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Implementing Industry 4.0: assessing the current state

Implementing
Industry 4.0

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Abstract

Purpose – The purpose of this paper is to introduce, summarize and combine the results of 11 articles in a special issue on the implementation of Industry 4.0. Industry 4.0 emerged as a phenomenon about a decade ago. That is why, it is interesting now to explore the implementation of the concept. In doing so, four research questions are addressed: (1) What is Industry 4.0? (2) How to implement Industry 4.0? (3) How to assess the implementation status of Industry 4.0? (4) What is the current implementation status of Industry 4.0?

Design/methodology/approach – Subgroups of articles are formed, around one or more research questions involving the implementation of Industry 4.0. The articles are carefully analyzed to provide comprehensive answers.

Findings – By comparing definitions systematically, the authors show important aspects for defining Industry 4.0. The articles in the special issue explore several cases of manufacturing companies that implemented Industry 4.0. In addition, systematic approaches to aid implementation are described: an approach to combine case-study results to solve new implementation problems, approaches to assess readiness or maturity of companies regarding Industry 4.0 and surveys showing the status of implementation in larger samples of companies as well as showing relationships between company characteristics and type of implementation. Small and large firms differ considerably in their process of implementing Industry 4.0, for example.

Research limitations/implications – This special issue discusses implementation of Industry 4.0. The issue is limited to 11 articles, each of which with its own strengths and limitations.

Practical implications – The practical relevance of the issue is that it focuses on the implementation of Industry 4.0. Cases showing successful implementation, measurement instruments to assess degree of implementation and advice how to build a database with cases together with large-scale studies on the state of implementation do provide a wealth of information with a large managerial relevance.

Originality/value – The paper introduces an original take on Industry 4.0 by focusing on implementation. The special issue contains both literature reviews, articles describing case studies of implementation, articles developing systematic measurement instruments to assess degree of implementation and some articles reporting large-scale studies on the state of implementation of Industry 4.0 and thereby combine several perspectives on implementation of Industry 4.0.

Keywords Implementation, Smart manufacturing, Smart industry, Industry 4.0, Readiness, Maturity

Paper type General review

1. Introduction

The manufacturing industry can be characterized by an increasing global competition revolving around production costs and quality. The US–China competition in the

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manufacturing sector is becoming fiercer with a risk of escalation into a trade war. Manufacturing firms have recognized that customers are more demanding than before. Consequently, many firms in the manufacturing industry adjust their production processes. Adjustments take place to improve the quality of both production processes and products to save costs and realize a faster time-to-market. In addition, many companies have started to improve the collaboration with their customers and suppliers by customizing products and services and interlinking processes in the supply chain.

Industry 4.0 has been introduced as a term to describe the trend toward digitization and automation of the manufacturing environment (Oesterreich and Teuteberg, 2016; Brettel *et al.*, 2014). Companies do this to shorten development periods, facilitate customization (“batch-size-one”), improve flexibility, decentralize decision-making and improve resource efficiency (Lasi *et al.*, 2014).

Many countries worldwide are investing in Industry 4.0 such as China, the USA and Europe. Nowadays, the visionary idea of Industry 4.0, or other synonyms like smart manufacturing, smart production or smart industry, to name a few, have been promoted steadily to describe the trend toward digitization, automation and the increasing use of information and communications technology (ICT) in the manufacturing sector (Oesterreich and Teuteberg, 2016). Industry 4.0 involves a structural change of the technology basis of the manufacturing industry, allowing flexibility in terms of product specifications, quality, design, production volume, production timing. Industry 4.0 also enables more efficient use of resources and cost optimization. It helps to ensure that customers are better served, and that optimization takes place not only through the value chain within companies but also through the entire supply chain of companies in an industry. This can strengthen the industry’s position as an engine for growth and as a source of innovation. It requires new skills and will result in new types of jobs. Industry 4.0 drives toward creating new concepts, business models and ways to create synergy.

This special issue is focusing on the implementation of Industry 4.0. We will start with defining Industry 4.0. It is important to have a shared understanding of the concept before we can discuss its implementation. Currently, the notion of Industry 4.0 can be seen as an upcoming literature stream and seems still mainly conceptually. Several publications have outlined what Industry 4.0 entails and what it may look like. In the first research question, we aim to define Industry 4.0 by combining the definitions as proposed by several authors in this special issue.

The special issue will then proceed by addressing a second research question, describing the implementation of Industry 4.0 in several case studies. Various European countries such as Germany, France and The Netherlands have introduced action agenda’s in recent years to indicate how to implement Industry 4.0. Several articles in this special issue will describe the implementation of Industry 4.0 using in-depth case studies. Moreover, a systematic case-based procedure is outlined by which the results of such cases can be fed in a database and used to suggest solutions for the implementation of Industry 4.0 in new cases.

During implementation, it is important to track progress and measure the status of the implementation. That is why, we address tools to systematically assess the implementation status of Industry 4.0 in the third research question.

In the fourth research question, we assess the current status of implementation among a larger set of companies. By assessing the current status, we will address a variety of issues. What are the current successful implementations of the concept? Are there niche applications only or do we witness increased activity and large-scale implementation? Are particular factors, be it institutions or network formation activities, important to increase the speed of implementation?

In short, this special issue will address the following research questions:

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- (1) What is Industry 4.0?
 - (2) How to implement Industry 4.0?
 - (3) How to assess the implementation status of Industry 4.0?
 - (4) What is the current implementation status of Industry 4.0?

In the following sections of this introduction to the special issue, we will introduce how the articles in this issue together answered the aforementioned research questions.

2. Summary of the articles and answers to the research questions

2.1 Clusters of articles answering a research question

2.1.1 Literature review cluster. In total, the special issue comprises of 11 articles. These articles can be divided in distinct clusters. The first cluster, which we will refer to as the literature review cluster, has three articles. These three articles are based on literature reviews and present a conceptual model of Industry 4.0 (Nosalska *et al.*, 2020; Chauhan and Singh, 2020; Garay-Rondero *et al.*, 2020). Hence, this cluster of three articles formulates answers to the first research question (What is Industry 4.0?).

2.1.2 Case-study cluster. The second cluster, which we will refer to as the case-study cluster, comprises of four articles. The articles in the case-study cluster explore in detail how separate manufacturing companies implemented Industry 4.0 (Hermann *et al.*, 2020; Johansson *et al.*, 2020; Veile *et al.*, 2020; Schott *et al.*, 2020). Hence, this cluster answers how Industry 4.0 is implemented in practice by manufacturing companies and thereby partly answers research question 2 (How to implement Industry 4.0?).

2.1.3 Maturity and readiness cluster. The third cluster, which we will refer to as the maturity and readiness cluster, comprises of two articles. In these articles, models and tools are created and applied with which the degree of implementation of Industry 4.0 in companies can be assessed (Santos and Martinho, 2020; Pirola *et al.*, 2020). These articles start with a normative idea how Industry 4.0 can be fully implemented. As Industry 4.0 is a concept that requires integration of technological, business and organizational aspects, several dimensions are formed in these models. A company can score either high or low on each of these dimensions. Hence, this cluster measures the degree of implementation of Industry 4.0 in manufacturing companies in practice and thereby answers the third research question (How to assess the implementation status of Industry 4.0?). The maturity and readiness tools that are derived from the models are also applied and hence also provide an answer to the fourth research question (What is the current implementation status of Industry 4.0?).

2.1.4 Survey/model cluster. The fourth cluster, which we will refer to as the survey and model cluster, comprises of two articles, the first of which provides the results of a survey among a large sample of manufacturing companies in Italy to assess how they implemented Industry 4.0 (Zheng *et al.*, 2020). The second article from this survey/model cluster shows how a large sample of manufacturing companies in South West of the USA implemented Industry 4.0 (Bosman *et al.*, 2020). Both articles thus provide additional answers to the fourth research question (What is the current implementation status of Industry 4.0?). However, both articles also systematically relate the characteristics of companies to the way these companies have implemented Industry 4.0. The articles show that differences between firms, e.g. difference in size, can significantly influence the type of technologies that companies invest in. Some of this detailed information explains how implementation of Industry 4.0 can be accelerated.

An overview of the clusters in provided in Table 1. After the overview, we will discuss the results from each of these clusters in more detail.

Table 1.
Overview of the
articles in the
special issue

Cluster	Addressing research question	Articles
Literature review cluster	(1) What is Industry 4.0?	Nosalska et al. (2020) Chauhan and Singh (2020) Garay-Rondero et al. (2020)
Case-study cluster	(1) How to implement Industry 4.0?	Hermann et al. (2020) Johansson et al. (2020) Veile et al. (2020) Schott et al. (2020)
Maturity and readiness cluster	(1) How to assess the implementation status of Industry 4.0? (2) What is the current implementation status of Industry 4.0?	Santos and Martinho (2020) Pirola et al. (2020)
Survey and model cluster	(1) What is the current implementation status of Industry 4.0?	Zheng et al. (2020) Bosman et al. (2020)

2.2 The literature review cluster defining Industry 4.0

The first three articles in different ways define Industry 4.0 ([Nosalska et al., 2020](#); [Chauhan and Singh, 2020](#); [Garay-Rondero et al., 2020](#)). The three articles are based on a systematic and comprehensive literature review, and all of them use the information from these reviews to create an overarching model. The first article, like most articles in the field of Industry 4.0, has an internal manufacturing company focus, the second article takes a supply chain management perspective by looking at multiple companies and the third article combines the two perspectives.

It is interesting to notice that “industry” as a term encompasses several engineering and business disciplines, not just manufacturing. This is why, the contrast between the articles is so interesting. These articles come from different disciplinary perspectives, manufacturing and supply chain management, each of which in different ways carefully defines Industry 4.0. We will now discuss the differences and commonalities between the two articles.

In [Table 2](#) are some of the main differences and commonalities between the three articles in the literature review cluster. The three articles are in the columns. The first row of the table reveals the disciplinary perspective of these articles. The next six rows specify aspects of the Industry 4.0 definition, beginning with the degree of formality of the definitions in the second row. The next rows refer to different types of definitions. Concepts can be defined in terms of their constituent parts or the mechanisms that tie the concept together (row 3). An example of such a definition would be to specify several technologies that are combined in a digital network to form Industry 4.0. Concepts can also be defined in terms of their causes or antecedents (row 4). An example of such a definition would be to specify the reasons why Industry 4.0 emerged. By contrast, concepts can also be defined in terms of their consequences or effects (row 5). An example of such a definition would be to specify that Industry 4.0 makes manufacturing more sustainable and efficient. Concepts can also be defined in terms of the category to which they belong, their environment or the complementary aspects with which they can be combined (row 6). An example of such a definition would be to specify that Industry 4.0 is one of the trends reflecting the digitalization in our societies. Finally, concepts can also be defined by contrasting them with other concepts (row 7). An example of such a definition would be to indicate how Industry 4.0 is different from supply chain digitalization. Each of these alternative ways of defining the complex concept of Industry 4.0 will be used to contrast the definitions of Industry 4.0 as provided by

	(Nosalska <i>et al.</i> , 2020) Defining Industry 4.0 from a manufacturing perspective	(Chauhan and Singh, 2020) Defining Industry 4.0 from a supply chain management perspective	(Garay-Rondero <i>et al.</i> , 2020) Defining Industry 4.0 by combining the two perspectives
Disciplinary perspective	Manufacturing perspective	Supply chain management perspective	Manufacturing and supply chain perspective combined
Degree of formality of definition	Explicit definition	Implicit definition	Implicit definition
Definition in terms of constituent parts and mechanisms	Formal definition in terms of constituents parts is derived from the literature	The main aspects are put together and summarized in tables	The main aspects are summarized in figures and tables
Definition in terms of causes or antecedents of I4	Generic causes of Industry 4.0 are described, there is almost no systematic analyses of relative or combined effect of antecedents on Industry 4.0, or on the speed or degree of implementation of Industry 4.0 practices		
Definition in terms of consequences or effect of I4	Generic performance effects of Industry 4.0 are described but not quantified Article focuses on direct effects on manufacturing	Wider societal and economic consequences are discussed	Article focuses on actors and factors in supply chain
Definition in terms of category, environment or complementary aspects of I4	Hardly described	Extensively discussed	Hardly described
Definition in terms of contrast of I4 with related concepts	Boundary of the concept is hardly set, and the contrast with other concepts is hence missing	Contrast between a manufacturing and supply chain management perspective is described. An overview of different units of analysis chosen in Industry 4.0 literature is provided	Boundary is set by the supply chain or network with all actors, components, processes and types of management to coordinate activities
Implementation of I4	Hardly discussed in the articles		

Table 2.
Differences and
commonalities
literature review
articles defining
Industry 4.0

the first three articles in our special issue (Nosalska *et al.*, 2020; Chauhan and Singh, 2020; Garay-Rondero *et al.*, 2020). The last row in the table will then address whether or not the articles explicitly refer to implementation of Industry 4.0.

The first article with the title “Industry 4.0: Coherent Definition Framework with Technological and Organizational Interdependencies” analyzes a large number of articles in a rigorous way (Nosalska *et al.*, 2020). The article describes how Industry 4.0 originated from a German government initiative presented at the Hannover Messe in 2011. The motivation of this initiative was to provide manufacturing systems that optimize the production costs while providing mass customized products to fulfill individual customer needs. An extensive list of new technologies and solutions are described that enable the seemingly contradictory requirements of low cost and customization in production. These technologies include, e.g. virtual reality (VR), radio frequency identification (RFID) and robotics. Yet, the authors stress that Industry 4.0 is not just a collection of new technologies, it is the consistent combination of both technological and business aspects. The enabling technologies are used to form an integrated system of both technological and business factors. Three main technological factors are distinguished: (1) cyber physical systems (CPS) that connect the physical and the virtual world, (2) smart factories in which personalized products can be created and (3)

internet of things (IoT) the network that allows communication in real and virtual worlds. Four main business factors are distinguished: (1) value chain integration providing real-time data collection, processing and intelligent decision support systems across the entire value chain; (2) new business models to capture value in new ways; (3) smart products that deliver higher value by providing data and by upgrading during its lifetime, for example; and finally, (4) customer position, referring to the personalized approach to customers as partners in the value creation process. All these aspects are then combined in a coherent but broad definition. Industry 4.0 is

a concept of organizational and technological changes along with value chain integration and new business model development that are driven by customer needs and mass customization requirements, and enabled by innovative technologies, connectivity, and IT integration (Nosalska *et al.*, 2020, p. xxx).

Such a coherent definition is scientifically and managerially relevant because it facilitates implementation by making the concept explicit by describing its main components. This article provides groundwork by carefully defining Industry 4.0, yet it does not explore speed or degree of implementation of Industry 4.0.

The second article with the title “A Review of Industry 4.0 in Supply Chain Management Studies” explores by means of a rigorous and systematic literature review how Industry 4.0 is considered in the context of the supply chain management (Chauhan and Singh, 2020). The vast majority of the literature on Industry 4.0 is found to consist of conceptual papers, a minority of papers is empirical, most of which are case studies. Different units of analyses are focused on in the extant literature. Most articles mention the supply chain as a unit of analysis, yet in practice, most articles focus on a focal manufacturing firm. This conclusion is further validated by the observation that relationships between firms are less investigated. The authors conclude that the scientific field of Industry 4.0 is still in an emergent phase. Rather than creating a systematic and comprehensive definition, the authors start providing a list of definitions from the contemporary literature. These definitions primarily define Industry 4.0 in terms of its constituting technologies. The authors then discuss a large variety of aspects related to the concept of Industry 4.0. The article provides a comprehensive view on Industry 4.0. Both the antecedents/causes and the consequences/effects of Industry 4.0 are carefully described after studying the literature. Like all articles, the constituting parts and mechanisms of Industry 4.0 are also described. The article is quite elaborate in terms of discussing the effect of Industry 4.0 on society at large. Socio-technical aspects such as the laws, regulation and standards but also the potential consequences of Industry 4.0 such as the privacy for individuals and the data security for companies are discussed. Like the first article (Coherent Definition Framework with Technological and Organizational Interdependencies), this article focuses on reviewing the literature and thereby defining Industry 4.0 rather than discussing the degree and speed of implementation.

The authors of the third article with the title “Digital Supply Chain Model in Industry 4.0” combine two literature streams in their literature review, one focusing on supply chain management and the other on Industry 4.0 (Garay-Rondero *et al.*, 2020). The first literature review explores the main concepts and models in supply chain management that emerged in a timeframe of 20 years, from 1989–2019. Traditionally, supply chain management is seen as a kind of pipeline structure of actors with different roles in which flows of goods, services, information and money are managed and controlled. Traditional roles of actors are suppliers, focal manufacturing firm, wholesalers or distributors, retailers and final customers. The article provides a clear contrast between traditional supply chain management and management of a digital supply chain. In fact, the chain has become a network, and the traditional roles, flows and processes have fundamentally changed. After their review, the authors conclude that a new overarching model of the digital supply chain network has

not yet emerged. The second literature review in the same article focuses on Industry 4.0 and explores to what extent the ideas and concepts of Industry 4.0 are having an impact on supply chain management and are integrated in the thinking of supply chain management models. That is hardly the case, and hence, the authors contribute to the extant literature by creating an overarching framework of how Industry 4.0 fits in the field of (digital) supply chain management.

2.3 The case-study cluster describing how to implement Industry 4.0

The next four articles study how Industry 4.0 can be implemented in practice and what the challenges are during implementation ([Hermann et al., 2020](#); [Johansson et al., 2020](#); [Veile et al., 2020](#); [Schott et al., 2020](#)). These articles study cases of companies that implemented Industry 4.0. In this cluster, the focus is on the implementation process (e.g. How to design such a process? What is a typical structure of an implementation process?). To design an implementation process, companies build on a shared understanding of what Industry 4.0 entails. Or, as it was formulated in [Hermann et al. \(2020\)](#): a critical requirement before the implementation can start is that everybody involved in the case study gains a common understanding of what is to be understood by Industry 4.0. Articles in the next cluster (the case-study cluster) are built on the foundation of the literature review cluster.

The fourth article has the title “Industrie 4.0 Process Transformation: Findings from a Case Study in Automotive Logistics” ([Hermann et al., 2020](#)). The article focuses on logistics and supply chain processes in a leading automotive company in Germany. This company faced the challenge to provide an increasing number of product variants, which led to increased process complexity and time-consuming process planning. The article studies how to design the transformation of logistics and supply chain operations that need to be implemented as part of Industry 4.0. In this article, literature reviews, focus groups and process design sessions were used to create a process to enable logistics and supply chain operations that could be applied in the company. The article reports the experiences, in that company with the subsequent steps of implementation, being (1) analysis of the current process, (2) development of a vision for the target process, (3) development of a strategic action plan to implement the target process successfully and (4) implementation of the target process. In the vision formation (step 2), it was deemed important to have a shared understanding of the concept of Industry 4.0. The authors describe how specific design principles for Industry 4.0 helped to create such a shared understanding. The implementation in the automotive company, being one case, contributed to a generic process indicating how to implement Industry 4.0 in practice in similar companies. Interestingly, in the analysis of the current process (step 1), the company formulated the need to assess the maturity of the company in terms of Industry 4.0. This maturity or readiness assessment then serves as a kind of starting point and level from which subsequent steps can be taken. We will discuss maturity and readiness tools in the next cluster of articles (the maturity and readiness cluster).

The fifth article has the title “Challenges of Handling Assembly Information in Global Manufacturing Companies” ([Johansson et al., 2020](#)). This article focuses on assembly information systems in manufacturing companies of complex products (vehicles, transport systems, machinery or equipment). In a multiple-case study approach and by applying several different instruments such as surveys, observations and interviews, the authors are able to derive six focus areas that represent a challenge when implementing Industry 4.0, in particular for assembly information. Especially when a company faces a varied and personalizes demand from its customers and thus needs to produce customized products, the assembly information will be different for each and every system that is produced. Many manufacturing companies work with assembly information systems that are low in maturity,

as many of them are on paper. The authors show how the maturity of assembly information systems can be captured in a maturity model with eight levels. For assembly-intensive manufacturing companies, especially those that still work manually, six typical challenges are found: (1) IT challenges, (2) process challenges, (3) assembly process disturbances, (4) information availability, (5) technology and process control and (6) assembly work instructions. These challenges hinder the implementation of Industry 4.0. It is interesting to notice that in this article, again, a maturity assessment tool is applied as part of the analysis of the current situation. In this article, that maturity tool does not assess the maturity of Industry 4.0 implementation but rather the maturity of assembly information systems.

The sixth article has the title “Lessons learned from Industry 4.0 implementation in the German manufacturing industry” (Veile *et al.*, 2020). The article explores how 13 large companies have implemented Industry 4.0 and the main lessons that can be learned from this. The companies comprise machine and plant manufacturers, electrical engineering companies and automotive companies. In a multiple case-study approach, the authors look at implementation from a socio-technical scientific perspective. That means that rather than technologies and technological processes, the study in detail focuses on technical, organizational and human aspects. Instead of seeing those aspects as separate, the authors in particular look at the overlap between technical, organizational and human aspects. This wide view on implications of Industry 4.0 within companies is important because, as the authors put it, “Neglecting a single dimension could block the entire implementation progress.” Six lessons are derived from the experience of the implementation, as studied in 13 companies:

- (1) Industry 4.0 requires fundamentally new competences by employees, the first lesson refers to these competences of employees and how to educate them.
- (2) As Industry 4.0 requires new knowledge, the second lesson refers to the changing relationship with various knowledge and research institutes.
- (3) The third lesson refers to necessary organizational changes into more flat and decentralized decision-making, strong links with spin-offs and the deration of multidisciplinary teams.
- (4) The fourth lesson focuses on corporate culture changes, the culture in companies should be characterized by flexibility, openness, willingness to learn and an entrepreneurial mindset.
- (5) The fifth lesson refers to the openness and trust that is required to share data with partner companies in the entire supply chain.
- (6) The sixth lesson indicates how Industry 4.0 should be integrated in the existing machinery and production systems.

The seventh article has the title “Case-based reasoning for complexity management in Industry 4.0” (Schott *et al.*, 2020) introduces a systematic approach to store the knowledge gained while solving particular issues during the implementation of Industry 4.0 in a manufacturing firm. The case-based reasoning involves the systematic analysis of the issue (the case-characteristics) and the proposed solution. The systematic analysis of issues facilitates a match between past issues and a current issue. By adding many of those past issues and their respective solutions, a database is formed that can be used to inspire solutions for current issues that resemble issues which appeared earlier on.

2.4 The maturity and readiness cluster assessing the implementation status

The next two articles (Santos and Martinho, 2020; Pirola *et al.*, 2020) describe a maturity model and a readiness assessment model for Industry 4.0. Maturity models and readiness assessment models for Industry 4.0 enable an objective and impartial evaluation of a company's position, by deciding what needs to be measured and how to assign a specific degree of maturity to a company regarding Industry 4.0 (Pirola *et al.*, 2020).

Creating a maturity or readiness model requires the combination of elements from other models, such as technology readiness, organizational readiness, maturity of human competences and so on. Both articles, however, integrate these elements, thus providing a more holistic tool for a complete evaluation of manufacturing companies' status regarding implementation of Industry 4.0. This integration is important according to ElMaraghy and ElMaraghy (2016). Isolated maturity or readiness models may seem to have no evident relation and can contribute to incremental improvements of productivity and flexibility for organizations. In practice, however, the integration of these aspects can deeply modify companies, supply chains competitiveness and society in general (Santos and Martinho, 2020).

The objective and impartial evaluation of a company's position regarding the implementation of Industry 4.0 can be used in different ways. In short, the two articles (Santos and Martinho, 2020; Pirola *et al.*, 2020) provide four purposes:

- (1) to measure the current state of the company (initial diagnostic and monitoring assessments);
- (2) to compare different companies (benchmark);
- (3) to plan the future desired state (goal); and
- (4) to provide basic guidelines to envision efforts and agreements for future developments needed to reach higher levels (in the direction of the goal).

Maturity and readiness models provide an important tool for companies that want to implement the concept of Industry 4.0. These models also provide an important tool for scientists.

Both articles describe the process of building up such maturity or readiness models. For both models, the instrument to measure maturity/readiness is provided in an appendix, meaning that interested companies or scientists can easily use these instruments to assess their own company's maturity or readiness. Both articles will now be discussed separately below.

The eighth article with the title "An Industry 4.0 Maturity Model Proposal" proposes a refined maturity model after reviewing three maturity models from the literature (Santos and Martinho, 2020). This model is developed on the basis of a literature review, interviews with engineers and managers and a pilot test in two industrial companies. The model in the article is combining five dimensions: (1) organizational strategy, structure and culture; (2) workforce; (3) smart factories; (4) smart processes and (5) smart products and services. After defining these dimensions carefully, the authors show the aspects that need to be mastered to show the maturity on each of these dimensions. These aspects are referred to as transformation capabilities and the company's maturity.

The ninth article with the title "Digital readiness assessment of Italian SMEs: is a case-study research" (Pirola *et al.*, 2020) that provides a similar tool as the previous article. Some additions and differences are worth mentioning. Firstly, the article extends the literature review by comparing both scientific and more commercial maturity/readiness models. Secondly, the article focuses on SMEs, an important choice because most maturity/readiness models almost implicitly seem to focus on large corporations. However, SMEs represent a

large majority of the companies, also in the manufacturing industries. SMEs lack the departmental division and the resources that large corporations usually have and hence require an adapted model. Thirdly, in the literature (e.g. [Schumacher et al., 2016](#)), it is clearly explained that the tool needs to be adapted to the industrial context of a company to be useful. Some practices, competences or technologies are not applicable in specific companies, and hence, these aspects should not be part of the readiness tool for each company. The authors, therefore, decided to make a kind of modular readiness tool, meaning that companies depending on their situation do or do not include specific aspects in the model. Fourthly, the authors describe in detail how the readiness assessment can be used to formulate strategies for further implementation of Industry 4.0. Finally, the authors present the results of applying their model on a heterogeneous sample of 20 SMEs in Bergamo, a city in the Northern part of Italy. These results provide a stepping stone toward the descriptive survey that reports results regarding Industry 4.0 for a larger sample of companies (see below [Zheng et al., 2020](#)).

2.5 The survey and model cluster measuring implementation in larger samples

In this cluster are two articles ([Zheng et al., 2020](#); [Bosman et al., 2020](#)), both of which used larger samples of companies, which allowed them to explore specific relationships using statistical analysis.

The tenth article with the title “The impacts of Industry 4.0: A descriptive survey in the Italian manufacturing sector”, analyzes the knowledge and adoption levels of specific Industry 4.0 technologies ([Zheng et al., 2020](#)). The article sees levels of knowledge in a company regarding specific technologies as a good predictor of later adoption of the same technologies. The article shows that the companies in the sample generally hold limited knowledge of the technologies, and that is in line with the overall limited degree of implementation of Industry 4.0. So, the survey confirms a link between knowledge of the combined Industry 4.0 technologies and adoption of these technologies in the sample. However, more detailed analyses show that the level of knowledge of separate technologies does not automatically lead to adoption. Some technologies are well known, but are less applicable in specific companies. In that case, high levels of knowledge can go with low levels of adoption. Another interesting finding is that the level of knowledge differs per technology. More specifically, departments in companies differ in their knowledge level of technologies. Both findings may hamper implementation because that requires the integration of multiple technologies and a fundamental change in the way the different departments of a company cooperate. The authors also show how companies depending on their size and their degree of “informatization” differ in terms of knowledge and implementation. The notion that applicability of separate technologies depends on the type of company and its context was also noticed in the ninth article ([Pirola et al., 2020](#)), which presented an adaptable or modular readiness model. In the next article, such contextual differences are further explored.

The 11th article with the title “How Manufacturing Firm Characteristics Can Influence Decision Making for Investing in Industry 4.0 Technologies” investigates Industry 4.0 investment decisions by a sample of manufacturers in the Midwest USA ([Bosman et al., 2020](#)). The article explores some of the barriers to implementation of Industry 4.0. Firstly, the infinite number of high-tech solutions and continuous technology upgrades can leave manufacturing firms overwhelmed. Secondly, the lack of interoperability of new technologies or their lack of conformance to standards with other technologies in the company and in related companies in the supply chain may hamper adoption of Industry 4.0 technologies. Thirdly, companies have problems in hiring the employees with the right competences to implement Industry 4.0. The authors show, like several articles in this special issue, that the way of implementing Industry 4.0 depends on the industry as a whole and on the company in particular. Or, to put it differently: implementation should be adapted to the context. Smaller

manufacturers, those with less than 20 employees or sales less than US\$10m, primarily invest in digital factory floor technologies that directly impact the productivity quality and safety of manufacturing processes. By contrast, larger manufacturing companies mainly support operation technologies.

3. Conclusion

We discussed 11 articles on the implementation of Industry 4.0 that are complementary. These papers highlight the different aspects of convergence of technological advancements in the area of information technology with new approaches in the area of manufacturing and supply chains. Some of them provide a definition of Industry 4.0, mention the challenges and provide suggestions to implement Industry 4.0. Others provide tools to assess the degree of implementation.

It is also interesting to notice what is missing after such a wealth of information on the implementation of Industry 4.0. The tenth and 11th article in this issue ([Zheng et al., 2020](#); [Bosman et al., 2020](#)) are examples of more large-scale empirical research on the implementation of Industry 4.0. Their results indicate that implementation of Industry 4.0 differs per sector and type of company. These results call for the formulation of specific implementation processes for different companies. Such implementation scenarios would help in developing a strategic agenda to accelerate the implementation of Industry 4.0. We think this would represent a promising avenue for future research.

References

- Bosman, L., Hartman, N. and Sutherland, J. (2020), "How manufacturing firm characteristics can influence decision making for investing in Industry 4.0 technologies", *Journal of Manufacturing Technology Management*, Vol. 31.
- Brettel, M., Friederichsen, N., Keller, M. and Rosenberg, M. (2014), "How virtualization, decentralization and network building change the manufacturing landscape: an Industry 4.0 perspective", *International Journal of Mechanical, Industrial Science and Engineering*, Vol. 8 No. 1, pp. 37-44.
- Chauhan, C. and Singh, A. (2020), "A review of Industry 4.0 in supply chain management studies", *Journal of Manufacturing Technology Management*, Vol. 31.
- ElMaraghy, H. and ElMaraghy, W. (2016), "Smart adaptable assembly systems", *Procedia CIRP*, Vol. 44 Nos 4-13, pp. 127-128.
- Garay-Rondero, C.L., Martinez-Flores, J.L., Smith, N.L., Morales, S.O.C. and Aldrette-Malacara, A. (2020), "Digital supply chain model in Industry 4.0", *Journal of Manufacturing Technology Management*, Vol. 31.
- Hermann, M., Bücker, I. and Otto, B. (2020), "Industrie 4.0 process transformation: findings from a case study in automotive logistics", *Journal of Manufacturing Technology Management*, Vol. 31.
- Johansson, P.E.C., Malmköld, L., Fast-Berglund, Å. and Moestam, L. (2020), "Challenges of handling assembly information in global manufacturing companies", *Journal of Manufacturing Technology Management*, Vol. 31.
- Lasi, H., Fettke, P., Kemper, H.G., Feld, T. and Hoffmann, M. (2014), "Industry 4.0", *Business and Information Systems Engineering*, Vol. 6 No. 4, pp. 239-242.
- Nosalska, K., Piątek, Z.M., Mazurek, G. and Rządca, R. (2020), "Industry 4.0: coherent definition framework with technological and organizational interdependencies", *Journal of Manufacturing Technology Management*, Vol. 31.

-
- Oesterreich, T.D. and Teuteberg, F. (2016), "Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry", *Computers in Industry*, Vol. 83, pp. 121-139.
- Pirola, F., Cimini, C. and Pinto, R. (2020), "Digital readiness assessment of Italian SMEs: a case-study research", *Journal of Manufacturing Technology Management*, Vol. 31.
- Santos, R.C. and Martinho, J.L. (2020), "An Industry 4.0 maturity model proposal", *Journal of Manufacturing Technology Management*, Vol. 31.
- Schott, P., Lederer, M., Eigner, I. and Bodendorf, F. (2020), "Case-based reasoning for complexity management in Industry 4.0", *Journal of Manufacturing Technology Management*, Vol. 31.
- Schumacher, A., Erol, S. and Sihni, W. (2016), "A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises", *Procedia CIRP*, Vol. 52 No. 1, pp. 161-166.
- Veile, J.W., Kiel, D., Müller, J.M. and Voigt, K.-I. (2020), "Lessons learned from Industry 4.0 implementation in the German manufacturing industry", *Journal of Manufacturing Technology Management*, Vol. 31.
- Zheng, T., Ardolino, M., Bacchetti, A., Perona, M. and Zanardini, M. (2020), "The impacts of Industry 4.0: a descriptive survey in the Italian manufacturing sector", *Journal of Manufacturing Technology Management*, Vol. 31.

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