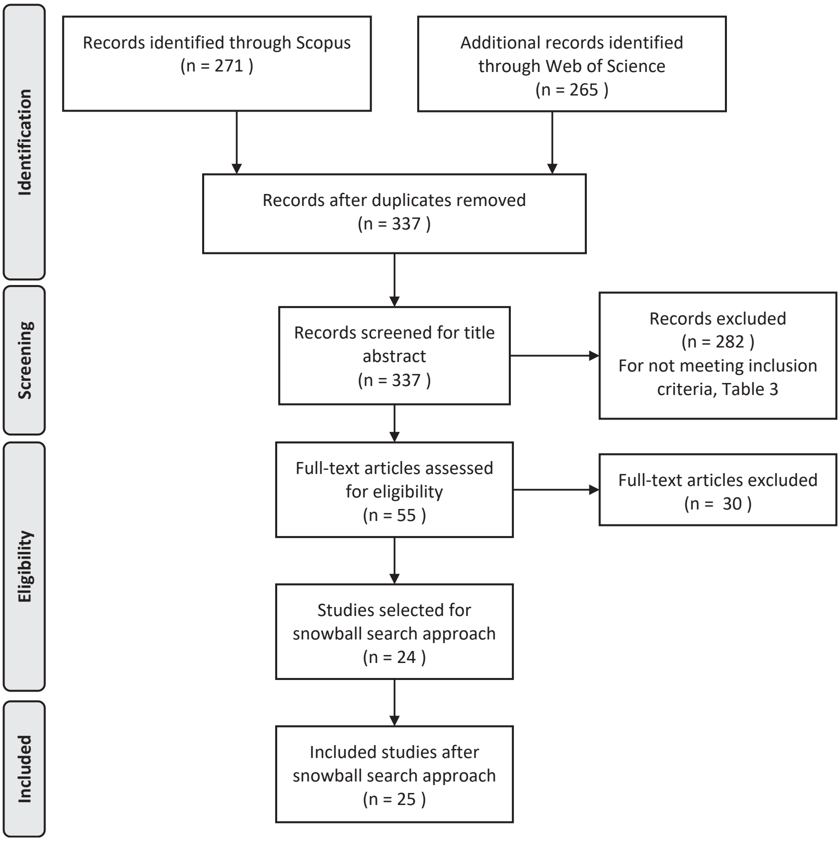


Fig. 3. PRISMA Flow Diagram. *Source:* Adapted from Moher et al. (2009).

operational cross-docking problem. After screening the 55 remaining studies, 25 studies remain in the selection.

The outcome of the systematic literature review is summarized in the PRISMA flow diagram in Fig. 3. The final number of selected studies is 25, obtained from the initial 337 records.

Descriptive and thematic features are extracted from the selected records. The studies are thematically classified by answering the review questions. Table 4 highlights how descriptive and thematic information is extracted.

RESULTS

In this section, the result of the systematic literature review is presented. First, a general overview of the literature is given in Section 'General Overview of Cross-Docking Literature'. Next, in Section 'Solution Methods and Industry 4.0 Adoption in the

Table 4. Classification Categories Used to Extract and Classify Collected Works.

Category	Information
Year	Year of publication
Country	Author's country of affiliation
Type of document	Conference paper, journal article, dissertation
Real-world cross-docking setting	Company industry, country, data source, implementation period and the cross-docking setting concepts
Decision-making level	What cross-docking problem was addressed?
Solution method	Exact method, (meta-)heuristic or simulation
Performance measures	Which performance measures were utilized?
Industry 4.0	Mentioning of Industry 4.0, use of Industry 4.0 concepts in the solution approach
Findings	Results of the model, relevant findings and future research directions

Cross-Docking Literature', we discuss considered problems, solution approaches and Industry 4.0 aspects of cross-docking. In Section 'Cross-Docking Characteristics', we discuss the cross-docking characteristics and in Section 'Performance Indicators' the used performance indicators.

General Overview of Cross-Docking Literature

The selection of papers includes 17 journal papers and 8 conference papers. Table 5 provides an overview of the source of data for the industry case studies as well as the country and industry at which the case company operates. Fig. 4 summarizes the different industries in which the considered companies are active. Cross-docking seems most popular among retail companies, the automotive industry and logistics companies.

Two papers explicitly share the results of an implementation phase of their model. Aulin et al. (2020) were allowed eight days to record data for variable sensitivity analyses (e.g., on the number of workers engaged and product flow). Furthermore, the research at Renault reported by Serrano, Delorme, and Dolgui (2015) for cross-docking internal operation planning was followed up with an 8-week implementation of a simplified version of the developed solution method. To shed light on the interaction between the company and the researchers, we classify the origin of the model data. 'Company data' in Table 5 stands for receiving data from the company operations, or product demand and supply, as well as the type of utilized equipment. When measurements or on-site observations are explicitly mentioned, the paper is denoted by 'Measured data'. Chargui, Bekrar, Reghioui, and Trentesaux (2018) and Chargui, Bekrar, Reghioui, and Trentesaux (2019b) are both an extension of Chargui, Reghioui, Bekrar, and Trentesaux (2016). In the latter case, a practical partner is mentioned as the source of data. However, the researchers explicitly state the test data are inspired by a case and not on a partition of company data. An example of both utilizing company data and measured data is Zenker and Boysen (2018). They received the fixed departure schedules of a postal service provider and historical data on the order inflow rate. Furthermore, in an on-site visit, the internal layout and operation were documented and used as constraints in the model.

Table 5. Classification of Selected Studies Concerning Real-World Settings.

	Real-World Setting		
	Data Source	Country	Industry
Aulin et al. (2020)	Measured data	Ukraine	Logistics
Azimi (2015)	Company data	Iran	Shipping port
Benbitour, Sahin, and Barbieri (2016)	Company data	France	Automotive
Benrqya (2019)	Measured data	France	Retail (FMCG)
Bodnar et al. (2017)	Company data, generated data	The Netherlands	Retail
Buijs et al. (2016)	Company data	The Netherlands	Retail (supermarket)
Chargui et al. (2018)	Generated inspired by case	ns	Retail (household products)
Chargui et al. (2019b)	Generated inspired by case	ns	Retail (household products)
Coindreau, Gallay, Zufferey, and Laporte (2019)	Company data	ns	Automotive
Fanti, Stecco, and Ukovich (2016)[L]	Company data	Italy	Textile
Fathollahi-Fard et al. (2019)	Company data	Iran	Shipping port
Horta, Coelho, and Relvas (2016)	Company data	Portugal	Retail (fruits and vegetables)
Jarrah, Qi, and Bard (2016)[L]	Company data	USA	Postal services
Khannan, Nafisah, and Palupi (2018)	Company data, measured data	Indonesia	Textile
Khorshidian, Akbarpour Shirazi, and Fatemi Ghomi (2019)	Company data	Iran	Food
Luo et al. (2019)	Company data, measured data	China	Paint
Nasiri et al. (2018)	Company data, generated data	Iran	Logistics
Pawlewski and Hoffa (2014)	Company data	ns	Logistics
Piao and Yao (2017)	Company data	China	Retail
Rijal, Bijvank, and de Koster (2019)	Company data	The Netherlands	Retail (supermarket)
Serrano et al. (2015)	Company data	ns	Automotive
Serrano, Delorme, and Dolgui (2017)	Company data	ns	Automotive
Serrano, Moral, Delorme, and Dolgui (2016)	Company data	ns	Automotive
Yu, Yu, Xu, Zhong, and Huang (2020)	Company data	ns	E-commerce logistics
Zenker and Boysen (2018)	Company data, measured data	Germany	Postal services

Note: Studies denoted with an ‘L’ are found in the state-of-the-art analysis of Ladier and Alpan (2016).

Solution Methods and Industry 4.0 Adoption in the Cross-Docking Literature

The outcome of the classification of the quantitative solution methods and the associated cross-docking problems is presented in Table 6. Here we distinguish between exact, heuristic, meta-heuristic and simulation methods. We observe that most research applies exact models to cross-docking problems. In addition, some different types of heuristics and metaheuristics are used. Some authors use simulation to validate their results. Research primarily considers internal resource operations or the truck-to-door scheduling problem.

Next, we study the 25 papers on Industry 4.0 related features. After studying the literature on Industry 4.0 in logistics in general (see Section ‘Industry 4.0 Components in

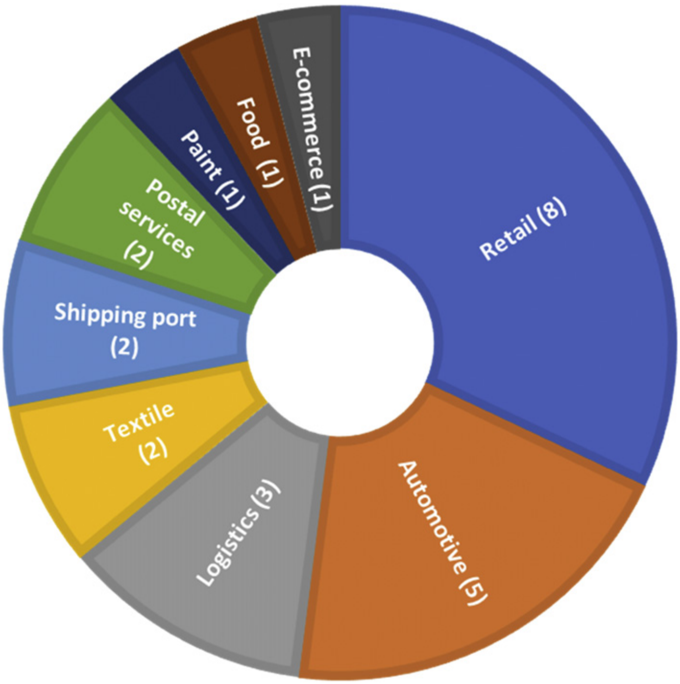


Fig. 4. Frequency of Industries of Practical Cases. The Number of Related Works Is Indicated in Parentheses.

Manufacturing and Logistics'), we defined several technological components related to Industry 4.0. These categories are cyber-physical systems, IoT, AGVs, artificial intelligence, smart sensors, and machine-to-machine communication (see Table 1). Only 7 out of 25 papers discuss one or more of these Industry 4.0 related components (see Table 6).

We consider networked automation, e.g., AGVs and robots that communicate to perform tasks, a concept belonging to Industry 4.0. From the seven papers, three consider automated conveyors but do not mention the interconnectivity of machines or networked systems. For an automated conveyor to work, RFID or other sensor technology is needed. In Jarrah et al. (2016), automated conveyors and automated flow through a building are briefly discussed, including the need for a controlling computer system. In Zenker and Boysen (2018), similar concepts are discussed, and the need for recognition technology, e.g., RFID, for automated sorters is discussed.

Of the seven papers, two relate to physical internet hubs (PI-hubs), namely Chargui et al. (2018) and Chargui et al. (2019b). Both papers consider PI applied to cross-docking hubs. The term 'physical internet' was introduced by Benoit Montreuil and considers the way physical objects are transported, handled, stored, supplied, realized and used (Montreuil, 2011). In the PI, in analogy with the digital internet, shipments will be transported through a network optimally utilizing various transport modalities and transfer hubs, where shipments are possibly decomposed into multiple packages, but eventually, all arrive at their destination upon agreed delivery time, without the sender needing to worry about how its shipment gets there. The PI '(…) combines standardized, modular and intelligent containers with new logistics protocols and business models, resulting in a collaborative,

Table 6. Classification of Selected Studies on Solution Method Approaches Utilized in the Study.

		Solution Method Approaches			
	Cross-Docking Problem	Method	Description	Simulation	Industry 4.0 Components
Aulin et al. (2020)	Internal resources operation	Tailored method	Multiple linear regression		
Azimi (2015)	Truck-to-door assignment, internal resource operation	Meta-heuristic	Genetic algorithm	X	
Benbitour et al. (2016)	Internal resource operations	–		X	
Benrqya (2019)	Internal resource operations	Exact	Cost model		
Bodnar et al. (2017)	Truck-to-door scheduling	Exact, meta-heuristic	Mixed-integer linear programming (MILP), adaptive large neighborhood search		
Buijs et al. (2016)	Truck-to-door sequencing, vehicle routing, internal resource operations	–		X	
Chargui et al. (2018)	Internal resource operations	–		X	Cyber-physical systems, IoT, M2M
Chargui et al. (2019b)	Truck-to-door scheduling, internal resource operations	Heuristic, meta-heuristic	Scheduling heuristic, tabu search		Cyber-physical systems, IoT, M2M
Coindreau et al. (2019)	Internal resource operations	Exact, heuristic	MILP, decomposition heuristic		
Fanti et al. (2016)[L]	Internal resource operations	Exact, heuristic	MILP		RFID
Fathollahi-Fard et al. (2019)	Truck-to-door sequencing	Exact, meta-heuristic	MILP, social engineering optimization adaptations		RFID
Horta et al. (2016)	Internal resource operations	Exact	MILP		
Jarrah et al. (2016)[L]	Truck-to-door scheduling, internal resource operations	Exact, tailored method	MILP, three-step approach		
Khannan et al. (2018)	Internal resource operations	Exact	MILP		
Khorshidian et al. (2019)	Truck-to-door scheduling, vehicle routing	Exact, tailored method	Bi-objective MILP, 3POM		

Luo et al. (2019)	Internal resources operations	Exact, meta-heuristic	MILP, hybrid genetic algorithm with local search and opposition-based learning		
Nasiri et al. (2018)	Truck-to-door-scheduling, vehicle routing, supplier and cross-docking selection, internal resource operations	Exact, tailored method	MILP; TSSA		RFID, cyber-physical systems
Pawlewski and Hoffa (2014)	Truck-to-door assignment problem	–	–	X	
Piao and Yao (2017)	Internal resource operations	–	–	X	
Rijal et al. (2019)	Truck-to-door scheduling	Exact, Metaheuristic	MILP, adaptive large neighborhood search		
Serrano et al. (2015)	Internal resource operation, distribution planning	Exact	MILP		
Serrano et al. (2016)	Truck-to-door scheduling, Internal resource operations	Exact	MILP		
Serrano et al. (2017)	Truck-to-door scheduling, Internal resource operations	Exact	MILP		
Yu et al. (2020)	Truck-to-door scheduling, Internal resource operations	Exact	MILP		RFID
Zenker and Boysen (2018)	Truck-to-door scheduling, internal resource operations	Exact, heuristics, meta-heuristic	MILP, greedy, fix-and-optimize, tabu search		RFID

Note: Studies denoted with an ‘L’ are found in the state-of-the-art analysis of Ladier and Alpan (2016).

highly distributed and leveraged logistics and distribution system' (Montreuil, Meller, & Ballot, 2010).

Transfer hubs play a crucial role within the PI, highlighting the importance of cross-docking operations. The PI exhibits multiple Industry 4.0 characteristics, e.g., cyber-physical systems, IoT, AGVs, track-and-trace systems, smart sensors, and machine-to-machine communication. In Chargui et al. (2018), the PI objects are called 'PI-containers', 'PI-movers' and 'PI-nodes'. PI-containers are modular and smart containers that can cope with different dimensions and weights, as decided by the system. PI-movers can be trucks, wagons, conveyors or lifts that are linked to the PI system. Finally, PI-nodes are locations where cross-docking operations are conducted on materials, e.g., assembly, picking, routing or monitoring. Chargui et al. (2018) show that PI cross-docking hubs (PI-hubs) that are fully automatic outperform manual cross-docking hubs regarding waiting times of inbound and outbound trucks, the total time a product spends in the cross-dock and the number of trucks waiting. Chargui et al. (2019b) conduct a robustness test under different internal resource breakdown disruptions for classical cross-docking systems, as well as for PI-hubs. They show the potential weakness of interdependence of machines in a PI-hub. Although it is likely that the PI increases efficiency and reduces costs, it may be more sensitive to machine failures compared to classical cross-docking systems (Chargui et al., 2019b).

Cross-Docking Characteristics

We classify the papers into the various characteristics of cross-docking settings in Table 7. From it, we can indicate that most of the case studies investigate a manual internal transportation mode, five consider an automatic mode and two consider a combined mode of transport.

For the door service mode, we find that most of the researchers design the door policy with an exclusive door service, one proposes a mixed service mode and three propose a combined door service mode. In an exclusive mode, each door is dedicated to receiving inbound or outbound trucks exclusively. A mixed mode is in place when a door may handle both inbound and outbound trucks. The combined mode is when some doors utilize mixed service while other doors have an exclusive service mode. None of the studies allows preemption to occur in the planning schedules. Preemption allows interruption of (un) loading of trucks, i.e., another truck is processed instead of the interrupted truck, which is parked to continue the (un)loading process later.

The temporary storage capacity determines if and how many goods can be stored temporarily. When the outbound truck is not present when a product is unloaded, the product must be moved to the storage area temporarily. This storage area has limited storage capacity when space is scarce within a terminal. If a terminal is large, the temporary storage capacity is often modelled as infinite. In some industries, temporary storage is not viable, e.g., frozen or perishable goods, in which case temporary storage capacity is considered to be zero. For temporary storage capacity, we find 10 records that allow unlimited storage capacity for the modelling constraints, 2 do not allow temporary storage at all (zero) and the remaining 13 studies implement a temporary storage capacity constraint.

Internal resource capacity describes the handling capacity of the internal transportation mode, which may either be limited or unlimited. For automatic modes, it considers the capacity of the conveyor belt network, and for manual modes of transportation, it considers, for instance, the maximum number of workers or forklifts. For internal resource

Table 7. Classification of Cross-Docking Characteristics.

	Strategic	Tactical Level Planning				Operational Level Planning	
	Internal Transport Method	Service Mode	Preemption	Temporary Storage Capacity	Internal Resource Capacity	Arrival Time Pattern	Departure Time Constraints
Aulin et al. (2020)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Azimi (2015)	Manual	Combined	No	Limited	Limited	Per truck	No
Benbitour et al. (2016)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Benrqya (2019)	ns	Exclusive	No	Limited	∞	Per truck	No
Bodnar et al. (2017)	Manual	Combined	No	∞	∞	Per truck	Outbound
Buijs et al. (2016)	Manual	Mixed	No	0	Limited	Per truck	Both
Chargui et al. (2018)	*	Exclusive	No	Limited	Limited	Per truck	No
Chargui et al. (2019b)	*	Exclusive	No	Limited	Limited	Per truck	No
Coindreau et al. (2019)	Manual	Exclusive	No	∞	∞	Per truck	No
Fanti et al. (2016)[L]	Combined	Exclusive	No	0	∞	Zero	No
Fathollahi-Fard et al. (2019)	Automatic	Exclusive	No	∞	∞	Zero	No
Horta et al. (2016)	Manual	Combined	No	Limited	∞	Zero	No
Jarrah et al. (2016)[L]	Automatic	Exclusive	No	∞	Limited	Per truck	Outbound
Khannan et al. (2018)	Manual	Exclusive	No	Limited	∞	Per truck	No
Khorshidian et al. (2019)	Manual	Exclusive	No	∞	∞	Per truck	Both
Luo et al. (2019)	Manual	Exclusive	No	∞	∞	Zero	No
Nasiri et al. (2018)	Manual	Exclusive	No	∞	∞	Zero	Both
Pawlewski and Hoffa (2014)	Manual	Exclusive	No	∞	Limited	Zero	No
Piao and Yao (2017)	Manual	Exclusive	No	∞	Limited	Zero	No
Rijal et al. (2019)	Manual	Combined	No	Limited	∞	Per truck	Outbound
Serrano et al. (2015)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Serrano et al. (2016)	Manual	Exclusive	No	Limited	Limited	Zero	No
Serrano et al. (2017)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Yu et al. (2020)	Automatic	Exclusive	No	∞	∞	Zero	No
Zenker and Boysen (2018)	Combined	Exclusive	No	Limited	Limited	Per truck	Outbound

Notes: The * sign indicates dual modes; Studies denoted with an 'L' are found in the state-of-the-art analysis of Ladier and Alpan (2016).

capacity, we find a nearly equal distribution of use of internal resource capacity, with 13 records including a constraint on internal resources, e.g., the number of workers or equipment, and the remaining 12 studies not including such constraints.

Concerning the arrival pattern, the majority (16 out of the 25) consider a scattered arrival pattern per truck, and in the other nine records, it is assumed that all trucks are available from the beginning of the planning period. If the arrival of trucks is concentrated and the unloading is non-restrictive, then it is assumed that times are defined per truck. This feature applies to both inbound and outbound trucks. Moreover, we find that over half of the studies assume no constraints on truck departure, e.g., no other appointment deadline earlier or further ahead in the distribution network for inbound or outbound trucks. Moreover, we observe that four studies assume deadlines on both inbound and outbound trucks, five include departure deadlines on outbound trucks exclusively and no study imposes deadlines on inbound trucks exclusively.

Performance Indicators

Table 8 shows the performance indicators used in the selected papers. In the last column, all performance indicators not included by Ladier and Alpan (2016) are displayed. These performance measures are included to illustrate whether novel indicators have gained popularity over the past five years. For instance, among the selection, there are multiple papers with internal resource performance indicators: internal resource utilization and storage surface area.

The most prominent performance measures among the studies are inventory level (total number of products stocked), truck processing time deviation (finishing (un)loading earlier or later than planned), makespan (the difference between the start of the first operation and the last operation, e.g., the last truck's dispatch) and distance travelled, i.e., the distance travelled within the terminal from door to door. The next most frequent performance measure is balanced workload, which is the fair distribution of workload among workers according to skills and capacity. Furthermore, we observe several performance measures that remain unutilized: working hours, number of touches (the average number of touches is an indicator of employee costs), unloading time and preemption cost. On the other hand, all other performance measures are only utilized by either one or two studies, e.g., congestion, which is caused by high traffic in certain areas of the building, delaying all processes, total product stay time, which is the total time a product spends in the cross-docking terminal, loading time, door utilization, which is linked to the efficiency of the (un)loading and the number of doors in use at a cross-dock, and products not loaded, i.e., missed orders.

From the collected information in this and previous subsections, cross-docking characteristics and performance measures have been provided. In the next sections, they are used as comparison components to analyze and discuss their contributions while also providing insights in the light of Industry 4.0.

DISCUSSION

In this section, we discuss the outcomes of our systematic literature review and we compare them with the findings of the state-of-the-art review conducted by Ladier and Alpan (2016). In doing so, we identify studies from 2015 to 2020 on the subset of cross-docking operational problems that consider a practical case, and we classify each paper according

Table 8. Performance Measures in Cross-Docking Literature.

	Performance Measures														
	Inventory Level	Working Hours	Distance Travelled	Congestion	Total Product Stay Time	Number of Touches	Truck Processing Deviation	Loading Time	Unloading Time	Door Utilization	Products Not Loaded	Makespan	Preemption Cost	Balanced Workload	Other Performance Measures
Aulin et al. (2020)				X										X	–
Azimi (2015)															Fleet size, internal resources utilization
Benbitour et al. (2016)			X												Storage surface area, number of picking train journeys
Benrqya (2019)	X														Supply chain cost
Bodnar et al. (2017)	X						X								–
Buijs et al. (2016)			X	X	X						X	X			Workers on site
Chargui et al. (2018)							X					X			Waiting time, number of trucks waiting, internal resource utilization
Chargui et al. (2019b)							X								–
Coindreau et al. (2019)	X													X	–
Fanti et al. (2016)[L]												X			–
Fathollahi-Fard et al. (2019)												X			–
Horta et al. (2016)			X												–

Table 8. *(Continued)*

	Performance Measures														
	Inventory Level	Working Hours	Distance Travelled	Congestion	Total Product Stay Time	Number of Touches	Truck Processing Deviation	Loading Time	Unloading Time	Door Utilization	Products Not Loaded	Makespan	Preemption Cost	Balanced Workload	Other Performance Measures
Jarrah et al. (2016)[L]										X				X	Number of changes in door-destination assignment, number of workers, loader utilization
Khannan et al. (2018)			X												Storage space
Khorshidian et al. (2019)							X	X				X			Risk aversion, product participation
Luo et al. (2019)								X				X			Order simultaneity
Nasiri et al. (2018)	X						X								Purchasing cost, waiting times
Pawlewski and Hoffa (2014)			X												–
Piao and Yao (2017)												X			Utilization of internal resources
Rijal et al. (2019)	X		X				X								–
Serrano et al. (2015)	X													X	Inbound/outbound transportation costs
Serrano et al. (2016)	X														Number of outbound trucks
Serrano et al. (2017)							X							X	–
Yu et al. (2020)	X						X								Longest waiting time, asynchronized operation penalty
Zenker and Boysen (2018)	X														–

Note: Studies denoted with an 'L' are found in the state-of-the-art analysis of Ladier and Alpan (2016).

to the elements of the comparison framework with industry practices according to Ladier and Alpan (2016) considering papers up to 2015. From them, we discuss the cross-docking characteristics, the implications for Industry 4.0 adoption and the used performance indicators.

Cross-Docking Characteristics and Industry 4.0 Adoption

We observe that 19 articles in our review assume a manual mode of internal transportation, 5 assume an automatic mode and only 2 propose a combined transportation mode. Two papers are counted to both manual and automatic as they compare the manual mode with an automated PI mode for the same industrial case inflow data (Chargui et al., 2018, 2019b), and for one study the mode of transport is not specified. Our observations indicate that the occurrence rates for internal transportation mode assumptions are similar to the occurrence rates in the state-of-the-art models before 2015, but with a higher share of the combined mode of transport. Completely automated systems are rare in the industry. Ladier and Alpan (2016) argue that this is because of the advantages in the flexibility of manual labour, even though automated systems may prove more efficient in some cases. However, it may be expensive to expand the capacity of automated systems to cover for fluctuations in demand. Combined modes of internal transport are therefore more common in industry than fully automatic systems. Automatic systems have been shown to outperform manual transportation in specific areas; however, fluctuations and uncertainty have a larger negative effect compared to classical systems. Future research can investigate strategies for combined modes of transport in different configurations.

Both the mixed-mode door service (i.e., a door may be for both inbound and outbound trucks) and exclusive door service types were found to be frequently occurring in practice, while a combined mode (i.e., mixed-mode combined with exclusive mode) was perceived as non-suitable by research and managers (Ladier & Alpan, 2016). The state-of-the-art research uses exclusive door service modes more than the mixed modes before 2015. Ladier and Alpan (2016) recommended more research to also test their solution approaches with the mixed service mode, as its occurrence in practice is non-negligible. We find similar occurrence rates in the literature from 2015 to 2020, in which an occurrence rate of the exclusive mode assumption on a nearly equal level and even less frequent utilization of the mixed service mode. Hence, this indicates that research has not yet increased the utilization of the mixed door service mode. Only Buijs et al. (2016) propose a mixed service policy for their practical case. They find a reduction of the internal travel distance by 40%, less congestion and other considerable cost savings from their proposed mixed service doors, in combination with other strategic policy changes. The remainder of the studies we found considered a combined mode of door service, which is in contrast with the findings from the preceding review. Bodnar et al. (2017) show that adding a few mixed service doors results in reducing the overall costs of the operation, compared to an exclusive mode of service. Our findings indicate that the gap in addressing the mixed service doors in literature has not been bridged by the contemporary publications that consider practical cases. Additionally, we observe a rise in popularity for combined modes of door service, even though several managers perceive this mode as not suitable. If researchers foresee that implementing a combined mode brings substantial benefits, we recommend to justify the benefits quantitatively and illustrate how the expected miscommunication can be overcome.

Ladier and Alpan (2016) reports preemption to be redundant for managers of cross-docking operations. Moreover, merely 9% of their state-of-the-art papers allow preemption in the model. None of the papers in our study allows preemption in their model, which indicates that researchers share a similar sentiment toward the benefit of preemption.

Cross-docking managers have to deal with capacity constraints. The on-sight survey by Ladier and Alpan (2016) supports this statement, as all managers interviewed dealt with resource limitations, and only one manager experienced a storage capacity significantly large to be considered infinite. However, they find that only 3% of the papers include capacity constraints. Within the publications of the last five years, more studies include capacity constraints: 9 out of 25 studies incorporate both a limited capacity for storage and limited internal resources. The rise in occurrences of limited capacity constraints could be explained due to the scope of the review, by exclusively considering practical cases. The selected studies often receive real data on constraints first-hand or were allowed to evaluate the practical settings on-site. This possibly resulted in a more representable model of practical industry capacity constraints.

Although there is an increase in the use of capacity constraints in current research on practical cases, we nevertheless observe that the gap for utilization of capacity constraints has not yet been fully narrowed.

The arrival time of inbound trucks is subject to the industry and product types and is typically either concentrated around certain periods or spread out over the day. It seems that the retail industry typically works under scattered arrival time patterns (listed as '/truck' in Fig. 5) because we find that six out of the eight studies that examine a practical retail case utilize this assumption. Additionally, we observe an indication that automotive industries tend to operate under scattered arrival patterns, as for four out of the five automotive cases, scattered arrival time is assumed by the researchers. With our findings, we want to highlight the importance of the development of customized cross-docking operational models for specific industries. We recommend continuing to address both types of constraints.

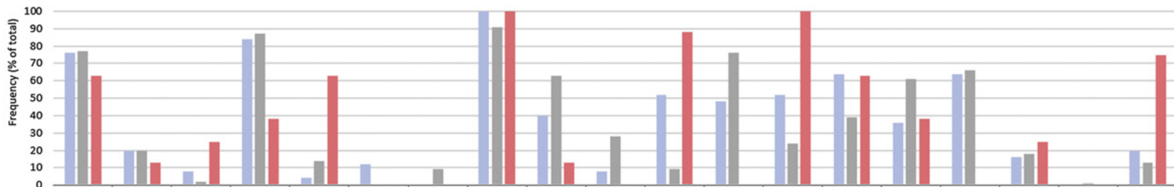
Similarly as before 2015, after 2015, the majority of the studies do not assume departure deadlines for the trucks. Ladier and Alpan (2016) found that nearly all industry managers organize themselves around setting and meeting a tight schedule of deadlines, and hence, the authors recommend future research to bridge the gap with the real-world constraints seen in the industry. We find that this gap has not been adequately addressed.

Finally, we observe in our literature review that Industry 4.0 aspects are rarely considered in the cross-docking literature. Most research either concerns the use of RFID technology for automated sorters or the use of cyber-physical systems in PI-hubs. In a sense, it is remarkable, since cross-docking forms the core of the PI (to enable the transfer of PI-containers at PI-hubs) and Industry 4.0 technologies are required for the PI (all of those from Table 1). However, we see little evidence for the adoption of Industry 4.0 in cross-docking judging from the included sources.

Performance Indicators

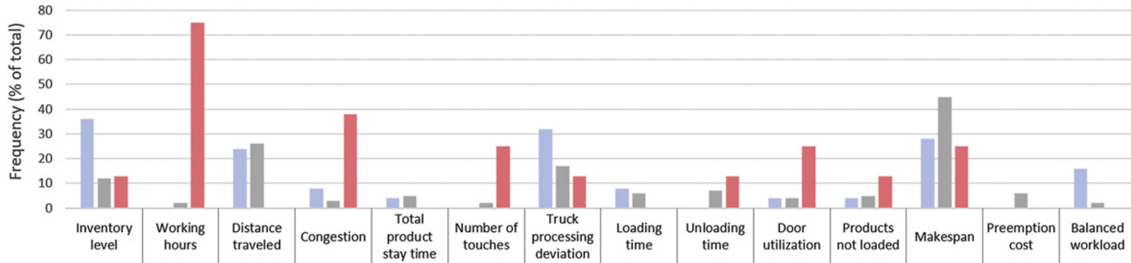
In this section, we discuss the performance indicators extracted from publications that consider a practical case in the last five years, compare our findings to literature before 2015 and provide findings to what was found to be popular for industry practices (secondary findings from Ladier and Alpan (2016)). The occurrence rates are summarized in Figs. 5 and 6.

Risks of congestion are found to gain importance to management as the size of manual internal transportation at cross-docking terminals increased (Ladier & Alpan, 2016).



	Strategical: Internal transportation method			Tactical level planning: Service mode			Tactical level planning: Preemption		Tactical level planning: Temporary storage capacity			Tactical level planning: Internal resource capacity		Operational level planning: Arrival time pattern		Operational level planning: Departure time constraints			
	manual	automatic	combined	exclusive	mixed	combined	yes	no	unlimited	zero	limited	unlimited	limited	per truck	zero	no	both	inbound	outbound
Literature 2015-2020	76	20	8	84	4	12	0	100	40	8	52	48	52	64	36	64	16	0	20
Literature ≤2015**	77	20	2	87	14	0	9	91	63	28	9	76	24	39	61	66	18	1	13
Industry 2015**	63	13	25	38	63	0	0	100	13	0	88	0	100	63	38	0	25	0	75

Fig. 5. Frequency per Cross-Docking Characteristics Found in Literature From 2015 to 2020, Literature before 2015 and Industry 2015 (**Secondary Data Ladier & Alpan, 2016).



	Inventory level	Working hours	Distance traveled	Congestion	Total product stay time	Number of touches	Truck processing deviation	Loading time	Unloading time	Door utilization	Products not loaded	Makespan	Preemption cost	Balanced workload
Literature 2015-2020	36	0	24	8	4	0	32	8	0	4	4	28	0	16
Literature ≤2015**	12	2	26	3	5	2	17	6	7	4	5	45	6	2
Industry 2015**	13	75	0	38	0	25	13	0	13	25	13	25	0	0

Fig. 6. Frequency per Performance Measure Setting Found in Literature From 2015 to 2020, Literature before 2015 and Industry 2015 (**Secondary Data Ladier & Alpan, 2016).

Concentrated arrival patterns tend to cause more congestion over scattered arrival patterns (Azimi, 2015) since the majority of the trucks need processing at the same time window, which causes the internal transhipment to have high traffic for sorting and preparing the products for dispatch. Thus, balancing the conflict between optimizing internal transport and the risk of congestion is an essential aspect for large manual cross-docking centres, especially for organizations with concentrated arrival times. We notice that congestion is only considered as a performance objective in two papers. Modelling congestion and measuring the costs lacks consensus. However, instead of minimizing congestion, several studies design congestion as a modelling constraint: Buijs et al. (2016) compensate actual movement speed from 2.3 m/s to 1.5 m/s for the material handling team, Bozer and Carlo (2008) restrict adjacent docking of trucks to avoid congestion and Bartholdi and Gue (2000) compensate the waiting time of workers additionally. We recommend future research to formulate constraints to compensate for congestion or to design the scheduling constraints further to avoid congestion as much as possible by default.

We observe some indications that literature might not share the same sentiment of value toward optimizing door utilization and the number of touches. Thus, it might be recommendable to utilize terminology that is common in practice or to justify which and how specific performance objectives improve those currently used in practice. In a few studies that utilize 'per truck' arrival times, there is an additional layer modelled for stochastic or uncertain arrival times (e.g., Azimi, 2015). In practice, arrival times are often outside of the operator's control but could cause delays for unloading other trucks and idle times for workers. Hence, in such cases, the planning model compensates for the scheduling process, e.g., buffer times in between trucks.

Workload forecasting is neglected by the majority of literature in the past (Buijs et al., 2014), even though this is found to be one of the most pressing concerns within the industry (Ladier & Alpan, 2016). We found that nearly every study uses deterministic demand and historical data to evaluate the solution approach. Forecasting customer demand can significantly improve the efficiency across the supply chain, as it facilitates effective upstream make-to-order production strategies and low inventory supply chains (Luo et al., 2019).

The effectiveness of planning under uncertainty can be measured through various sets of performance measures. For instance, potential indicators for uncertainty planning are found to be truck processing deviation, longest waiting time or the number of trucks waiting. In a review of uncertainty factors in cross-docking scheduling and operations, several other performance measures are categorized, and future research directions on uncertainty modelling can be found (Ardakani & Fei, 2020).

Working hours are common cost drivers for operations with manual transportation, and thus it is an important performance indicator for managers of such cross-docking terminals. Nevertheless, we find indications that the primary focus of research is on optimizing the cross-docking operations through other performance indicators since the occurrence rate of working hours as a performance measure is next to none.

Our review results indicate that the majority of literature is geared towards objective functions consisting of inventory level, internal distance travelled, truck processing deviation, makespan, number of workers on-site and internal resources utilization. Certain performance measures directly count toward the number of working hours, e.g., each additional meter travelled internally has to be completed by a worker. On the contrary, optimizing the makespan, i.e., reducing the length of a day of operation, might seem to effectively lead to fewer working hours, while in reality, the first and last truck's arrival is often out of control of management.

Since working hours are a major cost driver for manual cross-docking organizations, we recommend research conducted on manual modes of research to find ways to include working hours or other employee cost objectives in the solution model. An example of an integrated truck and workforce scheduling can be found in Tadumadze et al. (2019).

The state-of-the-art review of literature from before 2015 found that makespan has an occurrence rate of 45% in objective functions for cross-dock scheduling. This initial popularity of makespan for truck scheduling problems can be explained by its success in the general scheduling domain. However, as mentioned previously, makespan in cross-docking is often subject to the arrival of the last inbound truck, which explains why Ladier and Alpan (2016) indicated that makespan was not a primary performance objective for many managers.

We find that, for studies after 2015, there is a higher occurrence rate of the performance measures of truck processing time and inventory levels, compared to the time period preceding 2015.

For truck processing deviation, the time deviation between the scheduled arrival or departure time of trucks and their actual arrival or departure time is minimized. An example can be found in Khorshidian et al. (2019) that presents a new truck scheduling, distribution and portfolio selection model. The model was tested on an industrial case considering six performance measures including truck processing time deviation.

EXTENDED SEARCH ON INDUSTRY 4.0 IN CROSS-DOCKING

In this section, we describe our extended search on Industry 4.0 literature in cross-docking. Apart from the works of Chargui et al. (2018) and Chargui et al. (2019b), we found limited evidence for Industry 4.0 adoption in cross-docking research. This might be caused by the exclusion criteria of our systematic literature review. Since we focussed on practical cases in cross-docking, more theoretical Industry 4.0 research in cross-docking might be excluded. First, we conduct an additional literature search, more focussed on finding the intersection of cross-docking and Industry 4.0. Next, we review the research gaps identified by the literature and discuss the future research directions as identified by our review.

Industry 4.0 Components in Cross-Docking Literature

For this systematic search, opposed to the first review, we include publications from before 2015 and extend our search to more theoretical work. Again we classify the research in different Industry 4.0 sub-topics, as introduced in Section 'Industry 4.0 Components in Manufacturing and Logistics'. The sub-topics are (1) cyber-physical systems, (2) IoT, (3) machine-to-machine communication, (4) AGVs/robotics, (5) artificial intelligence and (6) RFID/smart sensors.

To find keywords related to Industry 4.0, we did a search query with the phrase ('industry 4*' OR 'smart industry'). The top 2000 papers are exported to VOSViewer, which is software used for visualizing scientific subjects (van Eck & Waltman, 2010). See Fig. 7 for an overview of keywords that occur at least 35 times in the 2000 papers.

Based on the bibliometric cloud, we select the following keywords for the new search query: 'Industry 4.0', 'Big Data', 'Cyber physical', 'Internet of Things' and 'Embedded Systems'. We also include the term 'Physical internet', since this is the subject of the only

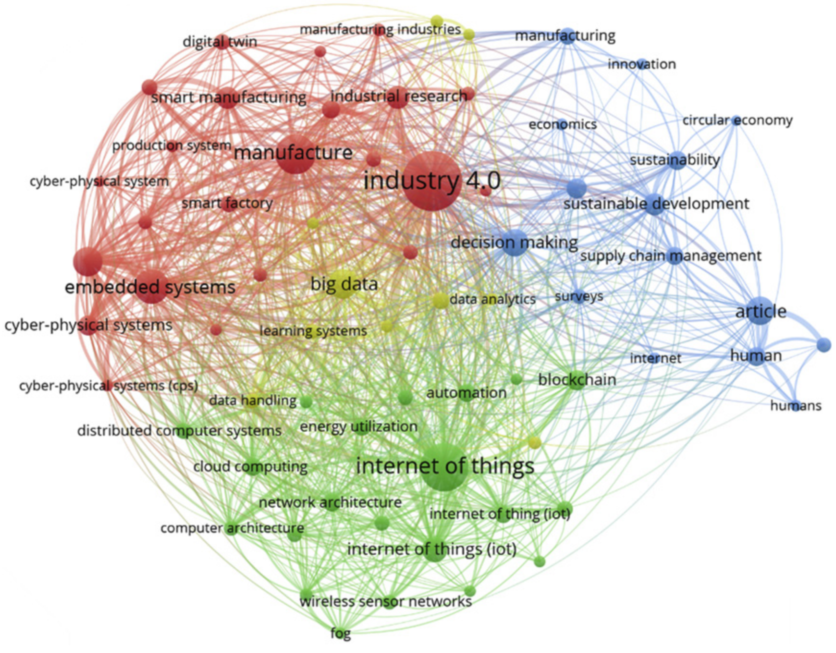


Fig. 7. Bibliometric Network Concerning Industry 4.0.

Table 9. The Search Criteria of the Systematic Literature Review.

Search terms for titles, abstracts and keywords	('cross-dock*' OR 'crossdock*' OR Cross dock*') AND ('industry 4*' OR 'big data' OR 'Cyber physical' OR 'Internet of things' OR 'IOT' OR 'Embedded system*' OR 'Smart industry' OR 'Artificial intelligence' OR 'cloud' OR 'automation' OR 'smart manufacturing' OR 'physical internet')
Filter	AND NOT ('ligand*' OR 'protein*')
Timeframe	1950–May 2020
Language	English
Source type	All
Document type	All
Publication status	All

sources about Industry 4.0 in cross-docking that we identified (Chargui et al., 2018, 2019b). Table 9 shows the resulting search criteria.

This search query resulted in 49 papers, after removing duplicates from Scopus and Web of Science. After an initial screening for which we check whether the papers indeed relate to cross-docking and industry 4.0, we remain with 30 papers. After reading all 30 papers, we find that many papers only consider automation, which we classify as being part of the third industrial revolution, or only used some popular phrases concerning Industry 4.0, but did not discuss the Industry 4.0 contribution in detail nor make a connection with cross-docking. Based on this, we end up with 13 relevant papers on

Industry 4.0 and cross-docking. All papers are published in the period from 2014 up to March 2021.

Table 10 shows the relevant information of the 13 included papers. We show the problem that is considered, the solution approach and the used performance measures, following our initial systematic literature review based on the framework of Ladier and Alpan (2016). Additionally, we show the Industry 4.0 practices that were discussed in the papers.

Most papers discuss the PI, as we already found earlier in the papers by Chargui et al. (2018) and Chargui et al. (2019b). The PI concept relies on several Industry 4.0 aspects: physical objects that are connected in a digital cyber-physical system, machines and sensors that are connected using IoT, M2M communication is necessary and often automated transport and sorting are done with AGVs or other robots. We found an additional source by Chargui, Bekrar, Reghioui, and Trentesaux (2019a) that concerns a similar subject but now applied to a more practical case of a train-to-truck cross-docking terminal. The authors first discuss different types of PI-hubs (road-road, rail-road, water-road) and discuss the use of PI-containers, i.e., smart modular containers that are interconnected with PI-movers (e.g., automatic conveyors, automatic storage and retrieval systems, and AGVs) for automatic transport between PI-nodes (e.g., loading docks and manoeuvring areas). They model a situation where PI-containers are unloaded from a train, sorted and grouped by a PI-sorter and loaded on trucks. Their metaheuristics are used to find optimal solutions for minimizing costs and energy consumption of conveyors. Pawlewski (2015) consider asynchronous multi-modal transport for cross-docking and discuss the potential of the PI. Additionally, they present an MILP for truck-to-door scheduling (Pawlewski, 2015).

In Pach et al. (2014), several future research directions for PI-hubs are listed with a focus on M2M: assignment of PI-containers to PI-hub doors, allocation of PI-containers to transporters and different modalities and the routing of PI-containers in the terminal. As the loading of trucks has proved to be the bottleneck activity in a PI-hub, the authors propose a method using PI-containers that are used to group smaller shipments, to reduce the number of loading movements. They illustrate a grouping approach using the following sequence: (1) the first container arrives at a loading area and sends a grouping proposal to known PI-containers that can be grouped, (2) the containers respond and communicate their arrival time at the loading area, (3) a decision is made on a grouping based on the size of containers, arrival time and grouping policy, and (4) the containers are sent an acceptance or refusal for grouping. The authors test three different grouping policies and compare them with a non-grouping situation. They show that the product throughput time can be reduced by 30% when using a grouping policy (Pach et al., 2014). Similarly, in three papers, Walha, Chaabane, Bekrar, and Loukil (2014), Walha, Bekrar, Chaabane, and Loukil (2016a), and Walha, Bekrar, Chaabane, and Loukil (2016b) discuss PI-hubs and M2M communication. Walha et al. (2016b) study rail-road PI-hubs and the container grouping problem. The authors propose a multi-agent system to generate reactive solutions. Their model consists of three types of agents that communicate with each other and respond to the environment: a supervisor agent, a set of group agents and a set of dock agents. The supervisor agent manages the creation of group agents. Group agents represent a set of containers. The dock agent sends information about dock availability and expected travel distance for containers. Especially with dynamic scenarios with disturbances, their model outperforms static approaches (Walha et al., 2016b). Finally, Sallez, Berger, Bonte, and Trentesaux (2015) propose a hybrid control method for routing inside a PI-hub, i.e., globally optimized routing for a complete PI-hub combined with locally reactive PI-containers that can respond to disturbances. Their model is robust

Table 10. Extended Cross-Docking Literature Review on Industry 4.0.

	Problem	Planning Level	Solution Method	Performance Measures	Industry 4.0 Components
Chargui et al. (2018)	Internal resource operation	Operational – Scheduling/routing	Simulation	Truck processing deviation, makespan, Waiting Time	Cyber-physical systems, IoT, M2M, RFID
Chargui et al. (2019a)	Internal resource operation	Operational – Scheduling/routing	MILP, simulated annealing, tabu search	Truck utilization costs, energy costs	Cyber-physical systems, IoT, M2M
Chargui et al. (2019b)	Internal resource operation, truck-to-door scheduling	Operational – Scheduling/routing	Scheduling heuristic	Truck processing deviation	Cyber-physical systems, IoT, M2M, RFID
Grefen et al. (2019)	Internal resource operation	Operational – Scheduling	-	-	IoT, AGVs
Kusumakar et al. (2018)	Internal resource operation, truck-to-door scheduling	Operational – Allocation/routing	Simulation	Driving precision	IoT, AGV, M2M
Pach et al. (2014)	Truck loading, container grouping	Tactical – Scheduling/ allocation	Heuristics, simulation	Makespan	Cyber-physical systems, IoT, AGV, M2M
Pan et al. (2021)	Truck scheduling, truck-to-door scheduling	Tactical – Scheduling/ allocation	MILP	Makespan	IoT, RFID
Pawlewski (2015)	Truck-to-door scheduling, truck scheduling	Tactical/scheduling	MILP, simulation	Truck driving distance	Cyber-physical systems, IoT, AGV, M2M
Quak, Van Duin, and Hendriks (2020)	Cross-docking interviews	–	–	–	Cyber-physical systems, IoT
Sallez et al. (2015)	Internal resource operations	Operational/routing	Simulation	Makespan, failures	Cyber-physical systems, IoT, AGV, M2M
Walha et al. (2014)	Internal resource operations	Operational/allocation	–	–	Cyber-physical systems, IoT, AGV, M2M
Walha et al. (2016a)	Internal resource operations, grouping containers	Operational/allocation	Heuristics	Number of trucks used, fill rates and travel distance	Cyber-physical systems, IoT, AGV, M2M
Walha et al. (2016b)	Internal resource operations, grouping containers	Operational/allocation	Heuristics, meta-heuristics, simulation	Number of trucks used, fill rates and travel distance	Cyber-physical systems, IoT, AGV, M2M

to unexpected situations, i.e., external disruptions (wrong placement of trucks, lateness of trains) and internal disruptions (conveyor breakdown).

Automated distribution and autonomous systems are other topics present in cross-docking research. Grefen, Brouns, Ludwig, and Serral (2019) discuss a multi-location IoT business process and illustrate this using a case study for the port of Rotterdam. They outline the complete business process of unloading sea containers and transporting them to customs using cranes and AGVs, all interconnected via IoT. The authors illustrate how a sea container can communicate during different moments of the business processes (e.g., request move by crane, open doors for customs). All types of messages described are machine-to-machine communication. They further discuss co-location in general, which is the concept of business processes that need to be executed in physical proximity of each other, e.g., a crane lifts a container at specific GPS coordinates. The paper does not present a mathematical model or quantitative data. In Kusumakar, Buning, Rieck, Schuur, and Tillema (2018), the autonomous manoeuvring of a truck from a parking area to a cross-docking door is discussed. Manoeuvring trucks to doors can be difficult for human drivers; humans might need much time or cause collisions resulting in financial damage. The authors propose a new approach where trucks are autonomously guided to docking doors using unmanned aerial vehicles that are connected to a truck using IoT. Their simulation shows that truck driving precision is high enough for use in practice and is robust for different types of layouts.

Smart sensors and RFID tracking is a topic relevant to automated cross-docking centres and automated sorters. Pan, Zhou, Fan, Li, and Zhang (2021) discuss the use of smart sensors and IoT in perishable goods inventory management and cross-docking. With the use of RFID tags in cross-docking terminals, perishable products can be better tracked and data about shelf-life are more reliable. RFID smart tags can be used to measure light, temperature and humidity near products, which are indicators used for predicting remaining shelf-life (Pan et al., 2021).

Summarizing our extended literature review, we observe that Industry 4.0 practices are being adopted in cross-docking research. Most research deals with PI-hubs and the related Industry 4.0 topics. Some research concerns automated distribution, with a special focus on automated sorting, for which smart sensors/RFID are needed to track physical goods. PI-hub research mainly focusses on the multi-modal transport aspect. Fig. 8 summarizes the frequency of Industry 4.0 practices considered in research, for both our initial search and the extended search.

Gaps and Future Research Directions for Industry 4.0 in Cross-Docking

In the review of Ladier and Alpan (2016), several promising future research directions were identified. These mainly covered gaps in the literature, namely the modelling of mixed service doors for truck loading and unloading, the consideration of uncertainty and deadlines for truck departures, the inclusion of storage capacity in models, the change of performance indicators more related to practice and the inclusion of uncertainty in general. In this section, we evaluate the future research directions mentioned in Industry 4.0 related literature (see Table 11). Since the review of Ladier and Alpan (2016) was oriented on cross-docking in general, there is little overlap in future research directions as identified by Industry 4.0 research. The main future research direction that is recognized by Ladier and Alpan (2016) and by most Industry 4.0 research is the addition of uncertainty, i.e., stochasticity, to the studied cross-docking models.

Fig. 8. Frequency of Industry 4.0 Elements in Research. The number of Related Works is Indicated in Parentheses.

Table 11. Research Directions Identified by Ladier and Alpan and Industry 4.0 Cross-Docking Related Works.

	Future Research Directions
Ladier and Alpan (2016)	Mixed service modes, consider truck departure deadlines and uncertainty, include storage capacity in models, use better performance indicators, include dynamicity and uncertainty in models
Chargui et al. (2018)	Resource allocation for PI-hubs
Chargui et al. (2019a)	Uncertainty (truck delays, order mutation) for PI-hubs
Chargui et al. (2019b)	Internal and external disruptions for PI-hubs
Grefen et al. (2019)	Add additional constraints on co-location, e.g., operating within certain temperature ranges
Kusumakar et al. (2018)	Technical remarks considering enhancing accuracy of the autonomous truck docking
Pach et al. (2014)	Departure time of PI-containers as a performance indicator. Add internal disruptions, consider future states of the system for the routing approach
Pan et al. (2021)	Technical remarks about deterioration rate
Pawlewski (2015)	No concrete future research direction
Quak et al. (2020)	General outlook on cross-docking, no concrete future research directions
Sallez et al. (2015)	Study heterogeneous PI-container sizes, study robustness by allowing backward motions of PI-containers
Walha et al. (2014)	Internal and external disruptions in PI-hubs
Walha et al. (2016a)	Internal and external disruptions in PI-hubs
Walha et al. (2016b)	Internal and external disruptions in PI-hubs, consider the routing problem for PI-containers

The potential of Industry 4.0 for cross-docking in saving costs and running more reliable operations has been shown but requires more research and validation in practice. In Section 'Industry 4.0 Components in Cross-Docking Literature', we discussed the latest literature related to cross-docking and Industry 4.0. We can make general recommendations for future research, based on our findings and the synthesis from the reviewed literature. In this sense, future research can be done in several areas: (1) the development of cyber-physical systems for cross-docking terminals that aid the communication between automated machines and transporters, (2) the further development of automated sorting machines using RFID technology, (3) the search for applications of smart sensors that can aid cross-docking facilities, (4) the internal operations and routing of automated distributed control systems, (5) the assignment of PI containers to PI-hub dock doors, (6) allocation of PI-containers to modalities and transporters, (7) routing of PI-containers inside terminals, using PI-conveyors, AGVs or other PI-nodes and (8) the addition of internal and external disruptions to PI-hubs.

CONCLUSION

In this chapter, we considered cross-docking literature between 2015 and 2020. Based on the literature study by Ladier and Alpan (2016), we did a systematic literature review to investigate to which degree the field of research has changed after their recommendations. We concluded that manual modes of transport remain the most frequently studied approach in cross-docking literature since human workers are perceived as more flexible. However, we showed that developments in technology have huge potential for more automated cross-docking terminals.

Through this review, we showed the use of different modelling constraints and performance indicators. We did not observe large deviations from the observations by Ladier and Alpan (2016). The small deviation compared with Ladier and Alpan (2016) is that more real-world constraints are used, but still, too few studies use mixed door service modes and industry-based performance indicators. Our literature review resulted in only seven papers that considered features of Industry 4.0 in cross-docking. Therefore, we performed an additional review extending the time horizon and removing the focus on practical cases only.

Concerning Industry 4.0, we collected 15 works in our second review. Most deal with PI-hubs, which is a concept for which several components of Industry 4.0 are used: cyber-physical systems, IoT, machine-to-machine communication and AGVs/robotics. Outside the field of the PI, research treated smart sensors for tracking perishable goods, RFID for automated sorters and autonomous distribution for cross-docking facilities. We conclude that Industry 4.0 is gaining attention in cross-docking research but is mainly focussed on PI-hubs. As points of further research, some authors have in common the importance of considering uncertainty and disruptions in PI-hubs, while others point out the incorporation of PI-containers KPI and features.

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HUMAN-ROBOT COLLABORATION IN A SMART INDUSTRY CONTEXT: DOES HRM MATTER?

Marie Molitor and Maarten Renkema

ABSTRACT

This paper investigates effective human-robot collaboration (HRC) and presents implications for Human Resource Management (HRM). A brief review of current literature on HRM in the smart industry context showed that there is limited research on HRC in hybrid teams and even less on effective management of these teams. This book chapter addresses this issue by investigating factors affecting intention to collaborate with a robot by conducting a vignette study. We hypothesized that six technology acceptance factors, performance expectancy, trust, effort expectancy, social support, organizational support and computer anxiety would significantly affect a users' intention to collaborate with a robot. Furthermore, we hypothesized a moderating effect of a particular HR system, either productivity-based or collaborative. Using a sample of 96 participants, this study tested the effect of the aforementioned factors on a users' intention to collaborate with the robot. Findings show that performance expectancy, organizational support and computer anxiety significantly affect the intention to collaborate with a robot. A significant moderating effect of a particular HR system was not found. Our findings expand the current technology acceptance models in the context of HRC. HRM can support effective HRC by a combination of comprehensive training and education, empowerment and incentives supported by an appropriate HR system.

Keywords: Human-robot collaboration; smart industry; human resource management; technology acceptance; vignette study

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INTRODUCTION

Smart and interconnected manufacturing and production technologies are often labelled under the umbrella of smart industry or industry 4.0 (Habraken, 2020), making use of interconnected and digitized systems (Kagermann, Wahlster, & Helbig, 2013). As integral part of this smart industry development, Artificial Intelligence (AI) enables computers and/or robots to perform tasks which would otherwise require human cognition (Tambe, Cappelli, & Yakubovich, 2019). One such smart solution that organizations increasingly use is the collaborative robot or *cobot*, which allows for direct interaction and collaborative work. Whereas in earlier days, technology development was focused on automation, nowadays smart industry technologies enable collaboration between humans and machines (Wilson & Daugherty, 2018). In smart industry, teams will therefore not only be composed of humans but also include these AI-powered robots (e.g. Davenport & Kirby, 2016; Habraken & Bondarouk, 2019).

In the last years, the phenomenon of so-called human-robot collaboration (HRC) has received increasing attention. Collaborative robots enable direct interaction between human operators and robots; thus, instead of robots replacing human workers, HRC allows human workers and robots working together in a shared environment while overcoming the classical division of labour (Liu & Wang, 2018; Villani, Pini, Leali, & Secchi, 2018). HRC is an important part of the new industrial revolution, which is often termed smart industry (the term we adopt in this chapter) or industry 4.0, and describes advanced digitalization and the combination of internet-oriented technologies (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014). Companies adopting smart industry execute several internal changes in order to integrate AI in terms of social robots into their working processes (Lasi et al., 2014). As such, integration of AI does not only refer to changes in manufacturing processes, but is also powering social robots that work as teammates. The corresponding changes on the work-floor consequently require adaptation by employees.

In order to work in this environment, new workforce competencies and management processes are required (Hecklau, Galeitzke, Flachs, & Kohl, 2016). Nevertheless, in the current management literature there are many open questions regarding novel human–AI collaborations (Glikson & Woolley, 2020). Moreover, there has been scant attention for the implications these HRCs have on Human Resource Management (HRM). Knowledge about the use of social robots as driving force behind this new industrialization is limited (Tambe et al., 2019). Since the new industrialization will sooner or later affect all industries (Barreto, Amaral, & Pereira, 2017), there is a need for an in-depth investigation of the phenomena of HRC and how to manage the implications of this collaboration (Shamim, Cang, Yu, & Li, 2016). New questions arise such as: what factors influence employees' willingness to collaborate with social robots? And what is the role of HRM in this relationship? Therefore, this study analyses factors that influence HRC and examines the role of HRM by answering the following research question: 'Which factors influence human-robot collaboration in the smart industry context and what are the implications for human resource management?' This question is answered by employing an online vignette-based experiment containing a short description of situations and a survey. A between-person vignette design is used in which different vignettes are assigned to different groups of respondents. This allows us to draw conclusion on whether HRM serves as support factor on people's intention to collaborate with the robot.

This study contributes to the existing literature on HRC in teams by examining factors that affect users' intention to collaborate with a social robot. In addition, we analyse whether HR systems influence the relationship between technology acceptance and willingness to collaborate. To our knowledge, these relationships have not been studied before and therefore help to further our understanding about HRC and the role of HRM. Our findings show that three technology acceptance factors are important to increase the users' intention to collaborate with a robot. In doing so, we expand the work on technology acceptance and HRC: our findings show that these factors can partly help to explain acceptance of smart technologies. Furthermore, we provide a grounding for future research on actual collaboration between humans and smart technologies. Practical implications are related to the increasing awareness and knowledge on factors which increase or decrease the effectiveness of HRC. We provide insights and argue that, for collaborative work in smart industries, a fitting HR system in combination with specific preparation, empowerment and incentives related to the challenges of HRC is needed. This enables businesses to enhance management and support of humans working in hybrid teams in order to increase team performance.

THEORETICAL BACKGROUND

In this section we shortly introduce the concept of collaborative robots. To understand what determines people's willingness to collaborate with these robots, we discuss technology acceptance theories and show which factors affect this collaboration. Lastly, we discuss the potential role of HRM as support factor.

Collaborative Robots in Smart Industry

Human-robot collaboration (HRC) is an important aspect of smart industry, whereby collaboration refers to the process of agents working together in order to achieve a common goal (Terveen, 1995). While humans and robots tend to have separate working spaces in the past, in a smart industry context collaborative robots allow for direct interaction and collaborative work between humans and AI We conceptualize HRC similar to Hoffman and Breazeal (2004) and thus rather from the standpoint of teamwork in which humans and robots work together in a partnership instead of acting upon each other. When conceptualizing HRC in this way, social adeptness and adaptability by the robot is required. Therefore, the robot as part of the team takes on the explicit or implicit intention of the team as its own in order to perform and to achieve a common goal. To do so, the robot should be able to perceive the team's intensions, beliefs and goals, and must share its own intentions (Bauer, Wollherr, & Buss, 2008; Seeber et al., 2020). The type of robot that holds these characteristics is the social collaborative robot (or sometimes called *cobot*). This paper examines people's intention to collaborate and interact with social robots.

Technology Acceptance

We build on and further expand previous work on HRC, by drawing on the technology acceptance literature. The literature on technology acceptance is well established (e.g. Lee, Kozar, & Larsen, 2003), but work on HRC is relatively scant. To advance this field of research, we combine technology acceptance theories. In line with Bröhl, Nelles, Brandl, Mertens, and Schlick (2016, 2019), we argue that acceptance of technology is crucial to predict successful human-robot collaboration or interaction. Inspired by the Unified Theory of Acceptance and Use of Technology (UTAUT) of Venkatesch et al. (2003), we examined factors that can be expected to influence intention to collaborate with a social robot. The technology acceptance literature is limited to the fact that they do not refer to actual usage of and collaboration with technology but rather account for technology usage intention (Venkatesh, Morris, Davis, & Davis, 2003). Therefore, we focus on intention to collaborate in order to get closer to understanding actual HRC. We hypothesized that six factors would affect intention to collaborate, performance expectancy, trust, effort expectancy, social support, organizational support and computer anxiety. We will further refer to these as *technology acceptance factors*. In order to examine these factors, we take into account the conceptualization and operationalization of the variables as reported in previous scholars.

Performance expectancy

Performance expectancy can be defined as 'the degree to which an individual believes that the system or technology will help him or her in performing a job' (Venkatesh et al., 2003). The probability of accepting and valuing a particular technology increases in case it enhances daily life. Technology, in our case, robots need to make tasks easier, enhance convenience and support everyday activities which are executed in teams. We assume that in order for humans to accept and collaborate with technology, it needs to enhance job performance and thus we propose the following hypothesis – *Hypothesis 1: Expected performance of the robot affects the users' intention to collaborate.*

Trust

Trust is often defined as having confidence in something to do the right action (Gaudiello, Zibetti, Sébastien, Chetouani, & Ivaldi, 2016). Tangibility, transparency, reliability and immediacy behaviours are important factors in developing cognitive trust (Glikson & Woolley, 2020). Different scholars found that trust significantly influences the acceptance of technology (Faqih, 2011; Pavlou, 2003; Wu, Zhao, Zhu, Tan, & Zheng, 2011). Thus, trust can be used to determine overall acceptance of technology (Gaudiello et al., 2016). We expect that trust affects how people perceive and, in the end, interact and collaborate with the technology. Thus, we propose – *Hypothesis 2: Trust in the technology affects the users' intention to collaborate.*

Effort Expectancy

Effort expectancy is the degree of ease of use of the system or technology (Venkatesh et al., 2003). Ease of use can be described as whether the technology is easy to facilitate, and therefore free of effort, which enhances the attitudes towards technology (Davis, 1989; Venkatesh et al., 2003). The importance of clear and understandable interaction with the system was already demonstrated by Thompson, Higgins, and Howell (1991), in their model of PC utilization. The least collaborative effort can be accomplished by minimizing individuals' collective effort to gain an understanding of communication (Kiesler, 2005). We expect that the degree of effort related to the use of a technology can either enhance or worsen the acceptance and collaboration with the system. Therefore, we propose – *Hypothesis 3: Effort expectancy related to the technology affects the users' intention to collaborate.*

Social Support

The social environment of employees plays a crucial role in HRC. The culture the organization stands for provides employees with norms and values which are ideally transferred into behavioural norms in order to meet organizational expectations (Mickan & Rodger, 2000). Values, norms and goals further strengthen motivation and commitment of employees, while commitment strengthens participation in teamwork (Pearce & Ravlin, 1987). This is also referred to as social influence, meaning whether the individual beliefs that he or she should use the system and whether important individuals expect this (Venkatesh et al., 2003). The TAM and Theory of Planned Behaviour (TPB) refer to the impact of the human's social environment as subjective norms (Ajzen, 1991; Davis, 1989). We argute that acceptance and collaboration with robots is affected by whether the social environment of an employee enhances and supports this process and propose – *Hypothesis 4: Support by the social environment affects the users' intention to collaborate.*

Organizational Support

Park, Rhoads, Hou, and Lee (2014) examined that support by the institution or organization is an important construct that 'reflects assistance or barriers to the behaviour associated with external conditions'. Further they summarized factors that influence technology acceptance and found supporting staff, consultant support, management support and training as relevant (Park et al., 2014). The concept of organizational support is reflected by the construct of facilitating conditions (Venkatesh et al., 2003). Facilitating conditions can be defined as whether an individual's beliefs that the organization itself and the infrastructure support the use of the technology (Venkatesh et al., 2003). We expect that the users' acceptance and collaboration with technology are influenced by organizational support that enables him or her to do so. We propose the following – *Hypothesis 5: Organisational support affects the users' intention to collaborate.*

Computer Anxiety

We define computer anxiety as the extent to which an individual feels unpleasant when using technology (Park et al., 2014). Computer anxiety is likely to be determined by people's computer skills, which become more important in a smart industry setting. For example, when referring to the increasing global skills gap, Bughin et al. (2018) found that basic cognitive, physical and manual skills will decline during the next years, while demand for technological skills (such as computer skills) will increase. Since robots are very complex in contrast to usual technologies like personal computers, these complex technologies require more involvement and a more diverse skill set which when not present can negatively affect the acceptance and adoption by the user. Different scholars provide insights on the significant effect of computer anxiety on attitudes and user behaviour (Park et al., 2014; Venkatesh, 2000). We expect that computer anxiety affects acceptance and intention to collaborate with the technology and propose – *Hypothesis 6: Computer anxiety affects the users' intention to collaborate.*

The Role of Human Resource Management

In smart industry, teamwork is becoming critical. Especially in highly complex environments, teamwork is more than simply assigning tasks, resulting in an urgent need for HR to support employees when working together with smart technologies (Libert, Cadieux, & Mosconi, 2020). In case employees are not supported properly, adoption to technologies can become stressful, and with that affecting the workers' health and satisfaction, which causes turnover, eventually (Libert et al., 2020). HRM can support organizations and their employees in dealing with changes that come with smart industry. Managers need to design HR practices with the intention to promote innovativeness and learning in the organization (Shamim et al., 2016). In order for employees to adopt to technologies and to effectively work together, a combination of preparation, empowerment and incentives is needed (Libert et al., 2020). Further changes must occur along attraction, retention and development of employees in this new industrialization. Thus, hiring should be on the basis of variety of skills, heterogeneous knowledge and attributes necessary for innovative behaviour (Shamim et al., 2016). Organizations need to design training programmes in a way which enhances the innovative capability and learning (Shamim et al., 2016) in order to strengthen employee's awareness and skills. Stachová, Papula, Stacho, and Kohnová (2019) propose the importance of knowledge sharing, learning and human development in this new industrial revolution. This requires cooperation with external partners like educational institutions in order to arrive at new educational opportunities (Stachová et al., 2019). Next to that, they might work on performance appraisals in order to facilitate learning and innovation, empowerment of the workforce, and the creation of incentives reflecting the contribution of employees to the company. Providing incentives and satisfactory training possibilities has a positive impact on employees' commitment (Jaworski, Ravichandran, Karpinski, & Singh, 2018). Knod, Wall, Daniels, Shane, and Wernimont (1984) argue something similar; involving people early, gaining expertise (if necessary, through recruitment) and educate and train the human workforce is necessary for future HRC. This suggests that HRM needs a shift in its core processes (e.g. hiring, appraisal, training and compensation) to support and facilitate the acceptance, adoption and collaboration with new technologies such as social robots.

Human Resource Management Systems as Moderator

HRM systems entail characteristics of a companies' values and norms and stand for how employees are managed inside the company. We suggest that certain HR systems would enable and support HRC while others have a negative influence or no influence at all. In other words, the effects of the technology acceptance factors are expected to be shaped by the HR system in place, such that a supportive HR system can enhance the positive effects of the acceptance factors while an unsupportive HR system may decrease the effect. For example, high levels of trust and performance expectancy interact with the HR system to increase the willingness to collaborate.

Lepak and Snell (2002) examined different employment modes and their association with a type of HR system: commitment-based, compliance-based, productivity-based, and collaborative. We focus on the collaborative HR system since it can be expected that it can support HRC. We further include the productivity-based HR system due to the fact that it is almost contrary to the collaborative HR system and we expect to achieve the most diverse outcome.

In a productivity-based HR system, employees get paid a market-based wage and managers are focused on employees' job performance. Jobs are more often standardized in order to find replacement in case the employee leaves the firm. Usually, firms which focus on productivity are more likely to establish shorter time horizon in order to ensure productivity and are more result oriented (Lepak & Snell, 2002). Since we examine how humans collaborate with smart technologies in the team context and the productivity-based HR system rather focuses on individual short-term performance, we expect that the effect of this system on the relationship between the technology acceptance factors and the users' intention to collaborate with the robot is rather neutral or even negative. Collaborative HR systems are characterized by sharing of information and development of trust between partners. A joint outcome is crucial and therefore, firms that apply this system invest heavily in relationship building. One finds team building initiatives to be part of this system and evaluations of employees rather emphasize developmental issues such as the extent of learning (Lepak & Snell, 2002). We expect a positive influence of the collaborative HR system on the relationship between the technology acceptance factors and the users' intention to collaborate with the robot, since this system is focused on the challenges of HRC, especially in the team context, and thus, might positively affect how humans work together with robots. Therefore, we expect that – *Hypothesis 7: The presence of a productivity-based HR system negatively moderates the relationship between the technology acceptance factors and employees' intention to collaborate with technology, such that the relationship becomes weaker when a productivity-based HR system is present.*

Hypothesis 8: The presence of a collaborative HR system positively moderates the relationship between the technology acceptance factors and employees' intention to collaborate with technology, such that the relationship becomes stronger when a collaborative HR system is present.

Conceptual Framework

We build on previous work on HRC. Primarily inspired by the UTAUT model, we hypothesized that six factors would positively affect the intention to collaborate: performance expectancy, trust, effort expectancy, social support, organizational support and computer anxiety. In addition, to study the role of HRM, we included different HRM systems as moderators. We hypothesized a moderating effect of the HR system on the relationship between the technology acceptance factors and the intention to collaborate, such that this relationship would be strengthened or weakened when the HR system was in place. Based on the work by Lepak and Snell (2002), we hypothesized that a *collaborative HR system* reinforces the relationship between the technology acceptance factors and HRC, whereas a *productivity-based HR system* would be detrimental in this relationship (Fig. 1).

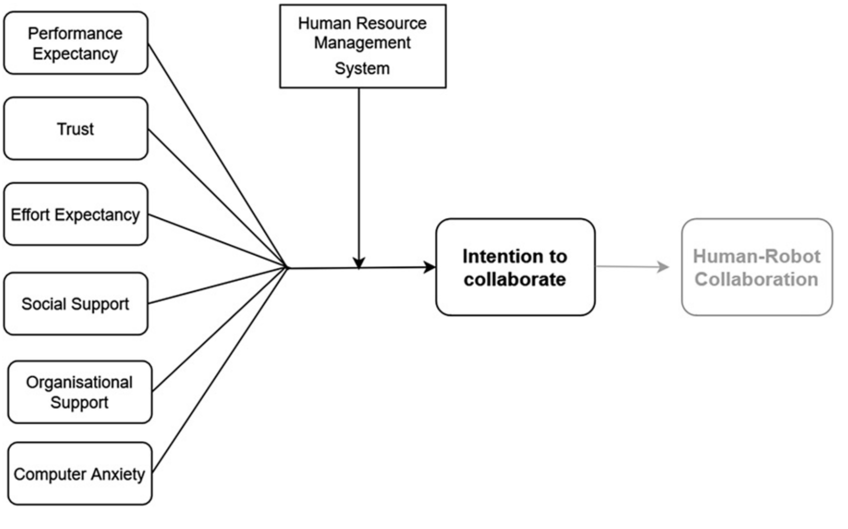

Fig. 1. Conceptual Model.

METHOD

Research Design and Data Collection

We adopted a quantitative experimental approach by investigating HRC using a vignette study, which combines characteristics of experimental designs and surveys. A vignette study contains short descriptions of situations or persons and a survey which respondents usually fill in afterwards (Atzmüller & Steiner, 2010). This type of approach usually shows high internal validity due to the experimental design, and high external validity due to the survey characteristics (Atzmüller & Steiner, 2010). We chose a between-person vignette design, meaning that each participant only reads one vignette which allows for comparisons across participants (Atzmüller & Steiner, 2010). This enables us to see whether the vignettes yield different effects on respondents and the relationship between the technology acceptance factors and intention to collaborate.

Participants of this study were men (31%) and women (69%) between 18 and 65 years of age. Attention was also given to differentiation among education levels, in order to provide sufficient control variables and to avoid biased outcomes. The online survey software distributed the three different vignettes randomly and evenly across participants. In total, 145 people participated in this study, with a valid sample size of 96 cases. Data were collected by making use of the web-based software Qualtrics XM. Participants were recruited through LinkedIn, PoolPool and personal networks. Participation in this study took seven minutes on average.

Measures

The survey consisted of 24 statements, where 21 items measured the independent variables and three items measured the dependent variable. Participants had to judge these statements on a five-point Likert scale (see Appendix 1).

Technology Acceptance Factors

We take into account the operationalization of the variables, as reported in previous scholars, thus items are based on insights from different technology acceptance models and theories. *Performance expectancy* consists of three items, measured according to the existing scale used by Venkatesh et al. (2003) in the UTAUT paper and the scale by Davis (1989) in construction of the perceived usefulness variable. *Trust* consists of four items and is measured by making use of items according to a scale developed by Schaefer (2013), measuring human–robot trust. Effort *expectancy* consists of three items and is measured using a combination of scale items by Venkatesh et al. (2003) and Davis (1989), who refer to the variable as ease of use. *Social support* is a combined scale, made up of the measure used by Ajzen (1991) to examine the subjective norm variable and the scale used by Venkatesh et al. (2003) to measure social influence, consisting of three items. Next, *organizational support* is measured by four items, combining items used by Venkatesh et al. (2003) in measuring facilitating conditions and the scale used by Park et al. (2014) to measure institutional support. Lastly, we measure *computer anxiety*, consisting of four items, by using the measurement scales developed by Venkatesh (2000) and Park et al. (2014) to test computer anxiety in the light of technology acceptance.

Intention to Collaborate

The dependent variable of this study is the user's *intention to collaborate* with the robot. We take into account the operationalization of intention to collaborate, as reported in previous scholars. The items used were whether participants believed working with the robot is a good idea, whether they think they would collaborate with the robot eventually and whether they believe they would like working together with the robot. These were based on two scales used by Venkatesh et al. (2003) to measure attitude towards using a technology and further to measure users' intention to use a technology.

HRM System

Our aim was to test for a significant effect of the technology acceptance factors on intention to collaborate. We expected that this relationship is moderated and thus, subject to change when a specific HR system is in place. In order to test for a moderating relationship, three different scenarios (vignettes) were used. The difference between the vignettes was related to the different types of HR systems, which were described. We conceptualized two vignettes according to Lepak and Snell (2002) as we did in our literature review. Shortly, *collaborative HR systems* are characterized by trust between partners and team building while in a *productivity-based HR system*, managers are focused on employees' job performance which are more often standardized (Lepak & Snell, 2002). The third vignette did not include information about a particular HR system and serves as reference category (Table 1).

Table 1. Operationalization HRM Systems.

	Productivity	Collaborative	No HR System
Standardized jobs	X		
Functional teams and networks		X	
Emphasize job performance	X		
Seek to increase short-term productivity	X		
Focus on interpersonal relations		X	
Result based	X		
Assessment of quality and quantity of output			
Focus on team performance		X	
Group-based incentives		X	
Straight salary	X		

Control Variables

Control variables used in this study are age, gender and education level which have proven to be important control variables in previous studies (Croson & Gneezy, 2009; Park et al., 2014; Schaefer, 2013; Venkatesh et al., 2003) and are thus relevant in the context of this study.

Data Analysis

Data were processed with SPSS version 26 and AMOS version 26. *First*, descriptive statistics (means, standard deviations), multi-collinearity statistics and correlation coefficients were computed to determine distribution of data and the relationships between the variables. Further, based on Gao, Mokhtarian, and Johnston (2008), Mardia's coefficient of multivariate kurtosis and its critical ratio was used as an indicator of multivariate normality (>-1.96, <1.96). In order to test for reliability of the construct, we estimated

Cronbach Alpha (>0.6) based on Churchill's (1979) and van Griethuijsen's et al. (2015) suggestion for a critical value. The level of statistical significance for the relationships was set at 95% ($p < 0.05$).

Second, ANOVA was estimated in order to show whether there is a significant difference in mean between the groups who received different vignettes.

Third, we conducted confirmatory factor analysis (CFA). CFA is known to be robust with different scales (e.g. Likert scales), but does require distributional assumptions. We checked for multivariate normality, sufficient sample size, priori model specification and random sample distribution. Based on CFA, outliers and three measurement items were excluded, due to low loading on the particular construct. In order to determine the best fitting measurement model, a competing measurement modelling strategy was used (Table 2).

Table 2. Model Fit Statistics.

Fit Indices	Cut-Off Criterion
Absolute fit indices	
Chi-square ($\chi 2$)	Lowest comparative value between measurement models
$\chi 2$/df	<5
Approximate fit indices	
Root means square error of approximation (RMSEA)	<0.08 but >0.01
Root mean square residual (RMR)	<0.08
Incremental fit indices	
Comparative fit index (CFI)	>0.90
Tucker-Lewis index (TLI)	>0.90

Source: Adapted from Hu and Bentler (1999).

In order to determine data-model fit, we employed a sequential evaluation process. We refer to Hu and Bentler (1999), who examined various fit indices used to evaluate model fit, to discriminate between models and to determine data-model fit. The model with the highest model fit was retained for further analyses.

Finally, we conducted multiple hierarchical regression analysis, considering the recommended minimum sample size of 50 and normal distribution of error terms. The hierarchical multiple regression analysis consisted of three models: the first model included solely the control variables, the second model included also the technology acceptance factors (independent variables) and the third model included the interaction terms in order to test for a moderating effect of a particular HR system.

RESULTS

Descriptive Statistics, Consistencies and Correlations

We present the means, standard deviations and correlations for the variables of this study below in Table 3. We do not find evidence to suggest multicollinearity since the variance inflation factors are between 1.4 and 1.6 and thus far below the recommended threshold of 10 (Belsley, Kuh, & Welsch, 2005; O'brien, 2007). Furthermore, the correlations between the independent variables, with a maximum of 0.688, are under the recommended threshold of 0.75 (Ashford & Tsui, 1991).

Table 3. Means, Standard Deviations and Correlations.

	Mean	SD	1	2	3	4	5	6
1. Performance	3.28	0.87						
2. Trust	3.38	0.80	0.466**					
3. Effort	2.67	0.78	−0.435**	−0.628**				
4. Social support	3.67	0.63	0.363**	0.416**	−0.460**			
5. Organizational support	2.64	0.91	−0.361**	−0.532**	0.436**	−0.254**		
6. Computer anxiety	3.04	0.96	−0.567**	−0.688**	0.580**	−0.391**	0.596**	
7. Intention to collaborate	3.21	0.97	0.628**	0.651**	−0.590**	0.431**	−0.445**	−0.845**

Note: **Correlation is significant at the 0.01 level (2-tailed).

Measurement Models

To determine the best measurement model, four competing theoretically informed CFA models were estimated.

- *Model 1* tested our hypothesized measurement model. The model consists of six factors matching our six variables. Performance expectancy included three items, trust four items, two items were loading on effort expectancy, social support included three items, organizational support two items and four items were loading on computer anxiety.
- *Model 2* tested a five-factor model that was fitted to the dataset in which items that loaded on organizational support were fitted to load directly on effort expectancy. Other factors were modelled the same as in Model 1.
- *Model 3* tested another five-factor model, fitted to the dataset in which items that loaded on computer anxiety, were fitted to load directly on effort expectancy. Other factors were modelled the same as in Model 1.
- *Model 4* tested another five-factor model that was fitted to the dataset in which items that loaded on trust were fitted to load directly on computer anxiety. Other factors were modelled the same as in Model 1.

The model fit statistics can be found in Table 4 and indicate that our hypothesized measurement model, Model 1, fitted the data better ($\chi^2_{(120)}$ = 187.852; χ^2/df = 1.57; CFI = 0.91; TLI = 0.89; RMSEA = 0.07 [CI: 0.055–0.098]; RMR = 0.065) than any of the other competing measurement models. As such, Model 1 was retained for further analyses.

Table 4. Model Fit Comparison.

Model	$\chi 2$	df	$\chi 2$/df	CFI	TLI	RMSEA		RMR	Meets Criteria
						Value	CI [90%]		
Model 1	187.852	120	1.57	0.91	0.89	0.07	0.055–0.098	0.065	Yes
Model 2	210.854	125	1.69	0.89	0.87	0.09	0.65–0.105	0.068	No
Model 3	200.568	125	2.01	0.9	0.88	0.08	0.059–0.100	0.069	No
Model 4	200.242	125	1.6	0.9	0.83	0.08	0.58–0.100	0.07	No

ANOVA

We conducted ANOVA, which examined the difference in mean between the three different vignette groups. Table 5 shows the mean scores for Vignette 1 (M = 0.243), Vignette 2 (M = −0.078) and the neutral Vignette (M = −0.164). Table 6 shows that the scores for intention to collaborate are not significantly different for the three groups (p = 0.228).

Table 5. Mean Scores on Intention to Collaborate of the Different Groups.

Descriptives	*N*	Mean	Std. Deviation
Productivity HR system	32	3.44	0.9142
Collaborative HR system	32	3.14	0.8834
Neutral	32	3.05	1.081
Total	96	3.21	0.9687

Note: Dependent Variable: Intention to collaborate. Vignette 1: Productivity HR System; Vignette 2: Collaborative HR System.

Table 6. ANOVA.

Intention to Collaborate	Sum of Squares	Df	Mean Square	*F*	Sig.
Between groups	3	2	1.485	1.501	0.228
Within groups	92	93	0.990		
Total	95	95			

Multiple Hierarchical Regression Analysis

In Table 7 the results of the multiple hierarchical regression analysis are presented. Model 1 includes the control variables. Model 2 additionally includes the technology acceptance factors to test the first six hypotheses. Model 3 further includes the moderators (vignettes) and Model 4 additionally includes the interaction effects in order to determine whether there is a moderating effect of the type of HR system on the relationship between the independent and dependent variables.

Model 1 shows that gender has a significant negative effect on intention to collaborate (ß = −0.50, p = 0.030), although this significance disappears in models 2, 3 and 4. Model 2 presents that three out of the six technology acceptance factors have significant effects on intention to collaborate, which are performance expectancy (ß = 0.18, p = 0.008), organizational support (ß = 0.15, p = 0.027) and computer anxiety (ß = −0.68, $p < 0.001$). Trust (ß = 0.06, p = 0.395), effort expectancy (ß = −0.10, p = 0.161) and social support (ß = 0.06, p = 0.314) do not have significant effects on intention to collaborate. Therefore, we accept hypothesis 1, 5 and 6, performance expectancy, organizational support and computer anxiety significantly affect the users' intention to collaborate with the robot. Moreover, we reject hypothesis 2,3 and 4, the effect of trust, effort expectancy and social support on intention to collaborate is not significant. Model 3 further includes the vignettes as predictors and shows that there is no significant effect of vignette 1 (ß = 0.2, p = 0.131) and vignette 2 (ß = 0.09, p = 0.196) on intention to collaborate. Model 4 tested the

Table 7. Results of the Multiple Hierarchical Regression Analysis.

Intention to Collaborate Predictor variables	Model 1	Model 2	Model 3	Model 4
Gender	−0.50*	−0.15	−0.12	−0.13
Age	−0.06	−0.03	−0.03	−0.05
Highest education	0.12	0.01	0.01	−0.02
Performance expectancy		0.18**	0.18	0.4**
Trust		0.06	0.07	−0.03
Effort expectancy		−0.10	−0.10	−0.29*
Social support		0.06	0.06	−0.1
Organizational support		0.14*	0.15*	0.33*
Computer anxiety		−0.68**	−0.68**	−0.73**
Productivity HR system			0.2	0.17
Collaborative HR system			0.09	0.09
Performance × productivity HR system				−0.25
Performance × collaborative HR system				−0.15
Trust × productivity HR system				0.11
Trust × collaborative HR system				0.15
Effort × productivity HR system				0.26
Effort × collaborative HR system				0.16
Social support × productivity HR system				0.11
Social support × collaborative HR system				0.12
Organizational support × productivity HR system				−0.23
Organizational support × collaborative HR system				−0.13
Computer anxiety × productivity HR system				−0.01
Computer anxiety × collaborative HR system				0.07
R^2	0.1	0.78	0.78	0.81
R^2 Change	0.1	0.67	0.01	0.03

Note: Dependent Variable: Intention to collaborate. Vignette 1: Productivity HR System; Vignette2: Collaborative HR System. Confidence level: *≤ 0.05, **≤ 0.01.

moderation hypotheses for which we additionally included interaction terms between the technology acceptance factors and the productivity-based – and collaborative HR system. The neutral vignette serves as reference category in this regression model and is therefore not included. The analysis shows no significant interaction effects. Therefore, we have to reject hypothesis 7 and 8 since the effect of the productivity-based HR system as well as the effect of the collaborative HR system on the relationship between the technology acceptance factors and employees' intention to collaborate is neither significant nor negative/positive as we suggested. Worth mentioning is the significant change in the *R*-Squared from Model 1 to Model 2 ($R^2 = 0.78$, $p < 0.001$). From Model 2 to Model 3, we do not find a significant change in *R*-Squared ($R^2 = 0.78$, $p = 0.265$); this is also the case from Model 3 to Model 4 ($R^2 = 0.81$, $p = 0.516$). Our final Model achieves an *R*-Squared value of 0.8., thus 80% of the variance in the dependent variable is predictable from our technology acceptance factors. Due to the significant *R*-Squared change value in Model 2, we will use Model 2 as our results and as input for the discussion.

DISCUSSION

We found that performance expectancy, organizational support and computer anxiety have a significant effect on the people's intention to collaborate with a social robot. Performance expectancy has a significant positive effect on the users' intention to collaborate with the robot; supporting Davis (1989) in that perceived usefulness is significantly correlated with self-reported indicants of using the technology. Most participants expect the robot to be relatively useful in their job and that it would make tasks easier. We underline the claim by Davis (1989), who stated that acceptance and valuation of a technology increases in case it enhances daily life. Second, organizational support significantly affects the users' intention to collaborate with the robot, meaning that in case individuals believe that the organization itself and the infrastructure support the use of the technology, the intention to collaborate with a robot increases (Venkatesh et al., 2003). Support by the institution or organization is therefore a significant important construct. Next, computer anxiety shows a significant negative effect on users' intention to collaborate. Computer anxiety is also referred to as the individual emotional state of a user and we found that this state affects whether individuals intend to collaborate with a robot. We would like to point out that computer anxiety is very much determined by computer skills, while referring to the global skills gap showing the ever-increasing demand for such technology-focused skills (Bughin et al., 2018). Our results correspond with earlier findings that showed significant negative effects of computer anxiety on attitudes and user behaviour (Park et al., 2014; Venkatesh, 2000). Finally, half of the participants agreed that they would collaborate with the robot eventually showing that the participants in our study do not fully support the use of smart technologies in team settings.

In our analysis, we also tested whether the presence of a particular HR system would moderate the relationship between the technology acceptance factors and users' intention to collaborate. We found that the presence of a particular HR system does not have a significant effect on the relationship between the technology acceptance factors and intention to collaborate.

Theoretical Implications for Human Resource Management

This study has theoretical implications for HRM in the smart industry context. Our results show that three technology acceptance factors are significantly important in order to increase the users' intention to collaborate with the robot; performance expectancy, organizational support and computer anxiety. With this, we can reinforce earlier findings (Davis, 1989; Venkatesh et al., 2003) and partly expand the theories on technology acceptance since individual factors show relevance in the context of collaboration between smart technologies and the human workforce.

In the transformation process towards human resource management in smart industry, companies need to take on a strategic approach. Intellectual capital and intellectual capital management are key in order to ensure competitive advantage (Stachová et al., 2019). Thus, HRM needs to focus on human capital, thus their employees, relationship capital with regards to external partner and structural capital in terms of organizational processes (Stachová et al., 2019).

In order to sustain human capital on a long-term basis, organizations must educate and engage their human capital early. We like to reiterate Knod et al. (1984) in it is important for HRM to adopt a proactive stance by including the user, who has to work together with the robot eventually, as early as possible. Education must not only include actual (on-the-job) training but also educating on general facts and features regarding the smart technology. Usefulness and performance of the smart technology must be perceived from the beginning in order for adoption and acceptance. Education and early involvement also serve in terms of a feeling of control and safety, which strengthens empowerment (Libert et al., 2020). Education in terms of technological skill development can further mitigate computer anxiety. In order to strengthen the users' awareness and broaden and deepen their skill set, training possibilities represent an important feature in HRC (Knod et al., 1984; Libert et al., 2020). Training can mitigate stress which affects the workers' health and satisfaction and eventually turnover (Libert et al., 2020).

In order to ensure successful long-term HRC, support by the HRM cannot stop after training and education but must consider relational capital. This includes sustainable learning and sustainable employee development. The involvement of partnerships with external parties, like educational institutions, is important in order to bring new knowledge to the internal environment. These intentional inflows and outflows of knowledge help to accelerate internal innovations (Stachová et al., 2019). Moreover, in order to strengthen the relationship to employees, incentives and other methods like performance assessment prove to be useful methods in empowerment and commitment (Jaworski et al., 2018).

Support from HRM can be directly linked to increased employee performance (Lee & Bruvold, 2003). Structural capital includes organizational processes, policies and culture. HRM contributes to enhancement of structural capital by providing space, support and security when it comes to novel HRC. A culture that values self-efficacy further enhances perceived support and work engagement as well as satisfaction and commitment (Caesens & Stinglhamber, 2014). Thus, in order for users to adopt to technologies and to effectively work together on a long-term basis, a combination of preparation (including training and education), empowerment and incentives is needed (Libert et al., 2020).

We contribute to the literature on HRM systems, by integrating different HRM systems as moderator variables in our study. In contradiction to Lepak and Snell (2002), we did not empirically find that these HRM systems are positively related to HRC. We argue that besides a fitting HR system, HRM must go through an overarching additional change process in order to successfully manage humans in HRC. Furthermore, we argue that the relation between particular HRM systems and their practices should be studied further.

Practical Implications for Human Resource Management

We found that technology acceptance models are applicable to study HRC. We believe that intention to collaborate, and in turn HRC, can be enhanced when keeping the significant technology acceptance factors in mind. For managers, these models can provide direction for effectively managing the human factor in HRC. The expected performance of the robot is important to perceive by the employees in order to strengthen their intention to collaborate in hybrid teams. Providing employees with detailed information on opportunities and drawbacks the technology brings can thus strengthen their intention to collaborate. Further, not just internal education but also collaboration with external educational institutions in order to bring new knowledge inside the company enhances HRC. HR managers can support intention to collaborate by providing the necessary environment, including infrastructure but also support and a fitting company mission. Lastly, HR managers can enhance collaboration in hybrid teams by being aware of employees' anxiety related to new technologies. Anxiety affects the intention to collaborate, thus support in skills development and efficient selection of fitting employees for hybrid teams can strengthen effective HRC. Although in our study, the interaction between acceptance factors and HR systems is limited, we consider a fitting HR system as important for effective HRM. We suggest that for effective HRC, intention to collaborate is decisive and intention can be strengthened by high expected performance, high organizational support and low anxiety. These factors in combination with a fitting HR system contribute to effective HRC.

Limitations and Suggestions for Research

An important limitation is the use of self-reported data in this vignette study, which bears the risk of self-reporting biases. Further research could address this issue by adopting a qualitative research method like interviews or observations in order to avoid these biases. Furthermore, the vignette was built by written descriptions of different HR systems. Respondents had to use their imagination in order to put themselves into the described scenario. We did not use a manipulation check in order to see whether participants actually experienced the manipulation; therefore, we cannot be completely sure that they were actually fully aware of the introduced HR system. In studying effective HRC, we also find a limitation regarding our sample. We aimed for a balance in gender, but it turned out that 69% of respondents were female while 31% were male. Next to that, we experienced that most participants were either of German or Dutch nationality. Further research could address this by distributing the survey randomly and evenly. While we examined which factors affect HRC, the role of the HR system and the implications for HRM, further research could investigate explicit methods and procedures for managing HRC in the smart industry.

CONCLUSION

Managing employees in the smart industry is a topic of interest for researchers as well as managers. Previous research generally focused on changes related to HRM processes (Hecklau et al., 2016; Liboni, Cezarino, Jabbour, Oliveira, & Stefanelli, 2019; Sivathanu & Pillai, 2018) rather than management of effective HRC in hybrid teams. Seeking to fill this gap in the human resource literature, this study aimed to examine factors affecting HRC when certain HR system is in place. Our findings show that performance expectancy, organizational support and computer anxiety significantly affect people's intention to collaborate with a social robot. We demonstrate the importance of the technology acceptance factors and a fitting HR system in firms. Based on our findings and support by Hecklau et al. (2016), who argue that in smart industry there are three main areas of HRM development: personal development, team development (collaboration) and organizational development, we emphasize that HRM matters in effective HRC in smart industry settings. We provided recommendations to HRM in terms of provision of comprehensive preparation, including training and education, empowerment and incentives in order to support HRC in hybrid teams.

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APPENDIX 1

Measurement Items per Construct[a]

Construct	Items
Independent variables	
Performance expectancy	I believe that I would find the robot useful in my job
	I believe that using the robot would make it easier to do my job
	I believe that using the robot would improve my job performance
Trust	I believe the robot is reliable
	I believe the robot would perform as instructed
	I believe working with the robot is not dangerous
	I believe I would be relaxed and calm when working with the robot
Effort expectancy	I believe it is easy to learn how the robot works
	I believe it is easy to work together with the robot
	I believe interaction with the robot is clear and understandable
Social support	I believe my team would expect me to work with the robot
	I believe my teammates would be happy if I work with the robot
	I believe support of the management in working with the robot would be important to me
Organizational support	I believe guidance and instruction is necessary to work with the robot
	I believe assistance in using the robot would be useful
	I believe I have the skills and knowledge necessary to work with the robot
	I believe I would be able to control the robot
Computer anxiety	I believe I would not have concerns about using the robot
	I believe a robot would not scare me at all
	I believe I would feel comfortable when working with the robot
	I believe I would not hesitate to use the robot
Dependent variable	
Intention to collaborate	I believe working with the robot is a good idea
	I believe I would collaborate with the robot
	I believe I would like working with the robot

[a]The grey measurement items were later excluded due to low construct loading and low reliability. All survey items were judged on a five-point Likert scale.

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ACCESSING AND INTEGRATING DISTANT CAPABILITIES IN SMART INDUSTRY PROJECTS

Ednilson Bernardes and Hervé Legenvre

ABSTRACT

Smart industry initiatives focus on intelligent and interconnected cyber-physical systems. These initiatives develop complex technical architectures that integrate heterogenous technologies, causing significant organizational complexity. Tapping into the digital capabilities of distant partners while capturing profit from such innovation is demanding. Furthermore, firms often need to establish and orchestrate inter-organizational collaborations without prior relations or established trust. As a result, smart industry initiatives bring together disparate organizational forms and institutional environments, distinctive knowledge bases, and geographically dispersed organizations. We conceptualize this organizational capability as 'distant capabilities integration'. This research explores the governance mechanisms that support such integration and their relation to value capture. We analyse 11 IoT case studies organized in three categories (process, product and technologies) of smart industry initiatives. Building on existing literature, we consider different ways to describe distance, including knowledge heterogeneity and organizational, geographical, institutional, cultural and cognitive distance. Finally, we describe the governance mode appropriate for upstream (developing foundational technologies) and downstream (leveraging existing distant technologies) smart industry initiatives.

Keywords: Smart industry; distant capabilities; digital transformation; proximity; ecosystem collaboration; innovation

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INTRODUCTION

Discussions, implementation efforts, and business initiatives on smart industries have intensified over the last decade. Smart industry initiatives involve intelligent and interconnected cyber-physical systems, digitization, and connectivity (Kagermann, Wahlster, & Helbig, 2013). They leverage the Internet of Things (IoT), a powerful suite of technologies and processes that enable tracking and counting, observing and identifying, evaluating and acting, analysing, and predicting in ways not previously possible.

In this chapter, we investigate both upstream and downstream smart industry initiatives. Downstream smart industry initiatives combine the physical with the virtual world by assembling heterogeneous and distant technologies into a technical and business architecture that delivers and captures value. Upstream industry initiatives generate foundational technologies that combine and integrate diverse complementary applications into technical and business architectures.

Smart industry projects leverage technology architectures with significant complexity as they encompass heterogeneous hardware, software and telecommunication capabilities. This technical complexity creates organizational complexity as multiple and diverse organizations need to be effectively and efficiently integrated to generate successful initiatives. External organizational complexity can severely hamper the successful development and exploitation of dynamic capabilities (Teece, 2007) that sense, seize and transform emerging technology opportunities. Furthermore, navigating through such complexity can erode firms' ability to capture value from these initiatives (Teece, 2018). So far, we have a minimal understanding of how organizations integrate heterogeneous technologies to support smart industry initiatives and how they capture value within such a complex and emerging environment.

Smart industry digital capabilities often reside outside the organizational boundaries, and firms need to identify and meld them (Chesbrough & Crowther, 2006; Gualandris, Legenvre, & Kalchschmidt, 2018; Pisano & Verganti, 2008). However, organizations often face geographical and organizational distances in searching for and connecting to those digital capabilities. While the geographical dimension captures the spatial distance between potential partners, the organizational distance is associated with firms' closeness regarding the extent to which they share the same relations space, reference and knowledge space, and institutional environment. Collectively, these dimensions capture the 'proximity' (or 'distance') between partners (Balland, Boschma, & Frenken, 2015; Boschma, 2005).

Tapping into the digital capabilities of distant partners and enabling the learning and innovation required for successful smart industry initiatives is demanding. Firms need to establish and orchestrate inter-organizational collaborations that bring together disparate organizational forms and institutional environments, with distinctive knowledge bases or geographically dispersed, sometimes without prior relations or established trust. We conceptualize such capacity as 'distant capabilities integration'.

While some projects may mobilize relatively simple relationships with familiar suppliers, innovation and value creation are increasingly organized around wider collaborative networks and ecosystems involving unfamiliar and distant partners (Jacobides, Cennamo, & Gawer, 2018). However, research and practice still lack an understanding of how these ecosystems and distinctive collaborative approaches combine heterogeneous and distant capabilities to produce more transformative innovation and value.

We explore the nature and functioning of the inter-organizational governance mechanism underpinning an increasing number of smart industry initiatives. Additionally, we consider the nature and position of the technology within the broader set of technologies and the selected governance mechanisms and their relation to value capture. We analyse various IoT case studies supportive of three major categories of smart industry initiatives. Building on existing literature, we consider different ways to describe distance, including knowledge heterogeneity and organizational, geographical, institutional, cultural and cognitive distance. Some cases focus on downstream initiatives that integrate multiple distant technologies and maximize the value captured from these projects. Other cases consider upstream initiatives that develop enabling technology that is deployed in downstream initiatives.

We organize the remaining chapter as follows. First, we briefly provide the conceptual underpinnings supporting our efforts. Next, we describe the study's methodology. We then report the cases and their analysis and the cross-case analysis. Finally, we synthesize the findings and briefly conclude.

THEORETICAL BACKGROUND

In this section, we lay down the conceptual basis of the study by briefly describing some of the foundational technologies commonly supporting smart industry projects and then briefly discussing the notion of proximity and its dimensions and relating it to knowledge search and governance.

SMART INDUSTRY LAYERS

This section outlines some of the foundational technologies encountered across a wide diversity of smart industry applications while highlighting the complexity of such broad-scale technical artifacts.

Smart industry projects bring together hardware, software, machines and humans. They orchestrate complex interactions, continuous data exchanges and multiple information processing capabilities; they integrate a wide array of technologies within complex architectures. Such architectures define interfaces and prescribe how heterogeneous technologies and distant capabilities interact together. Furthermore, these architectures evolve and expand over time, sometimes incorporating newer technological developments and approaches. Therefore, integration and interoperability are front and centre as they are crucial for full-system effective operations. Finally, different architectures offer different degrees of interoperability, adaptability, manageability and performance.

ARCHITECTURES ARE STRUCTURED AS LAYERS

Multiple 'reference' architectures have described the foundations of smart industries. Many of them come from IoT platform providers. Academia and industry have produced dedicated books and glossaries attempting to organize our understanding of these architectures. In addition, there is an abundance of standards-setting groups offering perspectives on ascertaining interoperability (Cheruvu, Kumar, Smith, & Wheeler, 2020). For example, Sinha, Bernardes, Calderon, and Wuest (2020) refer to the architecture as a multi-layer digital stack. Ancarani, Di Mauro, Legenvre, and Cardella (2019) describe four smart industries layers.

The first layer is the sensing layer, where assets, objects and devices acquire and transform data thanks to sensors, actuators, processors and other hardware. The second layer is the communication layer supporting the transfer of data using diverse network technologies. The third layer is the software layer, where multiple sources of data are stored, combined and transformed. The fourth layer is the application/service layer, housing services and value creation.

Notwithstanding such efforts, describing the architecture and the enabling technologies of smart industry applications remains a challenging exercise with inevitable limitations. Below, we outline some of the foundational technologies commonly found across a wide diversity of smart industry applications. While not an exhaustive list, it provides context for the complexity involved. This outline of technologies includes the following:

- Hardware technologies (e.g., sensors and processors).
- Network technologies (part of the communication layer).
- IoT platforms (within the applications/service layer).
- Edge computing (processing closer to the original data).

This heterogeneity of technology and the inherent integration difficulties challenge developers and researchers (Vogel, Dong, Emruli, Davidsson, & Spalazzese, 2020). And within organizations, leaders who need to select solutions or commercialize their technologies face many technological approaches and decisions (Firouzi, Farahani, Weinberger, DePace, & Aliee, 2020). They need to meld these technologies while capturing value successfully.

PROXIMITY, SEARCH, COLLABORATION AND GOVERNANCE

The dynamic capabilities literature suggests that a technical and business architecture's capacity to generate superior value will rely more heavily on the organizational actor's combinative capability (Kogut & Zander, 1992; Teece, Pisano, & Shuen, 1997). Those capabilities manifest when organizations move beyond local search and reconfigure knowledge bases through cross-organizational boundary recombination (Zander & Kogut, 1995). Firms may seek partners inside the local area in some instances and search for partners outside the local area in some other cases (Hanse, 2014). Therefore, knowledge linkages and proximity and distance are essential considerations.

PROXIMITY DIMENSIONS

The proximity between partners' attributes is crucial for coordinating economic activities (Bouba-Olga & Grossetti, 2008; Carrincazeaux et al., 2008). Internal or external collaborative partners' proximity in different dimensions facilitates knowledge creation and transfer, communication of strategic information, resolution of conflict, and, ultimately, successful innovation projects, such as smart industry initiatives (Boschma, Balland, & de Vaan, 2014; Hautala, 2011; Heringa, Horlings, van der Zouwen, van den Besselaar, & van Vierssen, 2014).

Boschma (2005) proposes a framework with five dimensions of proximity and argues that the interplay between them profoundly influences interactive innovation processes. In other words, differences across them characterize inter-organizational collaborations. Proximity along each of these dimensions facilitates interaction and reduces coordination costs, as differences across actors' characteristics can make understanding each other

Table 1. Dimensions of Proximity.

Cognitive proximity	Similarity in knowledge bases, technical domain, or product specialization.
Organizational proximity	Shared ownership, or whether partners belong to the same legal entity or are of the same organizational form or have previously established relationship.
Social proximity	The strength of social ties or personal relations across project teams.
Geographic proximity	Differences in the physical distance between actors.
Institutional proximity	Shared informal (e.g., norms and habits) and formal norms (e.g., rules and laws, culture, institutions, established practices, and routines).

challenging (Nooteboom, Van Haverbeke, Duysters, Gilsing, & Van den Oord, 2007). Table 1 displays the dimensions.

Collectively, these dimensions capture the 'proximity' (or 'distance') between partners (Balland et al., 2015; Boschma, 2005). We conceptualize the capacity to develop and orchestrate inter-organizational collaborations that bring together such disparate organizational forms and institutional environments, sometimes without prior relations, and established trust, with distinctive knowledge bases or being geographically dispersed as 'distant capabilities integration'.

PROXIMITY DIMENSIONS AND KNOWLEDGE SEARCH

Hansen (2014) contributes to the proximity research perspective by seeking to understand partner search criteria along proximity dimensions in collaborative innovation projects. He proposed that different qualities are associated with being proximate or distant that may facilitate or impede collaboration. Hansen further posits that the importance of those qualities may vary depending on the motive for collaborating.

These insights signify that proximity and distance will likely have different significance according to other collaborative reasons, technological layers involved and types of smart industry projects. It becomes essential, then, to analyse the importance of different dimensions of proximity according to different collaborative motives and project scope to identify the types of smart industry initiatives where proximity dimensions are essential and how organizations bridge the difference.

PROXIMITY, COLLABORATION AND GOVERNANCE

Past literature suggests that proximity dimensions drive managerial decisions and affect the success of collaborative approaches to innovation (e.g., Rallet & Torre, 2001). Proximity and distance appear as a frequent feature of decision-makers' partnering decisions, as different motivational contingencies require diverse partners at varying distances. Partner proximity can drive success in complex projects, but not all proximity dimensions will play the same vital role all the time.

For instance, Hansen (2014) remarked that the knowledge that various partners may bring to a project might be highly diverse, resulting in weak cognitive proximity. However, he notes that past research on proximity shows that specific dimensions can substitute for others. Indeed, past studies found that one dimension of proximity could replace another (e.g., Balland, 2012; Ponds, Van Oort, & Frenken, 2007). Thus, proximity along one dimension can help partners avoid or overcome their differences on another dimension.

Table 2. Main Traits of Different Types of Relationships.

Arm's Length	Collaborative Relationships	Strategic Collaborations	Ecosystems Relationships
Buyer–supplier relationships	Buyer–supplier relationships	Complementary partners	Heterogeneous complementary partners
Short-term, low involvement, precise specifications, no sharing of information, no or little trust, few mechanisms to promote joint work, interactions primarily focused on the exchange of purchase orders and invoices	Medium- to long-term projects, selective information sharing, increased trust, ongoing relationship, somewhat precise specifications, little to some shared risk, planning, investment, and reward, standard contracts	Long-term relationship, full information sharing, extensive trust, extensively shared vision, investment, risk, planning, and reward, less clearly specified and more exploratory contract terms, often some exclusivity	Long-term relationships, information and knowledge sharing, shared vision, shared investment, joint development, joint promotion, shared projects and rewards

Additionally, substitution and overlap effects can benefit smart industry collaboration, as the proximity of diverse partners involved can be weaker in some dimensions than others.

Different governance modes can smooth the coordination of activities that exhibit different proximity dimensions. Each proximity dimension has traits that may facilitate or impede success in collaboration and may vary in importance depending on the motives driving the partnership. Besides the proximity aspect in searching for partners, organizations also need to structure the relationship. Table 2 summarizes and adapts the governance and inter-firm relationship literature for our study; we outline how organizations may structure relationships with smart industry initiative partners. If we see these categories as a continuum, as firms move left to the right, they increasingly search for counterparts with whom they can develop a deeper and broader interaction and rely on fewer transactional contracts that contain fewer clearly defined specifications (Cohen & Agrawal, 1996; Fawcett, Ellram, Fugate, Kannan, & Bernardes, 2020).

The first three categories of strategies and ways of structuring relationships with counterparts represented above are traditional and involve identifiable partners in the sense that the focal organization knows who they deal with, as contracts are in place and the work to be done has been specified. However, we have recently witnessed a growing trend towards alternative strategies, such as open-source foundations and technology alliances that can be described as ecosystems (Jacobides et al., 2018). Ecosystems combine heterogeneous but interdependent organizations to combine complementary capabilities aimed at innovation and value proposition realization and delivery.

RESEARCH METHODS

In this section, we describe the procedures and techniques we followed to achieve the study's goals. We present the research approach and context, case selection and data source, and analytical methods.

RESEARCH DESIGN

While smart industry initiatives increasingly pursue innovation and value creation through collaborative networks and ecosystems, research and practice still have an inadequate understanding of how these technological ecosystems and collaborative approaches combine heterogeneous and distant capabilities to produce more transformative innovation and value. In addition, those issues are complex, dynamic and evolving. Therefore, we used an exploratory multicase approach as the research design.

Eisenhardt, Graebner, and Sonenshein (2016) noted the usefulness and crucial role that case studies play in studying innovation processes. As the concept of distant capabilities integration is at very early stages of development, we chose an exploratory multiple case study research design (Yin, 2009), which allows for theory-building through an empirical enquiry of a complex phenomenon (Eisenhardt, 1989; Meredith, 1998). This research design was ideal for understanding the underlying mechanisms that integrate distant capabilities and the nature and functioning of the collaboration governance mechanisms involved in a broad array of smart industry projects.

The multicase exploratory approach enabled the collection of rich data from primary (e.g., interviews and observations) and secondary (e.g., internal reports and press releases) sources. It allowed us to explore similarities and differences across cases, identify patterns and subsequently generate insights (Barratt, Choi, & Li, 2011). We followed established methodological recommendations to ascertain rigour (confirmability, dependability, credibility and transferability) (Gioia, Corley, & Hamilton, 2013; Miles, Huberman, & Saldaña, 2018).

RESEARCH CONTEXT

The purpose of this exploratory multicase study was to advance our understanding of how organizations access and integrate distant capabilities for smart industry initiatives. Examining the link between firms' smart industry initiatives and their governance mode concerning complementary capabilities vis-à-vis value capture is managerially consequential.

Collaboration governance choice pertains to the search for, access of, and coordination of complementary capabilities provided by partners. The existing literature suggests that they can range from straightforward collaboration with familiar and existing suppliers to unfamiliar and distant partnerships with complex ecologies of heterogeneous organizations. Besides, the literature indicates that such initiatives' focus ranges from processes to products to enabling technology development.

According to the phenomenon's nature, the literature has distinguished innovation into two general categories, product innovation or process innovation (Abernathy & Utterback, 1978; Henderson & Clark, 1990). Product innovations are new or improved goods. Process innovations are new thinking about making products and services and can be technological or organizational. Finally, as product or process grow in complexity, architectural innovation defines how foundational technologies can be integrated as a system (Henderson & Clark, 1990).

In this typology, products and technological innovations are material, while the other classes are non-technological and intangible, such as organizational reimagining (Meeus & Edquist, 2006). We focus on material and technological innovations in this study. Thus, we used theoretical sampling (Eisenhardt, 1989; Eisenhardt & Graebner, 2007; Miles & Huberman, 1994) to select cases corresponding to each of those categories: product, process and foundational.

DATA SOURCES

We used several data sources, including semi-structured interviews with focal executives, informal follow-up interviews, and secondary data sources, including archival material. We conducted 32 interviews using a semi-structured protocol, ranging from 60 to 90 minutes with two to four respondents per smart industry initiative. We asked informants about their company's experience with IoT, the IoT project description, technologies project's evolution over time, partners involved and nature of the relationship, challenges to implementation, and outcomes.

We created a summary of each interview and submitted it to the interviewees for accuracy and their thoughts and reactions. Some projects spanned multiple years, so we conducted interviews at different points to understand the initiative's evolution. We used secondary data to triangulate information from the primary data sources.

DATA ANALYSIS

Our unit of analysis was the smart industry initiative in each case study. The investigation involved an iterative approach of systematically combining theoretical concepts with field data (Dubois & Gadde, 2002; Saunders, Lewis, & Thornhill, 2009). Such strategy allows the researcher to cross-fertilize and develop new combinations of constructs through an iterative synthesis of existing theoretical concepts and new concepts emerging from the empirical reality (Kovács & Spens, 2005).

We follow that inductive process to derive insights and our framework. We conducted within-case analyses focusing on the smart industry initiatives' salient characteristics, heterogeneity and distance involved, and inter-organizational governance issues. We prepared case study reports and submitted them for informants' review, a measure recommended to improve credibility and truthfulness in case study research. Next, we carried out a cross-case analysis to identify similarities and differences across the three categories of projects and highlight any emerging patterns.

WITHIN-CASE ANALYSIS

This section summarizes our findings for three categories of smart industry cases, encompassing product, process, and foundation technology. First, we engaged in a sense-making process to identify the initiatives' value capture proposition within each category and its position within the technological architecture. Then, we cross-referenced each project's characteristics and scope with the literature on distance and technological heterogeneity to typify and describe them. Finally, we examined the inter-organizational activities' governance. The within-case analysis produced a concise description of the organizational and technical characteristics of each smart industry project.

SMART INDUSTRY INITIATIVES FOCUSED ON PROCESS

The first category projects encompassed a smart production process, smart maintenance of cranes, smart tracking of waste containers, and smart maintenance of production equipment. Table 3 presents a brief descriptive summary of the cases in this category. While not precisely equal, closeness was the preponderant norm in searching for and selecting a

Table 3. Cases on Smart Industry Initiatives Focused on Process.

Organization	Automotive Supplier	Steel Manufacturer	Waste Management Company	Cosmetic Producer
Project	Smart production process	Smart maintenance of cranes	Tracking waste containers	Smart maintenance of production equipment
Partners involved	Current equipment manufacturer and local specialist supplier	Current equipment manufacturer	A start-up that delivers the hardware	Office of current local telecom solutions provider
Technological integration	Performed by the automotive supplier with the support of the specialist supplier	Performed by the equipment manufacturer	Performed by the start-up	Performed by the telecom supplier

partner for the cases in this category. The focal organizations primarily worked with local suppliers with whom they already had some familiarity and used standard transactional contracts to manage the partnership relation.

The *first application* in this category aims to improve a factory's internal manufacturing process by aggregating different data sources within a central database to highlight production issues. Examples include equipment availability or breakdown and output quality issues. Production equipment generates rich data streams using sensors. The supervisory control and data acquisition (SCADA) systems transmit the data to the central database, where a business intelligence tool is used to perform analysis. The production equipment supplier provided the technology that captures and transmits data. Therefore, the project required developing a database and using software capable of handling the large data volume. An informant's statement captures the need to access external knowledge, its nature, and the decision's rationale:

> Today we need to invest, on top of the database, into a software that can help make things easier to work with the data. We want a low code solution, and we try to limit the number of layers of systems we use. We used a specialist company to work on our choice of database technology, and they also helped us on a specific machine connection to gain some speed.

In this project, the most pressing issue in ascertaining value capture consisted of aligning performance across the different layers, so data are effectively produced, stored and analysed. They used an existing IT supplier through a collaborative partnership to access the required capabilities and technology.

The *second initiative* in this category sought to enhance the maintenance process for cranes used in a steel manufacturing environment. This application sought to increase the efficiency of the equipment and transform fixed cost into a variable cost. Instead of incurring fixed costs by making capital investments in the machine, parts, maintenance programme, etc., the organization started paying per use of the equipment (time the cranes operate and weight they carry). The equipment produces and transmits data to the cranes' manufacturer, which uses it to perform predictive maintenance. The crane's manufacturer has integrated the necessary technologies within the cranes and had already worked on such projects with other organizations. The project led to a change in the pricing model, and the supplier now performs maintenance as a service based on the weight moved, the time required to complete the work, and the energy consumed. The steel manufacturer and the crane's supplier already had an established relationship. The most pressing issue in ascertaining value capture in this project required estimating the decision's financial implications. Access to the necessary capabilities and technology was achieved thanks to a standard collaborative partnership with a very familiar supplier.

The *third application* sought to track the location of thousands of waste containers used by organizational customers such as in construction, mines, harbour, and industrial sites. This application sought to reduce the time spent searching for the containers, prevent losses, and reduce the number of containers purchased. It encompasses a piece of hardware with extended autonomy to signal the container's place, a network layer to transmit the signal information, and a software layer to manage the location. A start-up supplied a complete solution, including the hardware and the software platform.

The most pressing issue in ascertaining value capture in this project was selecting tracking devices capable of satisfying stringent requirements, including quality, hardware ruggedness, and manufacturing scalability. The following informant's statement describes these aspects:

> The selection of the hardware provider needed to integrate some very stringent requirements in terms of ability to scale and deliver a large volume of defect-free hardware and they also needed to offer a robust piece of hardware that could sustain external shocks and tough environmental conditions.

The firm needed a partner able to deliver devices at a large scale (40,000 units). Besides, the devices must be highly reliable, as even a very low percentage faulty of the 40,000 devices in the field would cause huge logistical issues and costs. Thus, access to the required capabilities and technology was achieved through a collaborative partnership but involved an unfamiliar start-up partner, as no other option existed for the hardware.

Finally, the *fourth application* in this category sought to improve the maintenance of machines designed, produced, and used internally by a manufacturer across 11 global sites. When a piece of equipment in a given location presented problems, the organization needed to dispatch an expert. This project sought to enhance the maintenance process's efficiency, improve equipment availability, and reduce corporate maintenance experts' travel. The solution builds on augmented reality.

The supporting hardware, software and connectivity technologies are all off-the-shelf. The organization developed the solution in partnership with an existing IT provider's local office, which enhanced the software and integrated the different technologies required. One informant described the collaboration's nature as 'we provided clear requirement and scope to them. They could work from the start with the right use case, the right requirements, and to progress through iteration. We had a great cooperation'. Access to the required capabilities and technology was achieved through a standard collaborative partnership with a familiar local IT supplier who developed and integrated the solution.

SMART INDUSTRY INITIATIVE FOCUSED ON PRODUCT

The second category projects encompassed smart metering, smart pump capabilities, data services, and a smart consumer product. Table 4 presents a brief descriptive summary of the cases in this category. Again, while not precisely equal, some distance and heterogeneity were the preponderant norms in searching for and selecting a partner for the cases in this category. The focal organizations worked with one or multiple strategic and often somewhat distant suppliers with whom they could be unfamiliar and used more alliance-based contracts to manage the relationship.

Table 4. Cases on Smart Industry Initiatives Focused on Products.

Organization	Utility Company	Water Infrastructure Company	Motor Vehicle OEM	Tennis Equipment Manufacturer
Project	Smart metering and provision of data services	Better maintenance and provision of data services	Better customer service and provision of new data services	Complementary hardware and new data services
Partners involved	Alliance with two suppliers to setup a market standard	Supplier of a complementary technology to avoid lock-in with the core technology supplier	Collaboration with a university spinoff created for the project to avoid dependency on traditional suppliers	Partnership with a start-up
Technological integration	Performed through an ongoing collaboration encompassing development and commercial activities	Performed through a collaboration with the supplier	Performed as part of the collaboration between the OEM and the spinoff	Performed as part of the collaboration between the manufacturer and the start-up

The *first application* in this category sought to automate and increase the frequency and accuracy of metering data collection and creating additional services. The organization developed the software layer, an existing and familiar telecom provided the network and radio system to transfer the data, and a new supplier provided the meter expertise. The project entailed groundbreaking developments, as no off-the-shelf solution was available.

The idea was to develop an industry standard and new technology to sell in the open market. Access to the required knowledge and capabilities was through a strategic collaboration among the three organizations. The following informant's statement represents such governance outcomes: '*The value created benefits the three partners by creating a new technical standard on the market which led to differentiation*'. The engagement involved a more strategic collaboration and required co-investment, coordinated commercial strategy, periodic technology review and a royalty mechanism.

The *second application* in this category sought to control and maintain water infrastructure. This control system can be sold to the final clients or operated as a service for them. The organization developed the software layer and managed to access data through the supplier of electrical systems. This complementary technology provider allows the organization to bypass the water pump supplier, the core technology provider. The infrastructure moves the wastewater to a water treatment installation.

The most pressing issue in ascertaining value capture in this project was overcoming dependency on the water technology manufacturer, which favoured proprietary solutions that lock in clients. As water technology suppliers compete with their clients to sell installations to the final users, the competitive stakes were significant. The pump manufacturers can bypass their clients (utility companies) and offer an intelligent pump directly to clients with small installations (a large building like a hospital or a jail). So, to avoid dependency on suppliers who increasingly act as a competitor, they decided to capture data from the electric system and not the pump, hence developing a collaboration with the electric equipment supplier.

By implementing a solution where data are accessed from the electric system rather than from the water system, the organization could protect its competitive position. One informant described such dynamics in the following terms: 'It was important for our company to eliminate this dependency, to gain a better commercial position and some differentiation with the new solution'. The organization achieved that goal by strategically collaborating with the electrical system provider interested in generating more value out of this market.

The *third application* in this category sought to enhance customer service and provide additional data services for motor vehicle owners. The solution encompasses software and hardware on top of connectivity technologies. The organization's R&D expertise was in mechanical technology; it had a limited understanding of the project's diverse digital technologies. Initially, the organization co-developed a system with a supplier. However, the organization concluded that they would not secure exclusivity and the solution would become available to competitors. Therefore, it became necessary to ensure access to an alternative to ascertain value capture.

Developing the solution involved creating a spinoff organization from an academic institution to access the technology building blocks software, hardware and service. This strategic collaborative solution also allowed the organization to gain access to ongoing exploratory capabilities that provide a competitive advantage. The following informant's statement is indicative of the solution's outcome and the concerns with ascertaining value capture: 'We realized that working with them would be a great way to avoid supplier lock-in, to access solid technical expertise and funding opportunities for further research'.

The *fourth application* in this category sought to develop complementary wearable technology and online services that supplement tennis equipment. The hardware includes a sensor with a trained AI technology to interpret the sport's motion, and Bluetooth technology transmits data to the application layer. The project's outcomes allow players to observe their performance in real-time, monitor their evolution, and compare their performance to others.

The organization developed the solution through a strategic collaboration with a start-up, which was already developing connectivity solutions for other sports equipment manufacturers with exclusivity clauses in each sport. One informant described the value of complementarities, stating that 'as a company specializes in connected devices, you have an opportunity to build on complementary capabilities and to co-brand the connected device'. The start-up developed and integrated the technologies that were co-branded and sold by the tennis equipment manufacturer.

SMART INDUSTRY PROJECT FOCUSED ON FOUNDATIONAL TECHNOLOGY

The third category projects encompassed developing a low-power wide-area network (LPWAN), an open radio access network (RAN), and an open architecture for microprocessors. Table 5 presents a brief descriptive summary of the cases in this category. Distance, heterogeneity, and often scale were the prevailing norms in searching for and selecting needed partners for the cases in this category. As a result, there were often multiple organizations involved in an ecosystem sourcing relationship.

The first project in this category sought to provide technological foundations for multiple IoT applications across various sectors. This project is a connectivity solution that enables lower power consumption. Two organizations, one hardware and one software specialist, alongside a telecom partner representative, initiated an open, non-profit technology alliance (the LoRa Alliance) to standardize LPWAN, attracting over 500 members. The coalition supports and promotes the global adoption of the LoRaWAN standard by

Table 5. Cases on Smart Industry Initiatives Focused on Foundational Technologies.

Organization	IoT Platform Provider	Telecommunication Technology Provider	Electronic Firm
Project	Develop technologies supporting low-power wide-area networks	Develop an open radio access network	Develop a processor's instruction set architecture
Partners involved	Initiated by a hardware provider and an integrator and then supported by a technology alliance	A multi-firm collaboration conducted the pilot. The solutions were standardized and promoted through multiple ecosystems	Initiated by an academic institution turning into multiple ecosystems established around specific firms and foundations
Technological integration	A technology alliance addresses interoperability issues. Individual companies as an ecosystem of partners and suppliers contribute to integrate specific technologies for specific projects	A standard's body defined some standard interfaces. Integrators emerging from early adopters integrate specific implementations	One foundation ensures the integrity of the ISA and provides verification tools. Other ecosystems provide complementary technology or offer development platforms

ensuring all LoRaWAN products' and technologies' interoperability. Organizations now have their respective ecosystems of partners who provide multiple technologies needed to create specific IoT applications. We see extensive ecosystem sourcing collaborations taking place and characterizing this project.

The LORA alliance serves as a neutral, open ecosystem that brings together all companies interested in the technology. The following informant's statement captures the benefits of such governance:

> If we take the example of a smart city, instead of having one network for waste management activities, one for smart meters, one for the traffic light system, here you have only one. It started by attracting international players like Cisco and Schneider Electric, and then it allowed creating more local alliances for regional markets. This scheme is a great way to identify and integrate new partners.

Each solution encompasses heterogeneous sets of technologies delivered by the ecosystem partners. The hardware company ascertained value capture through proprietary technology, while the software partner contributed through a first-mover advantage in offering a complete LPWAN IoT platform.

The *second project* in this category sought to provide a technological foundation for 5G applications that enable smart industry initiatives. A network of organizations, including Facebook, telecommunications companies, start-ups, and technology suppliers, jointly piloted projects to deploy the first Open Radio Area Network (Open RAN) in areas where limited connectivity existed. This solution allows them to disaggregate the network and to mix and match different components from various suppliers. This organization creates more competitive solutions by reducing dependencies on an integrator.

The Telecom Infra Project (TIP), a foundation that brings together hundreds of companies to design, build and test advanced connectivity solutions, led the pilots. A more traditional industry-standard group, the O-RAN alliance, complemented the TIP ecosystem to establish Open RAN as a solid market contender. The Open RAN coalition is a lobby group that promotes policies favouring the adoption of Open RAN. The most pressing issue in terms of value capture was bringing together the various telecoms, hardware, and software vendors to design and promote the adoption of this new architecture. The following informant's statement captures the complexities and challenges involved: 'This was not a new problem within the telecommunication sector. We needed to create a new value chain with plug and play elements and to facilitate the introduction of new vendors that bring innovation and lower costs'.

The solution involved the establishment of complementary ecosystems with different goals over time. Again, a preponderance of ecosystem collaborations characterizes this project.

The *third project* in this category supports the design of processors dedicated to IoT applications. RISC-V is an open Instruction Set Architecture (ISA). Its openness and modularity allow the creation of domain-specific processors. Andes Technology's Chief Technology Officer describes how RISC-V allows integrating Artificial intelligence in IoT applications:

> For AIoT SoC development, RISC-V offers the advantage of a standard ISA that allows designers to create custom instructions for Domain-Specific Acceleration. This proposition provides a competitive advantage, product differentiation, and cost and power savings over alternative ISAs on the market.

A university started RISC-V and donated it to the RISC-V foundation, which brings together hundreds of companies who promote and advance the use of RISC-V.

Going from an ISA to a processor requires a broad array of heterogeneous capabilities to support the design, customization, testing and manufacturing of a processor based on the project. The following informant's statement captures the value creation benefits of such organization governance:

> If you just really wanted something off-the-shelf, then, of course, using something proprietary makes sense. But for innovative innovation developments, you are going to be able to collaborate more effectively. You are going to advance more quickly. The total cost of doing that will for sure lower.

The RISC-V foundations and complementary initiatives centred on RISC-V foster the development of those required capabilities.

CROSS-CASE ANALYSIS

In the cross-case analysis, we attempted to identify patterns across the various categories of initiatives. We outlined a set of factors and characteristics linked to smart industry projects during the within-case investigation. During the cross-case analysis, we organized those factors and features across the categories of smart industry initiatives. We transferred each element we identified for each project category from the original data displays to displays focused on a single construct.

This exercise allowed us to reposition the data from a case-by-case arrangement to a construct-by-construct scheme. Table 6 summarizes this information. We performed multiple iterations in the process of moving the data from case-based displays to construct-based displays. During this phase of the analysis, we sought out common patterns to draw insights and formulate conclusions.

We incorporated literature at this stage to compare and contrast our findings, essentially using the literature as an additional source of validation as advised by Eisenhardt (1989) and Kaufmann and Denk (2011). Comparing the projects reveals predominant patterns common across five dominant themes and case categories. These themes are the goals driving partner search, the organizational distance between partners, technological heterogeneity, partner selection decision criteria, and governance/coordination structuring partner relationships. While the specifics are not precisely equal for each category within

Table 6. Cross-Case Patterns Summary.

Project Focus	Predominant Partner Search Goal	Distance between Firms	Technological Heterogeneity	Partner Decision Criteria	Governance/ Coordination
Process	A partner who can integrate all required technologies most efficiently	Two close firms	Low	A close partner to minimize risks	Partnership
Product	A partner who can assist in integrating all required technologies and contribute towards the desired differentiation	Two or three distant firms	Low/medium	A partner, even if distant, that allows to control differentiation factors	Collaborative strategic development with close interaction and monitoring of the distant partner
Foundational technology	Partners who offer complementary technologies and market access	Multiple firms with heterogenous degrees of distance	Very high	Partners with complementary capabilities and access to market	Ecosystem collaboration involving promotion of a standard and interoperability

cases, they are congruent and would cluster around the same region on a potential continuum. Table 6 summarizes the patterns across the project categories and themes.

Partner Search Goal. The projects we sampled varied in the goals driving partner search considerably according to the project's focus.

Process-oriented smart industry projects present a relatively limited range in terms of value scope, mostly bounded internally, exploiting available technology, pursuing improvements, and ultimately improving efficiency. For instance, the third application in this category sought to reduce the time spent searching for containers, prevent losses, and reduce the number of boxes acquired. This application reveals a focus on reducing costs, improving operations, and increasing efficiencies in general. Correspondingly, our analysis shows that the goals driving partner search for this category mainly focused on identifying one able to integrate all required technology for the focal firm at the lowest price. This finding was familiar to the other cases in our sample in this category.

Product-focused smart industry initiatives exhibit a more ample reach than the previous class and some knowledge exploration activity – the focus shift towards the market to sell intelligent products. For instance, the fourth application in this category pursued developing a wristband, complementary hardware to the existing product, and additional online data services. Correspondingly, our analysis shows that the goals driving partner search for this category focused on finding a partner who could help the focal organization integrate all required technologies and contribute towards the desired product differentiation. Such a pattern was typical for the other cases in this category.

Foundational technology-focused initiatives display the farthest reach in terms of potential value capture, involving the development of enabling ground-laying technology potentially deployable in numerous applications as part of the solution. For instance, this category's first project has allowed users to assemble and sell the technological foundations

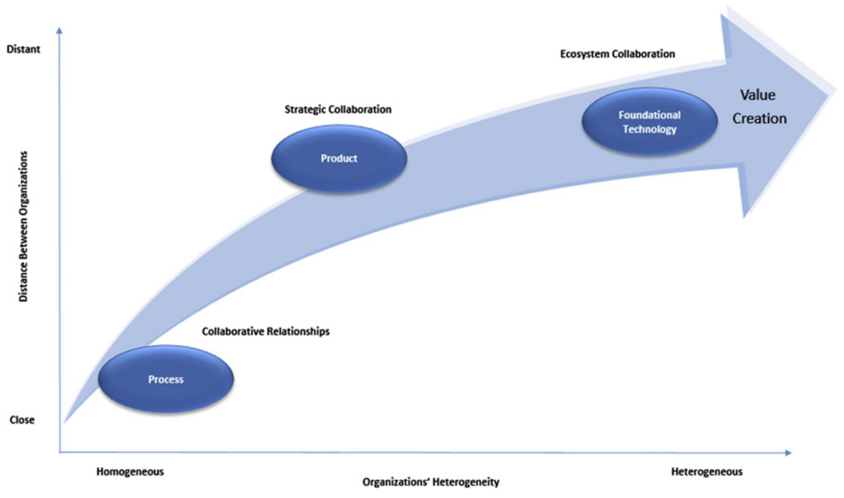

Fig. 1. Accessing and Integrating Capabilities in Smart Industry Initiatives.

for multiple tracking and monitoring solutions across various sectors. Our findings reveal that the goals driving partner search for this category focused on identifying those with complementary technologies and enabling market access. Table 6's second column shows the variation across the projects' bundles. Fig. 1 synthesizes the findings, and Figs. 2–5 provide additional details.

Distance (or Dimensions of Proximity). Here also, the projects we sampled exhibit a dominant pattern conforming to the project's focus. In general, *process-oriented* smart industry initiatives presented mostly limited knowledge distance, with projects predominantly exploiting or leveraging existing knowledge bases and exploiting technological competencies of the involved parts or those relatively easy to acquire on the market. For instance, this category's second project involved a supplier with experience implementing such projects with other clients and leveraging the focal organization's existing competencies. Furthermore, this category of projects also displayed a predominantly close organizational and institutional distance. The companies involved mainly showed the same corporate form or the same legal entity and operated under mostly similar norms. Finally, the physical distance among the participants was relatively close, involving mostly local or geographically proximate partners.

Product-focused smart Industry initiatives, in general, exhibited more distance regarding the knowledge, organizational and institutional dimensions, and sense of exploration. When knowledge and institutional distance were high, organizations tended to work with local or proximate partners. This distance relates to the company that contributes to integrating all required technologies for the project. For instance, the third case organization in this category focused its knowledge base and competence on mechanical technology. It had a limited understanding of the aspects encompassing user experience in a digital environment and little AI and software knowledge. The organization cooperated strategically with an academic institution (more distant organizational form) to advance the project and eventually created a spinoff. Similarly, the organization in the fourth application in this category cooperated with a start-up (more distant organizational and institutional form) to obtain multiple competencies.

Foundational technology-focused initiatives displayed the most significant distance as related to all dimensions. And this applies to relations across an assortment of partners who all contribute to developing solutions encompassing foundational technologies. For instance, the first application in this category required the combination of exceedingly heterogeneous knowledge bases and technologies and involved multiple technology providers, partners located across different countries, and numerous ecosystems. Table 6's fourth column shows the variation across the bundles of projects.

Technological heterogeneity. The projects we sampled exhibit a considerable amount of technological heterogeneity across the project's focus. In general, *process-oriented* smart industry initiatives presented less technical complexity than other initiatives. Organizations were accessing different technical competencies and skills restricted to engaging partners from diverse technological backgrounds to supply mostly packaged or off-the-shell existing solutions. Leveraging their existing knowledge base and infrastructure constituted a significant component of the implementation.

As organizations needed complementary technology unavailable in other parts of the organization to complete the solution's development and implementation, they usually sought partners with low cognitive proximity. However, those partners mainly were existing or familiar relations, close geographically. The range of technological layers addressed within the project was narrow. For instance, this category's first case leveraged the current SCADA system and the factory communication infrastructure and databases. The second case involved a partner already experienced in implementing the solution.

Product-focused smart industry initiatives exhibited scant to mostly medium technological heterogeneity. This category's projects required integrating and deploying existing components available either internally or through immediate partners, increasing the cognitive distance. For instance, partners' capabilities in the third and fourth cases enabled developing specialized software or hardware for specific needs and context.

Foundational technology-focused initiatives displayed high heterogeneity. They typically encompassed many layers, technologies, and applications that need to operate effectively together. They also involved the continuous development of new knowledge and solutions. For instance, this category's fourth case required the ongoing combination of knowledge bases and technology coming from organizations of very different sizes, geographic locations, and technical backgrounds. The result of those requirements is greater cognitive distance and technological heterogeneity.

Partner Decision Criteria. The projects we sampled exhibit a clear pattern in terms of the criteria for partner selection. *Process-oriented* smart industry initiatives are geared towards an integrated solution in a specific sector or geography and adopted by the organization that undertook the project. For instance, the fourth application in this category sought to improve the maintenance of machines designed and manufactured internally for their own use across global sites. We found that this category involved primarily identifying a close partner to minimize risks as the primary decision-making criteria.

Product-focused smart industry exhibits a similar integrated solution pattern still bounded to a specific sector or geography and sold to the organization's client who undertook the project. The first application in this category illustrates this pattern in the water-infrastructure control system market. Our findings indicate that this category mainly involved finding a partner, even a distant one when needed, which would allow maintaining control of factors contributing to differentiation as the primary decision-making criterion. The underlying motivation was ascertaining exclusivity.

The *foundational technology-focused* projects display a broader span by shifting towards applications across multiple sectors and geographies. Our analysis shows that partner decision-making criteria in this category are driven by identifying complementary capabilities that can form a complete solution and allow access to the market. Table 6's third column shows the variation across the bundles of projects.

Governance/Coordination. Finally, we also observed projects we sampled exhibit clear patterns in how they structured the relationships with partners conforming to the project's focus. In general, *process-oriented* smart industry initiatives tended towards partnership, where the organizational proximity enable trust. The leading firms seemed to typically reach out to local organizations already known to them before starting the project. For instance, the organization in the third case in this category engaged the local office of their telecom provider, which developed the necessary software and performed the technological integration. The other cases in this category displayed similar patterns.

Product-focused smart Industry projects tended towards strategic collaboration with more distant organizations, more structured cooperation agreements, and a deeper coordination level than the previous category. For instance, this category's first case involved a formal cooperation agreement encompassing co-investment, cost and profit-sharing mechanism, coordinated strategy royalty agreement, and periodic technological review. The following informant's statement captures the issue:

> When you go to, say a traditional supplier, it was more bargaining situation. It's a bit more complex, and then some suppliers are strong in hardware, but they are not as strong in software. Suppliers who were approaching maybe haven't shared completely the same vision we have.

The *foundational technology-focused* initiatives tended towards more sophisticated and non-traditional collaboration, ecosystems collaboration, which bring together distant partners and typically involve large scales. For instance, the third case on this category encompasses multiple ecosystems that interact, complement and support the original project. Start-ups that provide processor development services have their own ecosystems of partners for intellectual property, extensions and production. An ecosystem structured around a not-for-profit foundation offers global education and verification services. A group of companies orchestrates the development of complementary open technologies, and other ecosystems support the development of processor design capabilities in diverse countries. These ecosystems interact, and the assets and relationships criss-cross them. They illustrate the complexity and sophistication of the governance characteristic of this category. The multiplicity of ecosystems and the type of governance adopted enable the integration of a highly diverse set of organizations who have different agendas while sharing some common goals.

ANALYSIS AND DISCUSSION

Our analyses suggest that the scope of value creation and the partnership structure (search and selection criteria) needed to capture value correlate with organizational distance, technological heterogeneity and project focus. Distance and heterogeneity vary following the project focus, as do the goal for partner search and the criteria for selecting partners. As Fig. 1 summarizes, heterogeneity and distance increase as we move from process-focused projects to foundational technology-focused projects. Besides, heterogeneous sets of technologies correlate with the distance between the organizations and require more complex and sophisticated forms of governance and coordination. According to the smart industry project's focus, we can have more collaborative ties, strategic collaboration and development between relatively close and distant partners, or collaboration between heterogeneous partners within ecosystems. We next suggest the reasoning.

Process-oriented smart industry initiatives drive firms to find the most efficient way of gaining access and integrating a combination of new technologies. They do not seek exclusivity and true novelty. On the contrary, they tend to look for a reliable mix of available technology to deliver the expected outcome. Therefore, they go to the closest partner with the relevant capabilities to handle the technology heterogeneity. They can implement such an approach by selecting a company with which they have worked before and with which they share knowledge bases, social ties, norms, and even physical distance. On the other hand, suppose they search for partners with low levels of the various dimensions of proximity. In that case, they risk facing difficulties they will not be well placed to solve without investing significant time and energy in the relationship and the project itself.

Based on these findings, we conclude that if leadership teams are looking to exploit technology to improve the firm's processes and make them more efficient, this will likely be primarily an internally focused endeavour that involves partners as close as possible to them. Leaders do not have to seek access to distant capabilities systematically and, for the most part, do not need to worry about property rights or sophisticated coordination mechanisms. As suggested in Fig. 2, the decision should focus on partnership with local or known organizations to compensate for any cognitive distance required to bring in complementary knowledge bases and technology. Here, organizations can access needed knowledge through typical market mechanisms and look for the availability of familiar and proximate organizations to perform the integration, keeping the project as simple as possible.

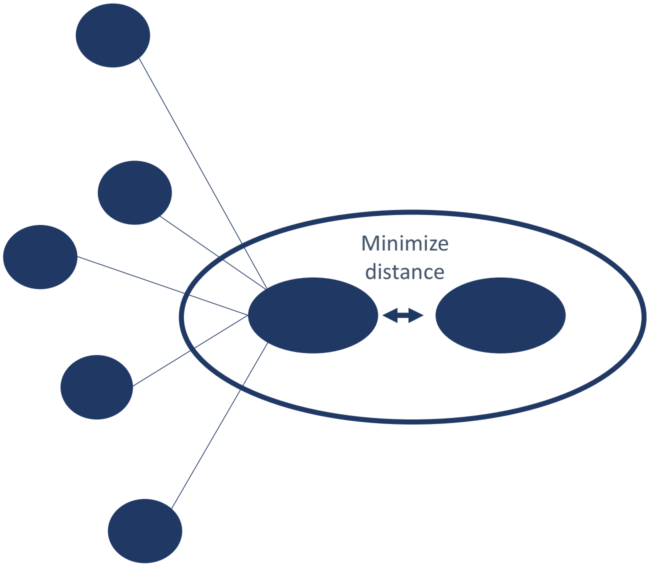

Fig. 2. Accessing and Integrating Capabilities in Process-Focused Smart Industry Initiatives.

Product-oriented smart industry initiatives face the challenge of producing something distinctive, not yet available in the market through competitors so that the organization can capture value from the initiative as a first mover. However, because the organization needs to design something distinctive to capture value through the market and some explorative capabilities, the decision will likely involve searching for a more distant partner, possibly an upstream player – see Fig. 5. Such effort will likely require managing a more structured and strategic collaboration with perhaps a single more distant organization. Formal development agreements will ascertain control of any intellectual property and the corresponding market benefits.

Firms need to ensure that they can derive a competitive advantage out of their offering. They need to ensure access to rare, hard to imitate, hard to substitute resources. This need explains why they establish partnerships with more distant partners. They need exclusive access to a combination of technologies that can help them deliver differentiation. Suppose they go to a close industry partner. In that case, it will be difficult for them to gain this exclusivity from a supplier that wants to serve the whole market and capture a large amount of value through proprietary solutions. A more distant partner can also allow access to emerging new technologies that can deliver a temporary advantage compared to the competition. The distance at stake here is knowledge (latest technology) and institutional distance (e.g., spinoff, start-up). However, the companies we studied sometimes tried to counterbalance these types of distance by establishing partnerships with geographically close partners.

Suppose the organization aspires to build a new digital service that needs to integrate new technologies. In that case, leaders should search for more distant partners when it gives the organization an advantage in building a competitive market offering and capturing its value. Indeed, keeping control becomes an important issue. The partner might be a start-up or might be unfamiliar with the industry. A crucial takeaway is that, while the contractual agreements may differ only slightly from the previous category of projects in some cases, the essential distinctive issue is the investment in social capital that

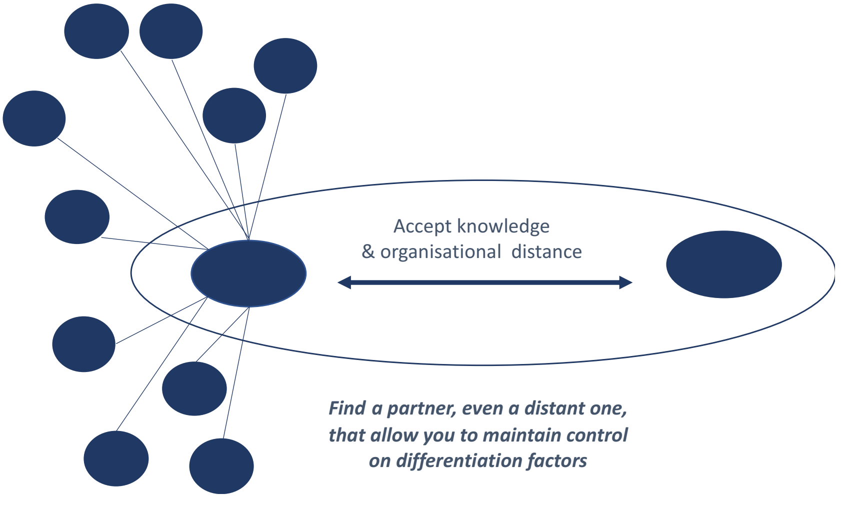

Fig. 3. Accessing and Integrating Capabilities in Product-Focused Smart Industry Initiatives.

starts from the very early stages of the project – and again, structuring the relation to ascertain control.

Foundation technology-oriented smart industry initiatives integrate ground-laying technologies in complex, multi-layered solutions. Selling technologies as part of more comprehensive solutions across multiple geographies and verticals generates value. These initiatives, therefore, involve high technological heterogeneity and distance across numerous dimensions. The solution is technologically advanced and innovative, so, as suggested by Fig. 4, the seller of foundational technologies must integrate a network of distant partners and possibly one or more complementary ecosystems to increase its ability to generate revenue.

These networks involve social structures that support the concurrent emergence and development of complex solutions and organizations. These ecosystems are developed around open standards, open architectures and open-source technologies. On the one hand, this increases the solutions' adoption and expands their potential markets. On the other hand, this can challenge the ability to capture value from foundational technologies that become more standard and open. As such, progress and value capture become dependent on the alignment and successful relationship and contribution among many participating organizations within the ecosystem. The development of such healthy and growing ecosystems enables adopting the foundational technologies in different sectors and geographies.

Out of the three initiative categories, heterogeneity mainly impacts the governance of foundational technologies. To develop a specific application, a company favours a partnership with a single or a small number of partners who have the necessary infrastructure to integrate the required foundation technologies. In contrast, an ecosystem is the best-suited governance form to handle foundational technologies diversity and complexity. Indeed, the ecosystem brings together a large group of firms that can perform joint development, ensure technology interoperability, and follow a standard. They also

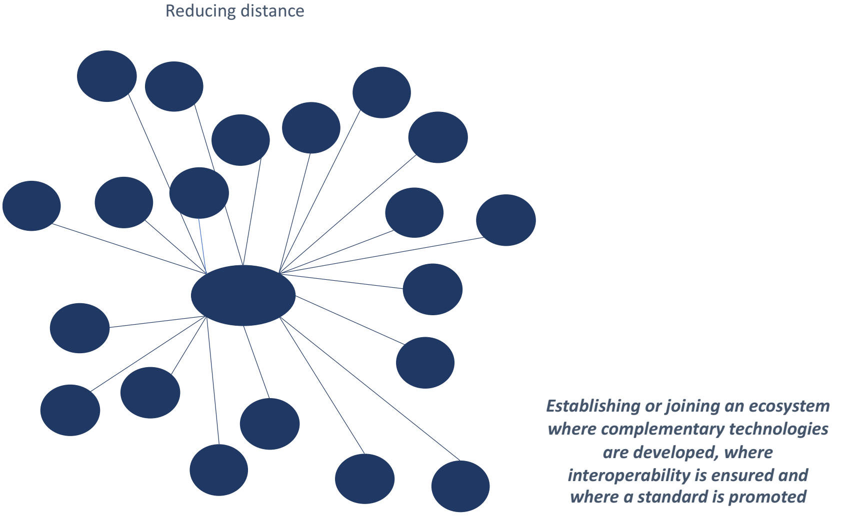

Fig. 4. Accessing and Integrating Capabilities in Foundation-Focused Smart Industry Initiatives.

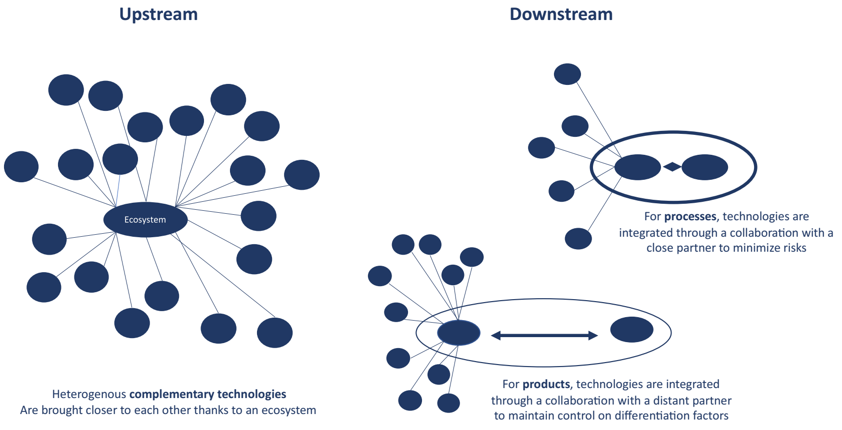

Fig. 5. Accessing and Integrating Capabilities Upstream and Downstream.

promote the technology they have coalesced around (IoT protocol or processor architecture we have mentioned) and their offerings. These dynamics create a sense of community; they reinforce relationships and bring these companies closer together. The ecosystem, therefore, enables complementary technologies to meet but also to mix and match easily. Moreover, active participation in the ecosystem reduces relationship distances; this turns diversity into an advantage as specific offerings can be integrated later within solutions that match the particular requirement. Fundamentally, the ecosystem creates proximity (cognitive, social and geographic, at least temporarily and to some degree).

Suppose we consider firms downstream as integrating multiple distant technologies and maximize the value captured from these projects and upstream as those developing enabling technology and need to find market access across numerous intermediaries, applications, sectors and geographies. Then, as suggested by Fig. 5, from a downstream perspective, smart industry initiatives combine the physical with the virtual world by assembling heterogeneous and distant technologies into a technical and business architecture that delivers and captures value. From an upstream perspective, smart industry initiatives generate foundational technologies that combine with diverse complementary technologies and integrate them into technical and business architectures.

CONCLUSIONS

When a company wants to build or sell an intelligent system, it will face various heterogeneity and distance levels. It will need to structure the relations and integrate the solution into some form of governance to capture value. Our study's outcomes suggest that the smart industry initiative's scope informs the degree of technological heterogeneity involved, which tells the needed distance (familiar versus unfamiliar, similar or distinctive knowledge basis, etc.) and appropriate governance to ascertain value capture. As initiatives move from process towards foundational technology, value creation potential increases tremendously, but so do the complexity and challenges of capturing a portion of that value. To ascertain control and value capture, leaders may need to access required knowledge through distant partners (low organizational proximity), such as academic institutions and start-ups. Geographic, cognitive, social and institutional distances also tend to increase.

The case analyses highlight that innovative industry initiatives can be resource-intensive regarding the technologies and knowledge bases required, their integration, and the organization needed to capture value. Collaboration with different external organizations, including traditional suppliers and non-traditional ones such as start-ups and research organizations, brings in the necessary knowledge and technological expertise. However, organizations need to skillfully interact with those external actors, combine the different knowledge bases, select the appropriate distance, and strategically structure the relations according to the heterogeneity of technologies involved to capture value from such initiatives.

We call that ability distant 'capabilities integration' and propose it as a dynamic capability. Dynamic capability is the organization's ability to integrate, build and reconfigure internal and external resources to address and shape changing business environments (Eisenhardt & Martin, 2000; Teece, 2018; Teece & Pisano, 2003; Teece et al., 1997; Winter, 2003). We see that these activities encompass all the initiatives we studied in this research to at least some degree. We put forward theory that distant capabilities integration will drive smart industry initiatives' success. Organizations with superior distant capabilities integration should not only produce innovative outcomes but also capture value from them.

In contrast, organizations unable to diagnose the required collaboration distance and corresponding relationship structure according to the initiative's heterogeneity and scope, while successfully interacting with external actors and integrating their knowledge bases into a coherent technological solution, will, at best, capture less value or, at worse, fail. We hope that our exploratory research helps decision-makers embark on smart industry initiatives and opens up a fruitful avenue for future research.

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DECISION-SUPPORT TOOLS FOR SMART TRANSITION TO CIRCULAR ECONOMY

Devrim Murat Yazan, Guido van Capelleveen and Luca Fraccascia

ABSTRACT

The sustainable transition towards the circular economy requires the effective use of artificial intelligence (AI) and information technology (IT) techniques. As the sustainability targets for 2030–2050 increasingly become a tougher challenge, society, company managers and policymakers require more support from AI and IT in general. How can the AI-based and IT-based smart decision-support tools help implementation of circular economy principles from micro to macro scales?

This chapter provides a conceptual framework about the current status and future development of smart decision-support tools for facilitating the circular transition of smart industry, focussing on the implementation of the industrial symbiosis (IS) practice. IS, which is aimed at replacing production inputs of one company with wastes generated by a different company, is considered as a promising strategy towards closing the material, energy and waste loops. Based on the principles of a circular economy, the utility of such practices to close resource loops is analyzed from a functional and operational perspective. For each life cycle phase of IS businesses – e.g., opportunity identification for symbiotic business, assessment of the symbiotic business and sustainable operations of the business – the role played by decision-support tools is described and embedding smartness in these tools is discussed.

Based on the review of available tools and theoretical contributions in the field of IS, the characteristics, functionalities and utilities of smart decision-support tools are discussed within a circular economy transition framework. Tools based on recommender algorithms, machine learning techniques, multi-agent systems and life cycle analysis are critically assessed. Potential improvements are suggested for the resilience and sustainability of a smart circular transition.

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INTRODUCTION

Unsustainable development continues to endanger and threaten our future, while resource, water and energy scarcity gives a red alarm for the linear (take-make-use-dispose) economy. Examples are superfluous. One-third of the entire food produced in the world is wasted (FAO, 2011) with a global loss of 750 billion dollars annually (FAO, 2016). Around 90% of the electronic and electric equipment wastes (mobile phones, computers, headphones, etc.) are dumped in landfills (Savage, 2006), summing up to 53.6 million tons worldwide in 2019 (Forti, 2020). Greenhouse gas emissions and energy requirements increase the pressure on businesses and society while resource depletion points out further global problems. In energy production, considerable energy losses occur due to fluctuations in supply and demand. Carbon emissions continue to increase while researchers inspired by circular economy (CE) develop energy storage, carbon capture and conversion technologies and search for innovative and sustainable business models improving resource- and energy efficiency.

A quick impact on circular business improvement can be achieved via the adoption and better integration of artificial intelligence (AI) and information technologies (IT). Many examples in several industries could be mentioned. For example, AI and IT can drive several applications in the automotive industry, such as short loop recycling for manufacturing and robotic disassembly for remanufacturing, able to enhance the environmental performance of the production processes (Bai, Dallasega, Orzes, & Sarkis, 2020). In the food industry, blockchain technology is able to address major challenges, such as traceability, trust and accountability, which can increase transparency and reduce food waste (Kayikci, Subramanian, Dora, & Bhatia, 2020).

This chapter addresses the accelerative role of AI and IT in transition to smart and resilient CE focussing on industrial symbiosis (IS), the main skeleton of collaborative CE. The key principles behind smartness are adopted from Allen (2004) being the ability of a system to be self-monitoring, analyzing and reporting, and self-learning. While IT provides the necessary means to collect, process and communicate data, AI offers the techniques for self-learning ability.

According to Chertow (2000, p. 314), 'IS engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products'. Some studies simplify the concept of IS as the use of waste(s) of a company as a substitute of primary resources of another company. This directly contributes to waste diversion from landfills and reduction in virgin resource depletion. Furthermore, cost reductions for both companies involved in IS are achievable via savings on waste discharge cost and primary resource purchase cost. However, as wastes are not produced upon demand but emerge as secondary outputs of production, IS is different from the usual business models, further challenged by multiple uncertainties (Yazan, Romano, & Albino, 2016). First, identification of an IS opportunity among multiple companies is a challenge because the location, quality and quantity of wastes produced and required might be unclear. Second, assessing the business feasibility raises the question, 'who is going to pay for running costs of IS, such as transportation, waste treatment or transaction costs?' Third, a challenge emerges when companies need to sign long-term contracts, because waste markets are dynamic and turbulent, leading to the hesitation of company managers getting engaged with sharp contract rules (Yazdanpanah, Yazan, & Zijm, 2019). The next challenge is about the monitoring of the IS. Although IS can provide environmental and economic benefits, running IS brings in new processes which might also consume resources and cause new emissions. To tackle all of these challenges, IT and AI can play mitigative roles within the concept of Industry 4.0.

It can be argued that the search for smart technologies in product life cycle management has been accelerated by the discovery of the Industry 4.0 production paradigm (de Sousa Jabbour, Jabbour, Foropon, & GodinhoFilho, 2018). The key concept behind the Industry 4.0 paradigm is to make the supply chain 'smart'. This can be understood as the transition towards a system of product design and supply chain management that is controlled through real-time feedback provided by information and communication technology (Frank, Dalenogare, & Ayala, 2019). Such feedback is useful for different CE principles, i.e., from optimizing important manufacturing parameters to symbiosis identification for stimulating biological and technical cycles (de Sousa Jabbour et al., 2018).

This chapter has the following remainder. Section 'Industrial Symbiosis Development' describes the development of IS highlighting its five main phases. Section 'Techniques and Methodologies for Industrial Symbiosis Development' provides a detailed investigation of methodologies used for IS implementation and analysis. Section 'The Industrial Symbiosis Support Framework' proposes a smart decision-support framework for IS, based on the investigation conducted in Section 'Techniques and Methodologies for Industrial Symbiosis Development'. Section 'Conclusions' concludes the chapter with a short discussion on the future need of AI and IT for a smart CE transition.

INDUSTRIAL SYMBIOSIS DEVELOPMENT

The development of IS has been largely addressed in the last 20 years, mainly via case study developments. The literature has devoted a high interest in understanding the mechanisms for the emergence of IS relationships and IS networks – i.e., networks involving at least three companies that exchange at least two wastes (Chertow, 2007) and several models have been theorized – readers interested in deeper understanding on the topic are referred to Baas and Boons (2004), Chertow (2007), Doménech and Davies (2011), Chertow and Ehrenfeld (2012). Section 'The Industrial Symbiosis Dynamics' addresses the IS dynamics described by the literature and Section 'The Industrial Symbiosis Lifecycle' concerns the life cycle of IS relationships.

The Industrial Symbiosis Dynamics

Recently, Boons, Chertow, Park, Spekkink, and Shi (2017) have described seven main dynamics of IS: (1) self-organization, (2) organizational boundary change, (3) facilitation brokerage, (4) facilitation collective learning, (5) pilot facilitation and dissemination, (6) government planning and (7) eco-cluster development.

According to the *self-organization* pattern, independent companies try to establish IS relationships autonomously, driven by the willingness to achieve economic benefits. They search for suitable symbiotic partners: after finding a partner, the symbiotic contracts are negotiated and, if the negotiation succeeds, the IS relationship becomes operative.

IS networks might be created when companies make *changes in their organizational boundaries*. For instance, a company can expand its current business to include new production processes; opportunities for IS can emerge among the existing and the new processes integrated. Alternatively, a company can disintegrate part of the existing business which may transform from internal IS exchanges to external ones.

IS networks can emerge as a result of a *brokerage process* undertaken by a facilitator, i.e., a third-party entity (e.g., companies not involved in symbiotic exchanges, universities, research institutes, government agencies, non-profit associations). Facilitators can assist companies in finding suitable partners and developing a space for cooperation, thus contributing to overcome the waste quantity and quality mismatch problem (Fraccascia & Yazan, 2018). Facilitators can engage companies into a *collective learning* process, aimed at developing an IS network, or implementing dynamics of *pilot facilitation and dissemination*, aimed at spreading knowledge among companies via being responsible for a wide range of activities (e.g., collecting and spreading technical data, organizing workshops and meetings among companies, conducting feasibility studies, implementing follow-up activities for IS operation).

Local governments can facilitate the emergence of IS through the dynamics of *government planning* and *eco-cluster development*. As *governmental planning*, governmental actors formulate strategies and develop and implement plans of action using incentives and enforcement, such as the Eco-Industrial Park Development Programme in South Korea (Park, Park, & Park, 2016). Finally, according to the *eco-cluster development*, IS is implemented as part of a wider strategy, defined by different local actors (e.g., local governments, companies, associations) coming together around the goal of achieving economic development and/or technological innovation.

The Industrial Symbiosis Life Cycle

The life cycle of IS processes at the inter-company level can be divided into five phases, each characterized by a particular aim and a number of tasks firms typically encounter (Fig. 1). The first phase concerns the *identification* of the symbiotic opportunity and their potential eligible industries (e.g., searching for alternative materials, identifying industrial partners). In the second phase an *assessment* takes place to determine the feasibility of the synergy (e.g., identifying economic and environmental benefits, testing the technology readiness, assessing the sustainability of the collaboration, allocating the cost, risk analysis, checking legal issues, etc.). The third phase deals with the *implementation and coordination* of the synergy (e.g., contracting, arranging transport, deploying required conversion technology, etc.). Then, in the operational phase, the symbiotic relationship is *monitored* (e.g., collecting synergy data, re-assessing the sustainability of a synergy or configuration, etc.). Finally, changes to the environment in which the symbiosis is implemented may cause a *reconfiguration or a discontinuation* of the relationship or network (e.g., new entrants in an eco-park may require re-identification, assessment, implementation and monitoring of symbiotic relationships).

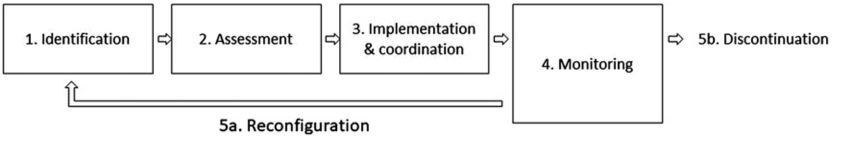

Fig. 1. Life Cycle Phases for Industrial Symbiosis.

TECHNIQUES AND METHODOLOGIES FOR INDUSTRIAL SYMBIOSIS DEVELOPMENT

The process of IS may be supported in various ways. Smart technologies can be effective in all of the previously explained life cycle phases of IS. The academic literature on this topic identified numerous methodologies and techniques to consider for IS facilitation (Lawal, Wan Alwi, Manan, & Ho, 2021; Lütje, Willenbacher, Möller, & Wohlgemuth, 2019; Maqbool, Mendez Alva, & Van Eetvelde, 2019; van Capelleveen, Amrit, & Yazan, 2018; Yeo et al., 2019a). This section is aimed at presenting these methodologies and techniques, together with their current application to the IS field. In particular, the following methods are discussed: agent-based modelling (ABM), material passports, environmental assessment and accounting methods, game theory, geographical information systems (GIS)-based exploration and scoring methods, machine learning and rule-based algorithms, material selection methods and optimization techniques.

Agent-Based Modelling

ABM is a methodology to study complex systems consisting of autonomous decision-making entities, which are modelled as independent agents. Each agent is described in terms of goals to be accomplished through interacting with other agents and rules of social engagement (Axelrod, 1997). The interactions among agents drive the spontaneous emergence of phenomena, structures and patterns, which are not defined a priori by the modeller. ABM is considered a useful approach to investigate the IS dynamics (Batten, 2009; Cao, Feng, & Wan, 2009; Demartini, Tonelli, & Bertani, 2018) but only in the recent 10 years such a methodology has been adopted to this aim – in fact, one of the first agent-based models for IS was proposed by Romero and Ruiz (2014), although the study does not carry out numerical simulations. ABM allows to reproduce and simulate the complex relationships among the companies involved in IS relationships, as well as the relationships between companies and the other stakeholders involved. Hence, the dynamics of identification, implementation and management of (potential) IS relationships can be easily simulated through ABM. A relevant advantage of ABM is that it can be used to simulate a specific system (e.g., industrial area) under different configurations (e.g., without IS and with IS), with the aim to investigate the marginal impact of each configuration (e.g., the benefits created in a given industrial area if IS is implemented). In fact, such an impact can be easily discovered by comparing the same system performance computed under different system configurations – for an overview of ISNs performance that can be computed through ABM, readers are referred to, e.g., Mantese and Amaral (2018). This characteristic makes ABM useful to investigate the impact that specific factors play on the emergence of IS.

From the operational perspective, the potential cooperation and competition strategies among companies involved in IS relationships were investigated through ABM (Abi Chahla & Zoughaib, 2019; Yazan, Fraccascia, Mes, & Zijm, 2018). In particular, the strategies of economic benefit-sharing in IS relationships were investigated by Albino, Fraccascia, and Giannoccaro (2016), who studied the impact of a contract scheme designed to foster the formation of stable symbiotic relationships and to guarantee that the IS is beneficial for all parties involved, and by Yazan, Yazdanpanah, and Fraccascia (2020), who studied the impact of adopting fair or opportunistic strategies when negotiating the contractual terms has on the establishment and operation of IS relationships over the long period. Fraccascia, Yazan, Albino, and Zijm (2020) investigated the impact of adopting a multiple sourcing strategy for wastes compared to the single-source strategy, which is traditionally adopted in the IS context. The impact of the mismatch between waste demand and supply, due to the fluctuations in the amounts of wastes produced and required, was investigated by Yazan and Fraccascia (2020). From the technological perspective, the extent to which online platforms for IS can support companies to find symbiotic partners, thanks to sharing information (e.g., the location of companies, the amounts of waste demanded and potentially supplied) among the platform users, is assessed by Fraccascia and Yazan (2018) and Fraccascia (2020). From the policy perspective, the effect of two measures – i.e., higher landfill taxes for industrial wastes and economic subsidies to companies operating IS – on the emergence of ISNs was investigated by Fraccascia, Giannoccaro, and Albino (2017). From the social perspective, Ghali, Frayret, and Ahabchane (2017) assessed the impact of social factors (i.e., social structure and dynamics, trust and knowledge diffusion on the spontaneous creation of symbiotic synergies among different companies. Finally, Zheng and Jia (2017) investigated the influence of promoting strategies associated with various dimensions of institutional capabilities, on the identification of opportunity sets for IS synergies.

The aforementioned studies each develop their own agent-based model and conduct numerical simulations by using software such as Netlogo and Matlab. This results in a significant limitation, since a comprehensive model to investigate all the aforementioned factors does not currently exist. All in all, ABM can support companies, IS facilitators and policymakers in two ways: (1) it allows to highlight factors impacting on the emergence and operation of IS and (2) it allows to investigate the business dynamics of companies involved in IS (e.g., the negotiation of contractual terms), thus facilitating the understanding of the complex phenomena underlined.

Material Passports

The current developments around material passports are expected to future benefit the identification and exchange of IS. In essence, a material passport is a tool that helps to keep track of all the materials of an object with the aim to identify the circular value of the object. A general application for material passports is currently developed in the building industry. The passport aims to provide different stakeholders in the construction supply chain the necessary information about a building to govern it as circularly as possible (Hansen, Braungart, & Mulhall, 2018). A more formal definition of a *material* passport is a digital interface to provide information about a single identifiable object over its life cycle that may be used to identify circular value and opportunities for its product and components (van Capelleveen, van Hillegersberg, Vegter, & Olthaar, n.d.). Among the characteristic properties that a material passport registers are a product's physical composition (i.e., material and component use), life expectancy, servicing history, quality of (sub) components, contaminations, separability of materials, value estimation for use, recovery and reuse, official declarations (e.g., hazardous statements), instruction manuals (e.g., dismantling guides) and CE performance indicators (e.g., energy certificates). There have been several passport variants proposed in the literature, some focussing on buildings (e.g., BAMB project reported in Debacker, Manshoven, & Denis, 2016), and others applied to discrete manufacturing (e.g., He & Bai, 2021) or developed for specific objects such as vessels (e.g., Danish Environmental Protection Agency, 2016). The value of these passports to IS facilitation is that that these provide the necessary information, typically in a standardized format, to object owners or object governance firms that enable these stakeholders with only few efforts to exchange this information with partners or (partly) disclose information on IS marketplaces (e.g., the Resource Passport of Excess Material Exchange, 2020). In conclusion, the two main goals of material passports are (1) to identify the value for use, recovery and reuse and (2) to support CE decision-making along the life cycle of a product.

Environmental Assessment and Accounting Tools

Environmental assessment and accounting tools are one of the most prevalent and long-lasted used tools to facilitate IS. The tools are core to industrial ecology, which studies the materials and energy flows through industrial systems. The tools aim to support the involved firms in a potential industrial symbiotic relation to understand the presumably environmental impacts generated by its implementation. Although impact calculation is an estimate or judgement of the significance and value of environmental effects, it can support decision-making by outlining the environmental gains and/or trade-offs that firms may evaluate with respect to environmental business or project objectives. While there are numerous methods for environmental assessment and accounting, there are a particular set of tools frequently used in IS, namely: (1) life cycle analysis (LCA), (2) input-output (IO) analysis, (3) material flow analysis (MFA), (4) eco-costing, (5) social network analysis and (6) biomimicry analysis. Many of the methods are based on the mass-balance principle and share the system approach, but differ in purpose, scope and data requirements. The methods addressed below support the process of IS in a number of ways: (1) analyzing environmental impacts, (2) expressing the environmental cost of environmental decisions in monetary terms and (3) analyzing the environmental stability of ecosystems.

Life Cycle Analysis

LCA is a methodology for assessing the environmental impacts that are associated with a product's life cycle (Finnveden et al., 2009). It is often used in the assessment of IS relationships to determine the environmental benefits of alternative symbiotic (network) configurations and product design (Daddi, Nucci, & Iraldo, 2017; Mattilla et al., 2010).

Input-Output Modelling

IO modelling is a methodology in economics that represents the interdependencies of different sectors of an economy. The method can also be used to analyze the interdependencies of material flows and can be applied at different levels. For example, enterprise IO modelling can be used to calculate the fit between the available waste and necessary primary input for the substitution under investigation (Yazan et al., 2016). Furthermore, efforts resulting from national IO modelling in the form of national IO tables have been used to identify the sectors that may be in need or can provide (waste) resources for IS applications (Chen & Ma, 2015).

Material Flow Analysis

MFA is an analytical method that quantifies the flow and stock of material, substance or products across an ecosystem, which is also used in several studies investigating the environmental benefits of IS (e.g., Sun et al., 2017; Van Berkel, Fujita, Hashimoto, & Fujii, 2009). The main drawback of MFA is the lacking view on the product cycle. Other variants of MFA differ by scale (e.g., by analyzing on a regional, national or worldwide level often referred to as material flow accounting) or by aspect scoping (e.g., by combining the costs associated with material flows often referred as Material Flow Cost Accounting (Ulhasanah & Goto, 2012).

Eco-costs

Eco-costs are a measure that expresses the financial investment required to be made to prevent environmental pollution or material depletion to reach the equilibrium between the environmental burden and the regenerative capacity of our earth (TU Delft, 2021). Eco-cost can be used as an extended instrument to express the financial costs related to environmental decision-making.

Biomimicry

Finally, *biomimicry* is a methodology to study how nature works by mimicking models from nature to study complex human problems. In the field of IS, biomimicry is studied using techniques such as social network analysis and food web analysis. This may reveal the properties and structures of IS networks in order to assess whether these correspond to natural ecosystems which may indicate the strength of network resilience (Genc, van Capelleveen, Erdis, Yildiz, & Yazan, 2019, 2020).

Game Theory

Game theory provides a set of tools to assist decision-makers in strategic decision-making environments. A game is defined as the interaction between players who are making decisions based on their individual goals and interests subject to environmental constraints. In game theory, it is usually assumed that players take rational decisions and consider the strategic behaviour of other players while making decisions.

By its strategic nature, game theory is a perfect tool to analyze IS and IS networks. This is due to the fact that IS is a 'coopetition' business model in which companies need to cooperate to create added value, reduce environmental burdens and dive into competition to pay a scant part of running costs of IS. However, the use of game theory for analyzing IS has been historically limited. Only few articles emerge in the literature particularly within the last five years. While most of the below-discussed literature deals with bottom-up IS, a recent article tackles the eco-industrial parks from the top-down perspective.

Yazdanpanah et al. (2019) set up an IS framework in which companies need to consider multiple dynamics of IS to properly filter the IS opportunities, i.e., Formal Industrial Symbiosis Opportunity Filtering. The paper refers to the environment in which IS might occur taking into account market and supply chain observability from the perspective of each player. Yazdanpanah and Yazan (2017) propose a cooperative game theory approach to assist companies on fair cost- and benefit-sharing and on stable IS relationship implementation. This is due to the fact the 'coopetition' nature of IS puts the stability and sustainability of IS under risk leading to interrupted IS relations. The authors demonstrate that the 'Shapley value' and the 'Core of the game' offer a space of cooperation in order to run fair and stable IS businesses. Yazan et al. (2020) combine enterprise IO modelling, non-cooperative game theory and agent-based simulation in order to demonstrate that cooperative behaviour can be learned over time by companies forming an IS network. The authors showcase an implementation of a cooperative network composed of companies who are initially reluctant to cooperate and learn emphatic and fair business strategy over time. In fact, the study suggests that opportunistic behaviour gets lost and companies fairly share costs and benefits with each other over time.

From the top-down perspective, a recent research by Jato-Espino and Ruez-Puente (2021) proposes game theory for facilitated IS in eco-industrial parks. The study offers a solution about how to strengthen the existing waste exchanges in a top-down designed network in order to mitigate the risk of operational failures or the departure of existing companies from the network.

Game theory in IS is in its infancy. More research should take place in order to tackle existing problems in already-running IS businesses and to provide future indications for company managers to adopt IS. In particular, game theory can be very useful to automate the initial feasibility assessment of IS for company managers who need more sophisticated tools to understand the best conditions offering the best economic, environmental and social outcomes. In fact, most of the studies relate only to economic assessment while proposing an environmental or social utility function is definitely needed. Such studies can be very helpful in particular for IS businesses that are environmentally and socially promising but economically challenging. Embedding game theory in AI and IT environments will reduce the uncertainty pressure on company managers who can look at the future with confidence in sustainable and circular business development.

Geographical Information Systems

The predominant type of *GIS* used in IS are IS region identification tools. IS region identification tools aim to support the strategic location of IS investments (van Capelleveen, Amrit, & Yazan, 2018). The key of such a system is its function to locate the regions that have a high economic viability for IS implementations. Aggregated data that reflect the regional economic, infrastructural or industrial characteristics are used to perform a multi-criteria evaluation (typically economic, environmental and social) to assess the viability of IS in that region. Examples of characteristics used include land destination, waste production projections, infrastructure density, urban development, industry diversity and access to nearby facilities such as power plants, boreholes and waste facilities (Aid, Brandt, Lysenkova, & Smedberg, 2015; Jensen, Basson, Hellawell, & Leach, 2012; Ruiz, Romero, Pérez, & Fernández, 2012). The multi-criteria evaluation systems typically rely on scoring methods such as analytic hierarchy process or fuzzy rule-based expert systems.

Another type of a GIS-based exploration tools are systems developed to determine the best location for a specific IS business case, for example, the spatial planning of district heating systems (Togawa, Fujita, Dong, Ohnishi, & Fujii, 2016) and the identification of waste heat potential of a region (Dou et al., 2018). Although this type of system has a different level of analysis than IS region identification tools, the technical function is similar, hence, these systems rely as well on a multi-criteria assessment using scoring methods. In summary, the GIS systems explained support to either (1) the strategic location to identify IS opportunities or (2) the optimized location to facilitate or implement a specific IS business case.

Rule-Based Matching

Rule-based matching is a popular technique used in IS markets. These systems support the process of connecting existing supply and demand. The match-making techniques in these platforms are often based on IO matching systems and make use of material or waste classification systems such as the European Waste Catalogue (EWC) and the Central Product Classification (CPC) to link the inputs and outputs. The literature reports a high failure of such systems and attributes these failures typically to a lack of sociability (Grant, Seager, Massard, & Nies, 2010). However, this dominant view on failures may also be the result of reported systems developed within research projects that were typically unable to overcome these barriers, e.g., the reviewed waste market platforms by Grant et al. (2010) and Maqbool et al. (2019). There also exist success stories in the literature (see van Capelleveen, Amrit, & Yazan, 2018), and there are corporate initiatives that are less visible in academic view (e.g., UCBCSD Materials Marketplace, Excess Materials Exchange, Synergie 4.0). There is an increasing interest in the application of machine learning techniques to support IS markets as a result of growing data availability and knowledge management (van Capelleveen, Amrit, Yazan, & Zijm, 2018).

Machine Learning

Machine learning is a methodology that improves computer algorithms automatically through the experience without explicit programmed rules. An Machine learning algorithm first identifies patterns in training data which it then uses to make predictions about new items or future data points (Bishop, 2006). Machine learning has been applied in a few applications of IS identification systems. Yeo et al. (2019b) suggest that a data-oriented approach could help build a knowledge repository that may reveal new IS opportunities. Their repository is built using natural language processing techniques that extract information about possible inputs and outputs from academic papers that can potentially form a symbiotic relationship. A further application of machine learning techniques is in recommendation systems for industrial symbiotic markets. The key strength of recommenders is the ability to support users in identifying item opportunities and proactively engage system use, resulting in both increased sales and a more active community. The work of van Capelleveen (2020) has identified three cases for recommender systems that can support the identification of IS. Firstly, a recommender system can reduce the search costs associated with identifying relevant IS ideas for a firm prior to revealing specific details of their operations (van Capelleveen, van Wieren, Amrit, Yazan, & Zijm, 2021). Secondly, a recommender can support the firm in classifying waste items with EWC code labels in order to support, for example, the search and matching process in IS platforms (van Capelleveen, Amrit, Zijm, Yazan, & Abdi, 2021). Finally, recommender systems can be employed to suggest the waste items in established marketplace platforms that match the firm's waste preference profile, e.g., by using the a priori and IO databases-based algorithms (van Capelleveen, Amrit, Yazan, & Zijm, 2018).

Material Selection Tools

Material selection tools are digital tools that support researchers, engineers and product designers in the material selection for a determined application considering the product constraints. A review performed by Ramalhete, Senos, and Aguiar (2010) identified and classified a number of tools that can support the material selection process. An example is the CES Selector, which is a software to support designers to select the most appropriate material candidate based on the technical properties of the materials. While there is a lack of reported use of these tools for the specific purpose of IS facilitation, there is a common use of the tools in product design, in particular in high-complex product design and products with stringent quality norms (Ramalhete et al., 2010). A plausible explanation for its currently low adaptation in IS design is the lacking database information about waste properties susceptible for reuse in product design. Capturing the growing knowledge around these waste characteristics into such databases would enrich such tooling by enabling the exploration of alternative use of 'waste material' in product design. While the primary aim of these tools is to support material selection for product design, there is a vast potential for use in IS identification as such tools may help to uncover potential alternative reuse streams for products.

Network Optimization

Quantitative tools are a popular methodology applied in eco-industrial parks used for *network optimization*. While there are a variety of mathematical optimization methods available from the literature, in the majority of cases mixed-integer linear programming (MILP) is used to optimize IS network configurations (Boix, Montastruc, Pibouleau, Azzaro-Pantel, & Domenech, 2011; Kastner, Lau, & Kraft, 2015; Montastruc, Boix, Pibouleau, Azzaro-Pantel, & Domenech, 2013). There are two major applications for the quantitative tools: network optimization and infrastructure optimization (Kastner et al., 2015). Network optimization attempts to search for, mostly from an economic or environmental point of view, the best configuration of interplant connections. Infrastructure optimization is concerned with searching for the most optimal infrastructure network that facilitates the transportation of by-product exchange. Typical network optimizations focus on energy and heat systems, water systems, material systems or combinations of different types of exchanges (e.g., Boix et al., 2011). Infrastructure optimization is often concerned with piping networks for steam, heat and water (Kastner et al., 2015). In conclusion, optimization methods can support companies, IS facilitators and policymakers: they allow to find the most optimal configuration of eco-parks based on multiple objects: environmental, economic and social.

THE INDUSTRIAL SYMBIOSIS SUPPORT FRAMEWORK

Table 1 displays the Industrial Symbiosis Framework developed in this section. The framework is developed as a matrix whose rows correspond to the techniques and methodologies that can be applied to IS and the columns to the IS phases where the methods can be applied. The framework reveals all the current and future tools that may be susceptible to develop smartness.

Techniques and Methodologies Aligned With IS Phases

With respect to the *IS identification phase*, machine learning is a useful technique to assist in determining the relevancy of potential opportunities for industries. Where humans would spend enormous amounts of time reviewing all potential opportunities for relevancy to a particular firm or industry, machines are able to identify this relevancy in short amounts of time. A prerequisite for many of these systems is the attribution of material and waste classifications (e.g., EWC, CPC) to items in IS marketplaces or synergies listed in knowledge bases. Also these tasks are experienced as time-consuming and provide an excellent opportunity for machine learning algorithms to be of support. Geographical location often plays a crucial role in the feasibility of IS. Therefore, GIS-based exploration and scoring methods provide a great ability for policymakers to reveal the areas susceptible for particular types of symbiosis and develop policy actions accordingly. Also for companies, GIS-based techniques are helpful, for example, to determine the strategic location of their facilities, or maybe by assessing the business climate for particular symbiotic opportunities. Material selection tools, often used by designers and process managers, can support the selection of appropriate alternative materials that may be waste-based, by reviewing the quality characteristics with respect to product requirements and other

Table 1. The Industrial Symbiosis (IS) Support Framework.

Techniques and Methodologies/ IS Phases	IS Identification	IS Assessment	IS Implementation	IS Monitoring
Agent-based modelling		• Investigating the factors impacting on the companies' willingness to cooperate and on the IS feasibility	• Explore factors affecting the IS emergence process • Explore the performance of operational practices	• Explore the operation of IS in the long period
Material passport	• Identify the value for use, recovery and reuse in a product	• Support CE decision-making along the life cycle of a product		• Monitor the circularity performance of the product and the implemented IS over the life cycle of a product
Environmental assessment and accounting		• Assess the presumable environmental impacts that will be generated by the implementation of IS		• Monitor the environmental impacts generated by the implementation of IS
Game theory		• Assess cost- and benefit-sharing options between companies	• Evaluate the potential consequences of fair and opportunistic behaviour for the stability of ISRs • automize decision-making for managers (future)	• Monitor the waste reduction and resource depletion mitigation within an eco-industrial park • Risk mitigation against operational failures in the design phase of eco-industrial parks (future)
GIS-based exploration and scoring methods	• Strategic location to identify IS opportunities • Determine the best location to facilitate or implement a specific IS business case • Quicker identification of opportunities through predicted geo-spacial relevancy (future)			

Machine learning and rule-based algorithms	• Quicker (waste taxonomy) tag assignment to waste items • Quicker identification of opportunities through predicted relevancy		• Analyze emergence patterns and their explanations (future)	• Suggest optimization strategies based on historical data analysis (future)
Material selection methods	• Uncover potential alternative reuse streams for products by reviewing the technical properties of the materials with respect to product requirements			
Optimization techniques		• Investigating the optimal configuration of interplant connections • Investigating the optimal infrastructure network for facilitating IS		• Control the optimal configuration of interplant connections through model parameters based on operational feedback (future) • Control the optimal configuration of infrastructure network for facilitating IS through model parameters based on operational feedback (future)

material options. Finally, material passports keep track of an object's composition, which may help to identify the value for use of those elements, recovery and potential reuse.

The *IS assessment phase* is characterized by determining the feasibility of a synergy. In this context, ABM can be a useful technique to explore which factors are able to impact on the feasibility of IS under specific circumstances. In this regard, companies' willingness to cooperate towards IS can be modelled as a fitness function, whose value depends on economic (e.g., prices and costs), environmental (e.g., the amounts of waste exchanged) and social factors (e.g., path dependence). Accordingly, the extent to which each factor can affect the companies' willingness to cooperate can be highlighted. The game theory approach can also facilitate the decision-making process for company managers in order to improve empathic thinking and observe long-term advantages of fairness in business strategy development. Optimization techniques, such as MILP, can help to investigate the optimal configuration of interplant connections in a park and infrastructure networks to facilitate IS. Of course, depending on the defined optimization goals (e.g., economic, environmental, social). Environmental assessment and accounting methods are critical tools in this phase to assess and balance different environmental impacts that are likely generated by the implementation of a symbiotic relationship. It provides support to the decision-making task if a symbiosis should be implemented from an environmental point of view, and what are the consequences of such implementation? In that regard, material passports may provide accurate data of an object that can be used in the environmental assessment described before in addition to its relation to circularity choices regarding the object (boundary shift assessment, understanding the effect of IS implementation on the objects circularity).

In the context of *IS implementation*, ABM can be used to explore a priori scenarios and practices not yet adopted. In particular, the factors that can influence the emergence of IS can be assessed and the effectiveness of policy measures aimed at supporting IS can be investigated. In this regard, the emergence of self-organized IS can be simulated under multiple scenarios under different economic, environmental, social and normative conditions. For example, the impact of economic incentives aimed at supporting the emergence of IS can be easily assessed via simulating the same IS system under two settings, i.e., one base scenario and one scenario where the incentive is implemented. The impact of the incentives can be assessed as the difference between the numerical performance of these scenarios. Through the same logic, also the effectiveness of operational practices (e.g., supply strategies, waste inventory practices) can be explored for specific industrial systems. Machine learning may provide a contribution by systematically analyzing data observation (e.g., governmental registers, news reports, etc.) of IS emergence in order to uncover patterns of IS synergies and IS network establishments. Cooperative game theory is particularly useful to analyze innovative circular business strategies to ensure the sustainability and stability of IS.

In the context of the *IS monitoring phase*, a practical critique sometimes mentioned towards many implemented symbiotic relationships or networks is that it may be resource-intensive and costly to monitor. Nevertheless, there are some advantages related to monitoring that may be highlighted that are or may become at some point beneficial. In the context of IS monitoring, ABM can be used to explore the operation of IS in the long period, in particular by assessing in advance the potential impact of changes in economic, environmental, social and normative factors on the potential waste flows among companies, as well as on the companies' willingness to cooperate. Environmental assessment and accounting techniques can not only be used to predict the environmental impacts of IS synergies but also to actually measure them while being operated. This is often more accurate and contributes to the body of knowledge regarding the effectiveness of IS implementation under practical conditions. Material passports help to identify the value for use, recovery and recycling and can thus potentially assist in specific cases in which the object makes use of an IS implementation. Then, the material passports can show, for example, how such implementation affects the CE performance of an object. Finally, a number of future suggestions to support the monitoring phase are driven by machine learning methods and optimization techniques. Machine learning may suggest optimization strategies based on historical data, and optimization techniques can be used for continued evaluation of model parameters, and control of implemented conditions of IS synergies, accordingly.

Embedding SMARTness Into IS Techniques and Methodologies

One of the main references for the use of the term 'SMART' originates from the acronym 'Self-Monitoring, Analysis and Reporting Technology', coined by IBM as a technology used in hard disk to monitor hard drive reliability with the aim of anticipating hardware failures (Allan, 2004). Regardless of being a direct result of SMART developed for hard drive, the principles behind SMART have been adopted in other areas and became known as SMART tech, e.g., smart wearables, smart TVs, smart devices, etc. The revolutionary innovation offered by SMART is to make these objects, devices and associated techniques aware of the its context by (1) directly linking the models to sensory input from the environment of real operation, (2) alerting the user to potential problems and guiding towards desirable and effective solutions and (3) learning from the new data provided to the model.

Nevertheless, many of the presented techniques discussed in the Section 'The Industrial Symbiosis Support Framework' are developed as tools which embed, hard coded in the models, the acquisitioned knowledge needed for operation. With the rise of possibilities provided by SMART innovations, we hypothesize that many tools may also benefit from a self-monitoring approach through sensors. For example, an opportunity arises for the material passports, where sensors can be used for measuring the state of an object, which can help to monitor the circular value and ultimately support in making maintenance decisions (Honic, Kovacic, Aschenbrenner, & Ragossnig, 2021). Although early studies show the applicability of the material passport, there is a considerable need for empirical evidence showcasing the environmental and societal effects of such a smart technology in context. Opportunities to embed SMART also arise in the development of GIS for facilitating waste transportation in IS processes (Yu, Yazan, Bhochhibhoya, & Volker, 2021).

Obviously, the potential for embedding smartness in IS tools is not limited to these examples provided but may be extended to the full framework of techniques displayed in Table 1. The SMART perspective, thus, opens new research avenues.

CONCLUSIONS

This section establishes a framework for AI and IT use to foster symbiotic relations between industries. Departing from the IS concept, several useful methodologies are synthesized from a functional perspective. Potential future improvements are critically discussed.

The twenty-first century is the era of sustainability and CE must be our future. We have made enough damage to our Earth, so our future efforts must focus on reversing this damage and constructing a livable world for all livelihoods. The ambition of profit must be minimized and economic gain must be spent on sustainable and circular technologies and business models; definitely not on investments pushing the society over-consumption. Therefore, the symbiosis should not only be implemented between industries but also between people, governments and industries. The concepts of rural and urban symbiosis must be well integrated into IS in order to achieve geographic complementarity and cooperation to accelerate CE transition.

In this big challenge, IT and AI must be our facilitators. Unfortunately, today the use of AI and IT to make companies and people consume more within the concept of linear economy is far more than the use of AI and IT to foster sustainable production and consumption. A circular and sustainable revolution is definitely needed to bring in quick and groundbreaking solutions, while an evolutionary approach is needed to assist companies, people and governments in order to achieve a smart CE transition.

To this aim, future research should be more interdisciplinary where the energy is spent through collective goals of companies and society by respecting the Earth's carrying capacity for human activities. This calls for education of students enrolled in programs such as AI, business IT, machine learning and engineering on the global sustainability challenges; thus, we can hope for future managers and researchers who are mathematically strong and environmentally and socially conscious. Next, fields such as business administration and management studies should provide students with non-conventional, sustainable and circular business models to achieve a *mental* transition in the industry and economic system. Furthermore, studies such as material science, nanotechnology, biology, ecology, electrical/electronic engineering, chemical engineering and energy systems which are dealing with resource use and consumption should provide students the necessary knowledge about resource- and energy efficiency. These educational improvements would facilitate industry-government-science collaboration which calls for a synergy among people with multiple skills and knowledge.

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SUPPORTING UTILITY MAPPING WITH A DEEP LEARNING DRIVEN ANALYSIS TOOL

Christian Versloot, Maria Iacob and Klaas Sikkel

ABSTRACT

Utility strikes have spawned companies specializing in providing a priori analyses of the underground. Geophysical techniques such as Ground Penetrating Radar (GPR) are harnessed for this purpose. However, analyzing GPR data is labour-intensive and repetitive. It may therefore be worthwhile to amplify this process by means of Machine Learning (ML). In this work, harnessing the ADR design science methodology, an Intelligence Amplification (IA) system is designed that uses ML for decision-making with respect to utility material type. It is driven by three novel classes of Convolutional Neural Networks (CNNs) trained for this purpose, which yield accuracies of 81.5% with outliers of 86%. The tool is grounded in the available literature on IA, ML and GPR and is embedded into a generic analysis process. Early validation activities confirm its business value.

Keywords: Utility mapping; ground penetrating radar; intelligence amplification; machine learning; convolutional neural networks; business value

INTRODUCTION

With the length of utilities exceeding 1.7 million kilometers, the Netherlands has a complex underground infrastructure (Rijksoverheid, 2015). Utility strikes occur in approximately 5.7% of all excavation work (Rijksoverheid, 2015). This equals 33,000 incidents annually, that is once every 3–4 minutes. Annual damages exceed 25 million Euros (Rijksoverheid, 2015). The risk of strikes can be mitigated by inspecting the underground a priori. Unsurprisingly, therefore, a business model has emerged for companies performing

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underground mapping. Ground Penetrating Radar (GPR) is used by analysts to detect underground utilities non-destructively (Cassidy & Jol, 2009). GPR analysis tasks are however reported to be repetitive and cost-intensive. This partially occurs due to the scarcity of GPR analysts and the steep learning curve preceding one's mastery. This chapter addresses this problem by designing and developing an intelligent system capable of supporting GPR analyses by means of Machine Learning (ML) models. We identify well-performing ML algorithms for predicting the material type of underground utilities detected with GPR, in response to an open automation problem posed by our industrial partner, Terra Carta. In doing so, we explicitly take an Intelligence Amplification (IA) approach in which the analyst is not replaced. Rather, through our smart ML agent, our goal is to amplify the analyst's intelligence. This allows analysts to quickly identify the material types of simple objects while using more creative, human intelligence–based approaches for complex ones. The main argument for this approach is that it the reduces substantially the repetitiveness of the analyst's work and makes on-the-shelf knowledge available repetitively, while creating a true human-machine symbiosis and smart working environment. Our research has high applicability in industries such as critical infrastructures (e.g. gas, water, communication) and oil industry. It constitutes a typical example of business process improvement within the Industry 4.0 (I4.0) paradigm: two core I4.0 technologies, smart sensing and ML are combined with the goal of achieving smart working in which the worker is augmented with AI, and the nature of work changes (also one of I4.0's main goals). This work further contributes to science and practice in multiple ways. First, it introduces IA to the literature on GPR analysis by means of the intelligent system. Second, it designs and validates three novel classes of ML algorithms. Third, it presents a review of the literature on ML for underground mapping. Fourth, it embeds the system into a general human-in-the-loop analysis process by means of an architectural model. Fifth, it presents early validation comments demonstrating industry demand. As mentioned earlier, the chapter has emerged in cooperation with an industry partner. The chapter is structured as follows. Section 'Background' presents the literature reviewed. Section 'Research Methodology' discusses the methodology used. Section 'ML Models Underlying the Intelligent System' presents the design of the novel ML algorithms. Section 'ML Performance' demonstrates model performance. Section 'ML Driven Intelligent System' discusses the design of the intelligent system. Section 'Discussion' discusses and explains our findings. Finally, Section 'Conclusion' concludes this chapter.

BACKGROUND

Origins of Excavation Damage

Utility strikes pose a significant problem to Dutch construction given the costs and dangers involved. There are multiple causes for this problem:

- Quickly rebuilding damaged infrastructure was the primary concern after World War 2 (Eng, 1987). No central registry for utilities existed then, leaving many unregistered.
- The accuracy of methods for geospatial positioning was lower compared to today's ones. This sometimes resulted in large deviations between registered and actual utility positions.

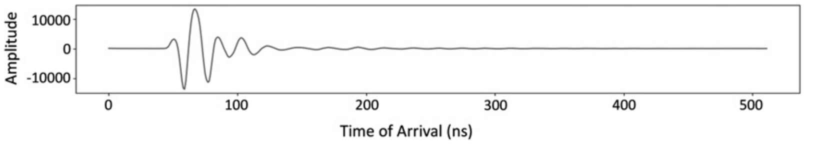

Fig. 1. A-Scan.

- Utilization of registries, which emerged in the late 1960s, remained optional until 2008. Only then, the government introduced legislation requiring their use (Kadaster, 2008; Rijksoverheid, 2019).

Today, the registries are centralized into the KLIC utility registry. Here, all excavation work must be reported. In return, the reporter will receive all available information regarding utilities near their construction site. Consequently, as any request is forwarded to network operators, they are required to register their utilities and maintain accurate maps. Additionally, to protect critical utilities, network operator experts must provide physical identification when excavation work is performed near them. Although much progress has been made, inconsistencies from the past ensure that incidents continue to occur today (Rijksoverheid, 2015).

Underground Mapping and GPR

Mitigating the risk of utility strikes is possible through a priori analysis. Companies specializing in underground mapping have harnessed technologies such as the GPR for this purpose. A GPR is equipped with antennas transmitting and receiving electromagnetic waves and is moved over the Earth's surface. When waves propagate into the subsurface medium, they are echoed back when they hit objects buried in this medium (Cassidy & Jol, 2009). These are subsequently received by the GPR. This behaviour allows one to analyze the underground non-destructively. In fact, GPR is the de facto standard method used in underground mapping today.

Visualizing GPR Data: A-Scans and B-Scans

Echoes received can be visualized in A-scans (Scheers, 2001). In those, the amplitudes of the echoes are plotted against time of arrival (ToA), often in nanoseconds. Analysts can already derive certain object characteristics from A-scans. For example, they can identify object depth and, possibly, the nature of object contents. Fig. 1 presents an A-scan. Since a GPR moves horizontally, consecutive A-scans produce a richer image called B-scan (Scheers, 2001). In those, the horizontal axis represents the time domain across multiple A-scans. The vertical axis contains A-scan echo backscatters. Fig. 2 presents an exemplary scan. On B-scans, underground objects are visible as hyperbolae. This signature results from spherical GPR wave emission. ToAs are longer first, but get shorter when the operator gets closer to the object. ToA is shortest when the GPR is directly above it. Moving away again produces longer ToAs, resulting in the characteristic hyperbolic signature. Analysts can derive richer insights from B-scans, especially when they can combine GPR data with additional information sources like the KLIC registry. This makes the utility strike problem manageable.

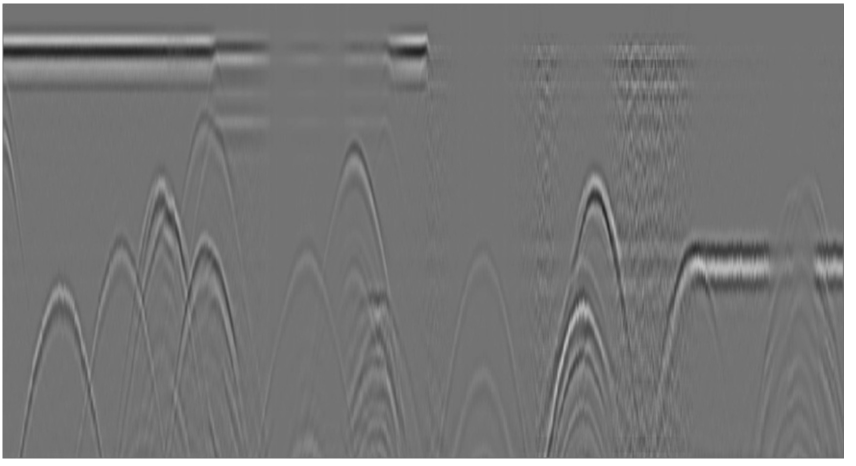

Fig. 2. B-Scan.

Challenges Experienced During Utility Mapping

Despite being widely used, GPR-based analysis presents certain challenges (Cassidy & Jol, 2009). Those are technical and organizational in nature. Key challenges experienced by GPR practitioners are:

- The interface between the air and the subsurface is small but significant. In fact, strong echoes are produced that are known as ground bounce.
- Waves emitted attenuate over time. As a result, shallow objects cause relatively strong echoes while deep objects are scantily visible. Compensating attenuation can be done with time-varying gain filters (Cassidy & Jol, 2009).
- GPR analysis tasks are reported to be labour-intensive. The industry partner reports that they are also repetitive. Human beings generally do not excel at such tasks (Cummings, 2014).
- Becoming a GPR analysis expert requires significant training in geophysics. Consequently, analysts are scarce (Versloot, 2019).

This work contributes to reducing those challenges by designing an intelligent system that amplifies the underground mapping process. Machine learning algorithms are used for this purpose. Therefore, we next position our work with respect to the Industry 4.0 paradigm, introduce the possible benefits of symbiotic or IA relationships between humans and machines and finally review the literature on applying ML to underground mapping.

Industry 4.0 and Intelligence Amplification

The Industry 4.0 paradigm was introduced to secure the competitiveness of the German manufacturing industry. It has now spread into a global development and comprises base technologies which, integrated with business processes, accelerate the fourth industrial revolution (Kagermann, Wahlster, & Helbig, 2013).

Base Technologies

Technology has become increasingly important since World War 2 (Isaacsson, 2014). The nascence of the transistor has created unprecedented technology growth. Computers, once available only at the most sophisticated research institutes, have moved into peoples' homes and hands. Increased interconnectivity between devices through the internet has democratized information which resulted in the third industrial revolution (Isaacsson, 2014; Lasi, Fettke, Feld, & Hoffmann, 2014). In the fourth revolution, which is currently underway, the role of technology is similarly significant. This time, however, different technologies serve as its primary driver. Specifically, the Internet of Things, cloud services, big data and analytics are the key technologies in this revolution (Kagermann et al., 2013). They are the so-called base technologies (Frank, Dalenogare, & Ayala, 2019). Machine Learning is an instance of analytics.

Business Impact through Front-End Technologies
According to Frank et al., front-end technologies interface between base technologies and business actors (Frank et al., 2019). They can also be considered to be application areas. The initial Industry 4.0 document considered one front-end technology, Smart Manufacturing (Kagermann et al., 2013). Frank et al. added three others, yielding these Industry 4.0 application areas all driven by base technologies:

- *Smart Manufacturing:* considers internal production operations.
- *Smart Working:* considers operational activities.
- *Smart Products:* considers end products.
- *Smart Supply Chain:* considers improved processes through supply chain integration.

Frank et al. argue that Smart Working comprises 'technologies [supporting] worker's tasks, enabling them to be more productive and flexible to attend [to their] (…) requirements' (Frank et al., 2019). This definition aligns with the operational improvements for GPR analysts' tasks discussed previously. This work can thus be cast as an attempt to produce a Smart Working system.

The Need for Integration
Traditionally, organizations have developed in a siloed fashion (Britton & Bye, 2004). Organizations distributed responsibilities for IT acquisition and operations to individual departments that would guard these strongly. This impacted organizational technology and application landscapes, which have traditionally been very scattered. This results in for example interoperability problems and vendor lock-ins. The Industry 4.0 principle radically breaks with this view-point. Rather, it prescribes that technologies are integrated both with other technologies and into production processes (Diez-Olivan, Del Ser, Galar, & Sierra, 2019). This integration occurs at various levels:

- *Horizontally:* distinct base technologies are combined to create integrated solutions (e.g. combining the IoT for acquiring data with ML for creating predictive models).
- *Vertically:* individual or integrated base technologies are integrated with business processes through front-end technologies to provide business value.
- *Circularly:* horizontal and vertical technology integration is combined to create a sound and relevant IT-based solution for a business problem, considering their lifecycles as well.

The intelligent system designed in this work integrates circularly. Horizontal integration is provided by means of integrating ML with big data and cloud services, while vertical integration is achieved by embedding it into a generic analysis process in Section 'Embedding the System Into GPR Analysis Process'.

Intelligence Amplification: A Symbiotic Relationship Between Humans and Technology

Although base technologies can automate human tasks, one should consider the degree of automation a priori. For example, our industry partner claims that GPR analysts cannot be fully replaced by Industry 4.0 base technologies; they must remain in the loop. In the dawn of the computing era, technologists however considered automation to be binary: problem-solving was either entirely automated or fully left to human beings (Cummings, 2014). This viewpoint shifted in the early 1950s. Scholars, attempting to characterize the field of human-computer interaction, proposed a set of heuristics to distinguish between what 'men are better at' and what 'machines are better at': the MABA-MABA heuristics (Fitts, 1951).

Those were later expanded into Levels of Automation (LoA), which explain to what extent humans interact with information systems in a decision-making situation (Cummings, 2014; Parasuraman, Sheridan, & Wickens, 2000). They extend the binary view of automation and allow humans and machines to work together. Machines can increase human intelligence by amplifying it (Ashby, 1957). This observation emerges from machine capabilities for problem-solving, which Ashby argues it comes down to a suitable selection (Ashby, 1957). Freely interpreted, the core of his argument is that solving a problem equals picking the best solution out of a set of candidates. Since he claims that intelligence is measured as one's 'power of appropriate selection', and that devices can amplify this power (i.e. assisting in picking a solution), he analogizes that intelligence can be amplified. Ashby's comparisons would be the basis of further research and the nascence of the research area known as IA. Intelligence Amplification, by means of the front-end technologies interfacing between base technologies and business actors, is intrinsically related to the Industry 4.0 paradigm discussed before. Intelligently supporting GPR analysts by means of ML algorithms, which we cast as an Industry 4.0 instance, can namely also be cast as an IA instance. Following the concerns raised by our industry partner, this work explicitly takes the point of view that GPR analysts should be amplified rather than replaced. This way, the operational aspects of their tasks can be improved for simple objects while human creativity is still required for complex ones. We next review the literature already available for this research goal.

Machine Learning Approaches for Underground Mapping

Recently, ML algorithms, today especially deep learning (DL) ones, have been used to eliminate repetitive tasks in various business domains. They allow for '[discovering] regularities in data through the use of computer algorithms and [by using them] to take actions' (Bishop, 2006). Analyzing GPR data is essentially a classification problem: the analyst, given contextual data, classifies an object with respect to its material type. Since GPR analysis is often repetitive and GPR analysts are scarce, applying ML here can be worthwhile. In fact, many studies have validated ML approaches for underground mapping. They can be grouped into four distinct groups (Pasolli, Melgani, & Donelli, 2009a). Primarily, studies report on (1) detection and localization, rendering it trivial today. Less work has focused on (2) material recognition and estimation of (3) dimension and (4) shape.

Machine Learning for Recognizing Material Type, Shape and Size
Given the popularity of Support Vector Machines (SVMs) during the early 2010s, they were primarily used then. Consequently, various SVM approaches were identified. For example, El-Mahallawy and Hashim combine noise reduction and discrete cosine transform (DCT) A-scan signal compression with SVM classification (El-Mahallawy & Hashim, 2013). DCT-based features yielded superior results over time series and statistical ones. Shao et al. also use SVMs but apply other signal processing methods. They first sparsely represent an A-scan by '[expressing] a signal as a linear combination of elementary waves' (Shao, Bouzerdoum, & Phung, 2013). In another study, Pasolli et al. combine SVMs with B-scans (Pasolli et al., 2009a). They also demonstrate that estimating object size is possible as well (Pasolli, Melgani, & Donelli, 2009b). The subfield of DL experienced a breakthrough in 2012 (Jordan & Mitchell, 2015). Since then, scholars have applied DNNs to material recognition. Zhang et al. validate an architecture of three neural networks for recognizing object shape, material and size (Zhang, Huston, & Xia, 2016). Their network also computes object depth and medium conductivity. It however only supports a limited number of material types. More recently, Almaimani successfully applied Convolutional Neural Networks (CNNs) to material recognition (Almaimani, 2018). Contrary to previous approaches, no feature extraction was performed. Rather, a B-scan slice is used as a feature vector. Although her results are promising, she welcomes more research that demonstrates the applicability of CNNs to material recognition.

RESEARCH METHODOLOGY

Creating an intelligent system is a typical design problem in which an artefact that aims to improve a problem context is designed and developed (Wieringa, 2014). Design science methodologies can be used to attain scientific rigor during such research. They ensure that artefacts are both theoretically sound and practically relevant. Several methodologies exist for design research. Choosing one partially relies on the practicality of the research at hand, since certain methods rely more heavily on theory than others, while those often allow researchers to align their work with practice more easily. Sein et al. argue that methodologies like the Design Science Research Methodology by Peffers et al. 'fail to recognize that the [artefact] emerges from interaction with the organizational context even when its initial design is guided by the researchers' intent' (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007; Sein, Henfridsson, Purao, Rossi, & Lindgren, 2011). They would produce insufficient agility when working with industry partners. Inspired by Action Research, they conceptualize the Action Design Research (ADR) methodology. It iteratively interweaves artefact development with organizational intervention and evaluation and is especially relevant for business problem–oriented research. The research carried out in this work has been triggered by the business problem discussed in Section 'Introduction'. Additionally, artefact design and development was performed in strong collaboration with an industry partner. The ADR methodology, therefore, guided this work.

ML MODELS UNDERLYING THE INTELLIGENT SYSTEM

Rationale

Histograms can be used to count the number of instances across a range of values in a statistical sample. Weia and Hashim created histograms based on A-scan signal backscatters and a thresholding algorithm, demonstrating that various material types can be discriminated for human analysis (Weia & Hashim, 2012). We apply their feature extraction approach for training ML models. Therefore, one of the classes of CNNs trained is a histogram-based one. El-Mahallawy and Hashim harness the Discrete Cosine Transform (DCT), which is known for signal compression, for training SVM classifiers (El-Mahallawy & Hashim, 2013). CNNs could however perform better for multiple reasons. First, training SVMs requires the configuration of a kernel function a priori. Kernels are generic functions for computing similarity and may not be entirely suitable to the ML problem at hand. This cannot be known in advance. Second, SVMs cannot be used for multiclass predictions (i.e. when the number of material types is >2). Third, SVMs do not scale well with larger datasets. CNNs do however learn kernels themselves, are capable of generating multiclass predictions and do scale with larger data volumes. This work therefore replicates the application of the DCT with CNNs. Generally speaking, however, the ML community suggests that minimum feature extraction must be applied when training CNNs (Chollet, 2018). That is, since they can learn filters themselves, data should be input as raw as possible. This work therefore also validates a CNN trained on slices of slightly pre-processed B-scans. In total, therefore, three classes of CNNs are validated in this work: a histogram-based class, a DCT-based class and a B-scan window-based one.

CNN Architecture

The CNNs contain various components combined into an architecture. Specifically, it uses a convolutional block and a densely connected block. Fig. 3 presents the architecture. It contains those components:

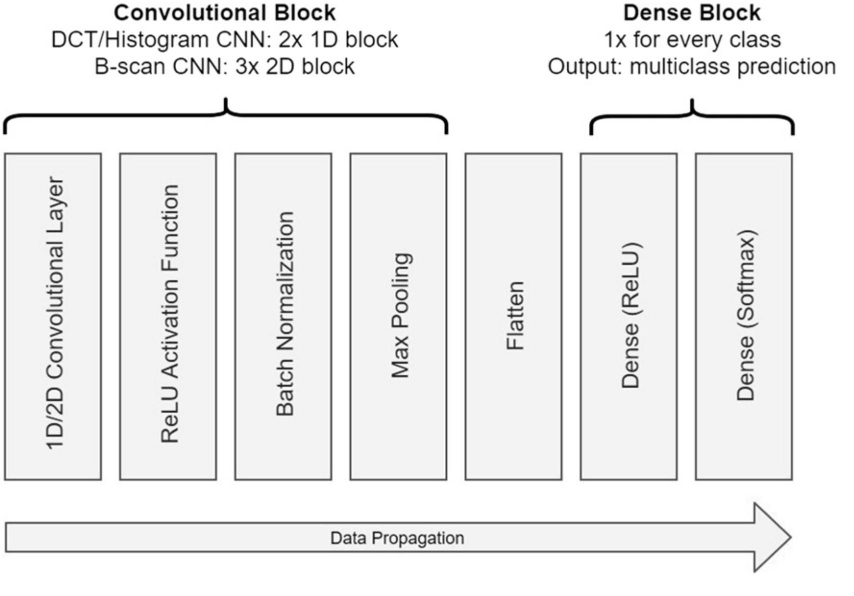

Fig. 3. CNN Components.

- The convolutional block contains a convolutional layer, batch normalization and max pooling. Those are appropriate for learning from image-like data (Chollet, 2018). The DCT and histogram-based CNNs have two since data are already sparsened; the B-scan one has three.
- The densely connected block contains two Dense layers. They convert the patterns identified by the convolutional block into a multiclass prediction. All CNNs have one densely connected block attached to the final convolutional block. To interface, a Flatten layer is added in between.

GprMax Simulations

A training set was generated using gprMax, which implements the finite-difference time-domain (FDTD) method for simulating GPR imagery (Giannopoulos, 2005). In total, 770 B-scans were generated using gprMax Python scripts. A custom wavelet generated by the GPR used by our industry partner was emitted in the simulations to mimic the real world as much as possible. Every simulation represents a B-scan composed of 150 A-scan traces. One A-scan is composed of 1,024 signal backscatter amplitudes. In total, six target classes were simulated: a concrete sewage, high-density polyethylene (HDPE), iron, perfect electricity conductors (PECs) like steel and copper, tree roots and stoneware pipelines. In the simulations, object contents were varied and objects were buried at various depths. The soil was randomly varied over the entire spectrum of available soil types and signal interference was introduced by adding noise.

Data Pre-processing

Before training, the simulations were pre-processed as follows:

(1) The gprMax output file was first converted to a readable GSSI file.
(2) Ground bounce was removed with a median-based filter (Versloot, 2019).
(3) Energy decay (i.e. exponential) gain was used to reduce signal attenuation.
(4) Feature-wise normalization was applied to reduce amplitude variance without changing the A-scan waveform shape. In DL, this benefits model performance (Chollet, 2018).
(5) Feature extraction was applied which was dependent on the algorithm.
    - For the histogram-based CNN, histograms computed using the interval $[-5\sigma, 5\sigma]$ were included. Specifically, since the bin size was $\sigma/10$, the feature vector extracted contained 101 features.
    - For the DCT-based CNN, the DCT was computed using SciPy's signal processing package. Inspired by (El-Mahallawy & Hashim, 2013), only the 14 first DCT coefficients out of 1,024 compose the feature vector.
    - For the B-scan–based CNN, a window of 25 traces was sliced left and right of the hyperbola. Since an A-scan is composed of 1,024 amplitudes, feature vector shape was (51 and 1,024).

Training, Validation and Testing Data

DL datasets must be split into training, validation and testing data (Chollet, 2018). With training data, predictions are generated that can be compared to actual targets. Validation data are used to identify the effectiveness of subsequent optimization. Finally, final performance is measured with testing data the model has not seen before. This way, one can assess its predictive and generalization powers. Creating these sets can be done naively by simply holding out certain proportions for training, validation and testing data (Chollet, 2018). However, with imbalanced datasets, this could produce overly confident model performance. Using K-fold cross-validation, performance is computed as the average over K training attempts. This yields more accurate performance metrics, but is K times more expensive. Typically, based on empirical results, the value of K ranges between 5 and 10. We use $K = 10$.

Hyperparameter Tuning

DL architectures must be configured before training them. This can be achieved through hyperparameter tuning (Chollet, 2018). It involves parameter (i.e. neuron) initialization, choosing a loss function and other performance metrics as well as an optimizer, learning rate (LR), batch size and a number of training iterations (epochs). This work tunes model hyperparameters manually based on evidence from the literature. To accommodate ReLU, we used He uniform initialization for neuron initialization, since it performs best (Kumar, 2017). Categorical cross-entropy loss is used for multiclass predictions (Chollet, 2018). We also utilized accuracy which is more intuitive to humans. Adam optimization is used, striking a balance between sound methods and novel approaches (Ruder, 2016). With the LR Range Test, an optimum default LR is found and then decayed linearly (Smith, 2018). Before training the models with maximum computational resources and with the full data set, we used *KERAS_LR_FINDER* to perform the LR Range Test. This allows us to find the maximum learning rate with which the model does not overfit. We performed this test for all three algorithms and per algorithm chose this learning rate as the base learning rate. We subsequently apply a linear decay rate. Batch size is set to 70 given hardware constraints.

Finally, the number of epochs is 200.000. However, training is stopped early when the model has not improved for 30 epochs. The best model is saved to disk. This way, the training process stops exactly in time (Chollet, 2018). More details can be retrieved from (Versloot, 2019).

ML PERFORMANCE

Data Pre-processing

Fig. 4 presents the results of data pre-processing. The upper part presents a raw A-scan. Clearly, the air-ground interface is strong and signal attenuates with time. After pre-processing, ground bounce is no longer present, signal strengths are relatively equal and amplitudes are normalized. Likely, resembling a real-world scenario, regular noise is still present in some A-scans.

Initial Model Performance

Table 1 presents initial model performance across 10 training folds. Multiple hypotheses have emerged why model performance is mediocre:

(1) Primarily, we considered the model to be underfit – that is, every unique object appears only once in the data set. It is hypothesized that expanding the data set results in better performance.

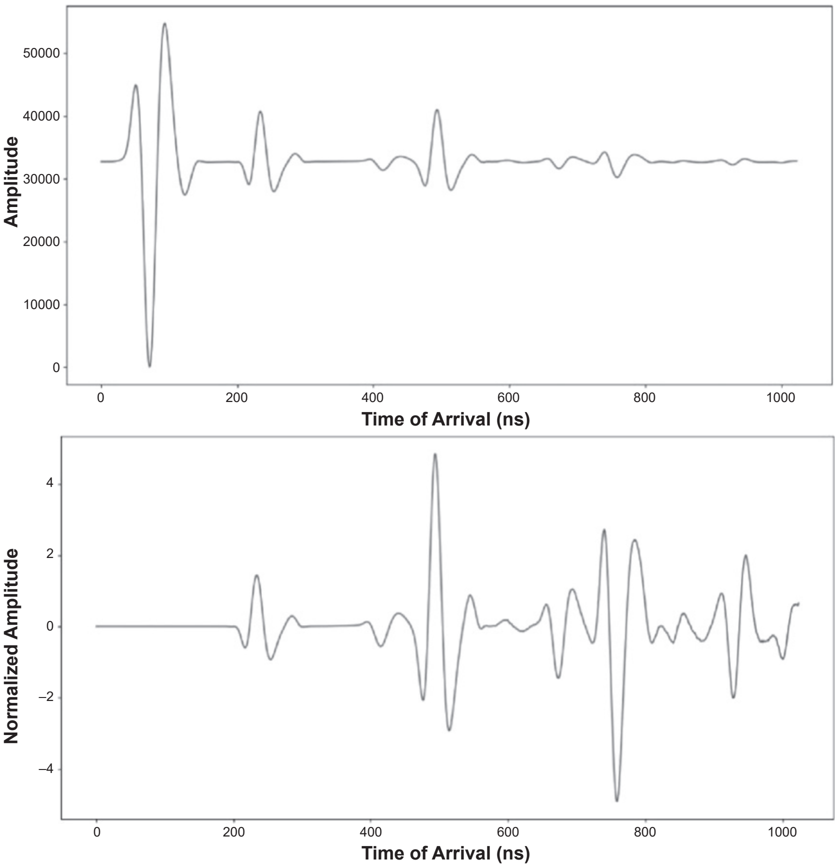

Fig. 4. Unprocessed (Above) and Pre-processed A-Scan (Below).

Table 1. Initial Performance of the DL Models.

Model	Average Cross-Entropy Loss	Average Accuracy
Histogram based CNN	1.3162	61.30%
DCT based CNN	1.2176	61.82%
B-scan based CNN	1.3613	67.53%

(2) Different material contents produce different echoes. Initially, the model did not separate material types with respect to content. We hypothesize that by using material types and contents as targets, performance increases.
(3) The training process converged quickly. This could be caused by slow LR decay and a consequentially overshot optimum towards the end of the training process. Increased LR decay may produce better models.
(4) Pre-processing including feature extraction currently applied may be sub-optimal.
(5) Generally, different hyperparameter tuning could yield better performing ML models.

Variation Performance

Initially, model performance for all three algorithms was mediocre, with accuracies ranging between 60% and 70%. The three CNN classes were retrained with various variations for testing these hypotheses. The first variation we performed was to expand the dataset to approximately 2,425 simulations, since we observed that one simulation was unique with respect to the object's unique characteristics and by consequence could only be present in one set (i.e. training/validation or test set).

The histogram-based and DCT-based CNNs did not improve any further. The B-scan based CNN, however, did improve, albeit primarily through dataset expansion. Other variations subsequently improved performance incrementally. Those variations included studying the effect of separating the material and its contents when generating target classes, increasing the decay of the learning rate and studying the effects of varying input (i.e. applying different gains). The effects of varying the number of DCT coefficients, the number of histogram bins and the width of B-scan windows were also studied. Similarly, various model variations were studied, with variations in batch size across the three algorithms as well as differences in hyperparameters. Combining those variations into one yielded the most promising results in terms of loss. For these variations, most B-scan CNN accuracies were in the range of 77–82%. Some variations produced outliers to 86% on individual folds. Table 2 presents the performance of the variations to the B-scan CNN.

ML DRIVEN INTELLIGENT SYSTEM

The Industry 4.0 paradigm combines base technologies like ML with front-end technologies to provide business value. This section discusses such an interface between ML models and GPR analysts. It also integrates it into a generic analysis process using an ArchiMate model.

System Design and Instantiation

The intelligent system is a web application that is capable of analyzing GPR imagery uploaded by the user. When started, a GPR radar file can be uploaded, which is interpreted by the back-end and presented on-screen. Subsequently, the user can fine-tune signal processing applied to the image, altering time-varying gain and ground bounce removal as desired. The browser window immediately adapts the visualization. The user can also click on a hyperbolic signature. When doing so, a window is sliced around the mouse pointer and input into the ML model running in the background. Its prediction is displayed in a popup message. A line drawn on-screen shows the user where he has clicked. Fig. 5 illustrates the tool when used in practice.

Embedding the System Into GPR Analysis Process

Fig. 6 shows how the intelligent system can be embedded into a generic analysis process. It starts when a customer requests a quote for utility mapping.

This is followed by negotiations and contractual agreement. The project is then added to project planning. At the planned date, a GPR operator records data on site. For this, he configures the GPR and performs measurements. When finished, data are downloaded in the office and sent to the GPR analyst. An analysis request is then added into project planning. When analysis is due, a GPR analyst loads the data into a specific analysis tool. Which tool is used is dependent on the GPR manufacturer; it is often proprietary. First,

Table 2. Performance of Variations to Initial B-Scan Based CNN.

Variation	Average Loss	Average Accuracy
Expanded dataset to 2,426 simulations.	0.8834	77.57%
Used separate materials and contents as targets.	1.1695	70.20%
Increased LR decay 175,000 times.	0.8665	77.57%
Reduced shape to (25, 1,024).	2.0215	79.18%
Expanded shape to (75, 1,024).	0.9112	79.18%
Original B-scan input scaled down to 33% of original image size.	0.9706	78.23%
Swish with (101, 1,024) shape.	0.8798	78.81%
Leaky ReLu (α = 0.10) with Glorot uniform initializer and (101, 1,024) shape.	0.9805	77.62%
Tanh activation function with Glorot uniform initializer and (101, 1,024) shape.	0.8783	81.16%
Batch size = 5.	2.8527	48.23%
Batch size = 15.	1.1110	66.16%
Batch size = 25.	0.9294	77.87%
Batch size = 35.	0.8599	80.96%
Batch size = 50.	0.8108	81.54%
Batch size = 90.	0.9900	79.39%
Batch size = 115.	0.8369	79.72%
Batch size = 140.	0.7931	80.63%
No gain applied in pre-processing.	1.3299	67.65%
Strong exponential gain applied.	1.2134	67.35%
Linear gain applied instead of energy gain.	0.8517	79.93%
Combined (101, 1,024) shape, Tanh/Glorot, batch size = 50, linear gain, 175.000× LR decay.	0.8390	78.44%
Combined (101, 1,024) shape, ReLU/He, batch size = 50, linear gain, 175.000× LR decay.	0.7419	79.31%
Combined (101, 1,024) shape, ReLU/He, batch size = 50, original gain, 175.000× LR decay.	0.7758	79.76%

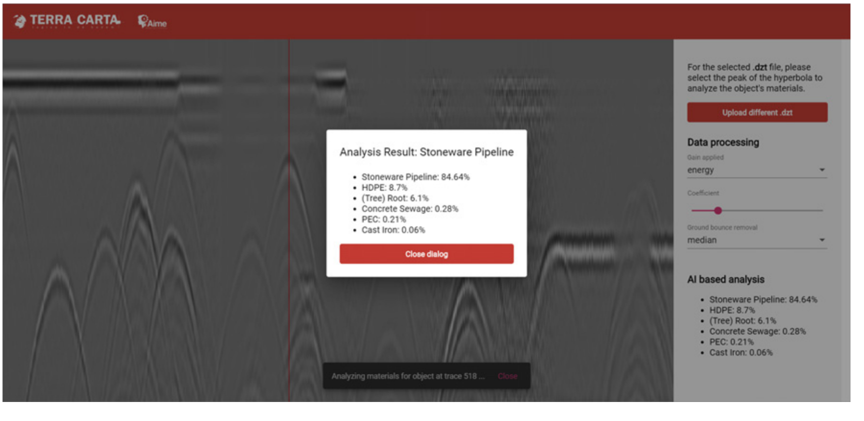

Fig. 5. Hyperbolic Signature Classified Using the System.

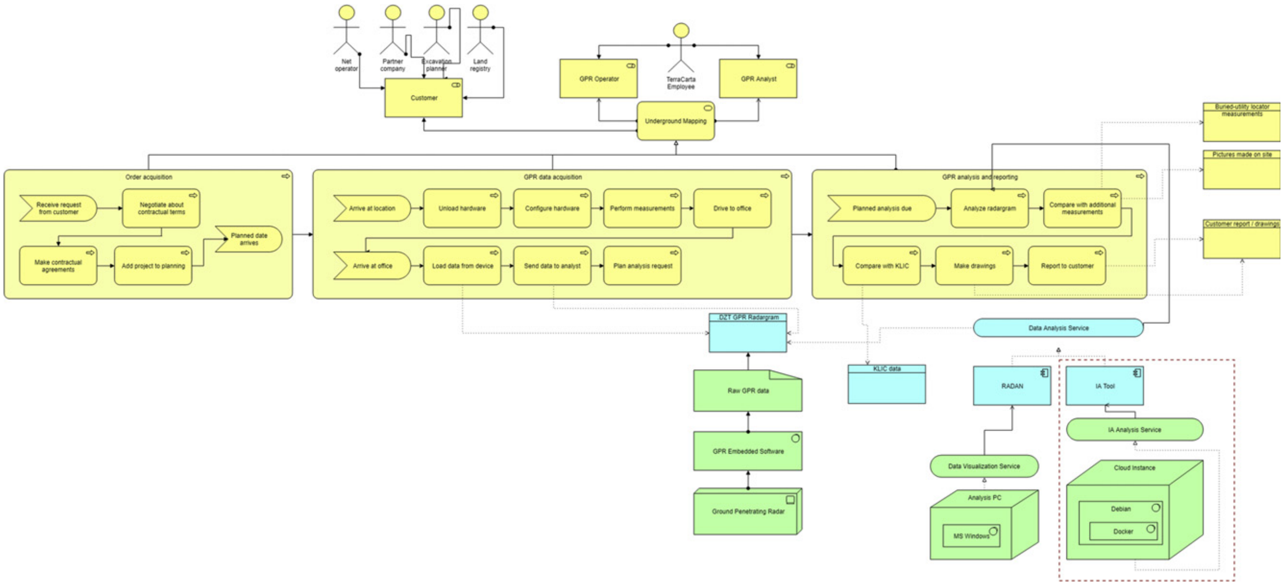

Fig. 6. ArchiMate Model for a Generic GPR Analysis Process.

the GPR image is inspected and preliminary classifications are made based on intuition. Those are compared with additional information such as the KLIC registry or pictures made of trenches dug near utilities. This adds certainty to the analysis. Finally, a drawing is made of the identified utilities. This drawing is then consolidated into a report and sent to the customer. This concludes the analysis and allows the customer to work safely. The intelligent system is part of the 'data analysis service' composition and is highlighted with a dashed box. Its business value lies in assisting the user during analysis with respect to material type. This is currently not supported by existing tooling.

Early Validation Comments

Resulting from utilizing the ADR methodology, the intelligent system was developed in a spirit of co-creation with an industry partner. Consequently, practitioner feedback has been processed into artefact design from the start. Additional feedback was acquired from their upper management and a GPR analyst. It acknowledges the business value provided by the artefact. Specifically, one remark stood out, being that 'this tool could potentially change entirely the way I do my work'.

DISCUSSION

Explaining Performance Differences Between CNNs

The histogram- and DCT-based CNNs were inspired by previous work harnessing SVMs for material type classification (El-Mahallawy & Hashim, 2013). SVMs can only handle relatively sparse data. GPR data are however anything but sparse, with a 100×1024 pixel B-scan slice already yielding approximately 100.000 features. Consequently, scholars were required to reduce input data dimensionality. Histograms and the DCT substantially reduce dimensionality, presumably without data and thus discrimination loss (El-Mahallawy & Hashim, 2013). Precisely this sparsity may in our case result in poor performance when CNNs are applied. In fact, accuracies were only slightly better than random selection while non-sparse feature vectors yielded accuracies averaging 80%. We therefore argue that applying dimensionality reduction to GPR input data for CNNs does indeed deteriorate model performance. We suggest that this behaviour occurs because feature extraction is effectively applied twice. This can be explained through the inner workings of a CNN: the convolution operation applied to the input data effectively allows the network to learn a preconfigured amount of filters itself. We thus suspect that applying feature extraction techniques to reduce input data dimensionality blinds CNN convolution operations to idiosyncrasies in the data, resulting in the relatively poor performance observed. This is in line with the general argument in the DL community to use minimum feature extraction with CNNs (Chollet, 2018).

Effectiveness of Variations

Next, the effectiveness of variations applied to the CNNs is discussed. The discussion primarily focuses on the B-scan CNN variations, since only for this class improvements can be reported. Specifically, the effectiveness of data set expansion, varied activation functions, varied batch size, varied signal gain and combining individual variations is discussed. Based on initial model performance, we hypothesized that our models were underfit given the lack of variety present in our data set. This point of view was confirmed by expanding the dataset from 770 to 2,426 objects, introducing redundancy and extra random noise. This improved the model by approximately 10–15 percentage points. It is however unclear if it remains underfit. State-of-the-art activation functions like Swish and Leaky ReLU did not lead to substantial performance improvements. For Leaky ReLU, there is a slight chance that this observation emerged from misconfiguring the α parameter (Versloot, 2019). However, we argue that it is more likely due to the compactness of our CNNs. That is, Swish and Leaky ReLU avoid the death of ReLU powered networks. In those, neurons can die as a result of the vanishing gradients problem, which becomes stronger when networks are deeper (Versloot, 2019). For Swish, improved model performance was observed in very deep networks (Ramachandran, Zoph, & Le, 2017; Versloot, 2019).

The models used in this study were compact with only two or three convolutional blocks and one densely classified block. Therefore, we argue that ReLU suffices for compact CNNs for GPR imagery. The activation function Tanh resulted in model improvements (Versloot, 2019). It is unclear why this behaviour occurs. However, we believe this might be related to the Batch Normalization and/or L2 Regularization techniques applied to the CNNs. Since Tanh activates on the [−1, +1] range, it might be a more native fit to regularized networks compared to, for example ReLU. Unsurprisingly, increasing batch size improved model performance (Versloot, 2019). This is in line with the mathematical constructs revolving DL model optimization (Chollet, 2018). Neither a surprise are the increasing memory requirements. The DL practitioner should thus always strike an optimal balance between batch size and hardware capabilities before training a DL model. Besides energy gain, we also trained variations without any gain, with strong gain introducing inverted attenuation and linear instead of exponential gain. Fig. 7 demonstrates the effect of those variations on an arbitrary B-scan. The results demonstrate that regular gain performs best, followed by linear gain. Apparently, the main object reflection is considered to be most discriminative for the material type. Although they are not the main discriminator, sub reflections do benefit the discriminative power of the model. This argument is supported by the observation that both stronger and no gain introduce worse performance. Finally, combinations of individual variations were retrained to assess model performance. All three combinations from Table 2 resulted in better model performance, sometimes substantially with respect to observed loss. Why this occurs remains unknown (Versloot, 2019).

Study Limitations

The study reported in this chapter is limited in multiple ways. The first is how the simulations were generated. We used GprMax 2D for this purpose, which simulates wave

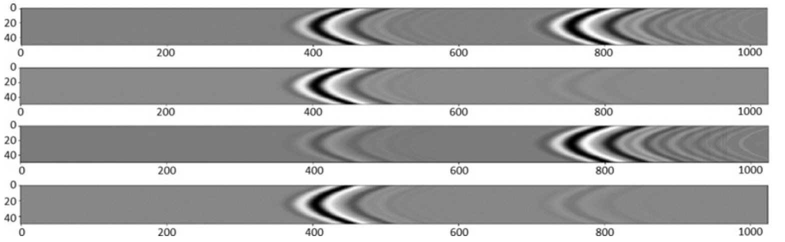

Fig. 7. Regular, No, Strong and Linear Gain Applied; Rotated 90° Counterclockwise.

emission and reception in 2D. Real GPRs however emit and receive them in 3D. This may result in deviations between similar hyperbolae in 2D and 3D imagery. Since no data are mixed, this does not impact the discriminative power of our model (Versloot, 2019). However, the intelligent system should be used with caution. The second limitation is the noise traditionally present in GPR imagery. Although random noise was added in the simulations, it is unknown whether this fully captures the noise levels present in real imagery. Third, during the training process an issue with applying gain was discovered as a result of pre-processing GprMax output data (Versloot, 2019). It is assumed that this issue did not impact ML performance, but it must be corrected should the intelligent system be used with real data. Fourth, the CNNs trained in this work were tuned manually with respect to their hyperparameters. Although this is acceptable practice in the ML community, tooling has emerged which converts finding suitable architectures and hyperparameters into a large search problem (Chollet, 2018; Versloot, 2019). Although the results show that our tuning efforts already lead to plateauing model performance, it may be the case that even better hyperparameters can be identified. Fifth, as illustrated in Section 'Explaining Performance Differences Between CNNs', it remains unknown whether the model is still underfit. It may be the case that model performance can be increased by, for example adding similar objects, objects with peculiarities and objects disturbed by the presence of other objects. Finally, validation feedback was only acquired from within one organization, being the industry partner of this work. To derive additional insights like adoption criteria, it must be validated more broadly.

CONCLUSION

In this work, an intelligent system for predicting utility material types from GPR imagery was designed and developed. It is driven by three classes of CNNs specifically trained for this purpose. Two of them, the histogram-based and DCT-based ones, were inspired by previous research on this problem. The third was inspired by the DL community's wisdom that data should be as raw as possible when using CNNs. GprMax was used for simulating the utilities.

Initially, model performance for all three algorithms was mediocre, presumably due to underfitting resulting from a lack of variety in the dataset. By training various variations to the initial algorithm, including expanding the dataset to 2,426 utilities, performance of the B-scan model was increased to approximately 80%. The histogram-based and DCT-based models did not improve. The system was embedded into a generic GPR analysis process. Early validation comments were retrieved from our industry partner, confirming its business value. Our work therefore contributes to science and practice in multiple ways:

- First, CNNs can successfully be applied to GPR-based object material recognition. Although previous studies achieved this as well, the models trained in this work predict a more varied set of targets which partially overlap in terms of electromagnetic properties.
- Second, the literature on automating utility mapping by means of ML was introduced to IA.
- Third, the feasibility of this approach was demonstrated by designing and developing anintelligent system that interfaces between the ML models and GPR analysts.
- Fourth, this work has allowed our industry partner to validate novel ideas related to interpreting GPR imagery, possibly optimizing their analysis process by consequence.

Multiple suggestions for future work can be made:

- Primarily, it is suggested that the data set is further expanded to assess whether the CNN is still underfit. Possibly, model performance can be improved even further.
- Second, we suggest assessing automated hyperparameter tuning suitability for GPR analysis.
- Third, the compatibility of GprMax 2D simulations and real-world GPR data could be explored.
- Fourth, the generalizability of training CNNs on data simulated for the GPR used by our industry partner to other GPRs could be investigated.
- Fifth, the intelligent system designed and developed in this work could be validated more thoroughly, acquiring insights in design and adopting criteria for tooling supporting GPR analyses.

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