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Lessons learned from Industry 4.0 implementation in the German manufacturing industry

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Abstract

Purpose – Industry 4.0 is assumed to yield extensive industry-spanning opportunities. However, exploiting these opportunities requires a targeted implementation of Industry 4.0. The purpose of this paper is to generate a deeper understanding of relevant implementation action. Existing recommendations are mostly general, highly aggregated and difficult to grasp. Yet, specific and concrete actions that need to be taken to accelerate the realization of Industry 4.0 are essential.
Design/methodology/approach – The article uses 13 semi-structured in-depth expert interviews as the source of empirical data. The interviews were conducted with managers from Industry 4.0-experienced German manufacturing companies. All interviews are analyzed using qualitative content analysis.
Findings – The study reveals relevant and targeted aspects for Industry 4.0 implementation: the development of Industry 4.0-specific know-how, securing financial resources, integrating employees into the implementation process and establishing an open-minded and flexible corporate culture. Further aspects include comprehensive planning processes, cooperation with external partners, proper handling of data interfaces, interdisciplinary communication, an adaptable organizational structure and data security.
Research limitations/implications – The paper is limited to German manufacturing enterprises and should be transferred to other industries and countries.
Practical implications – The study supports managers to effectively implement Industry 4.0 within their organizations and consequently benefit from Industry 4.0 and derives recommendations for future research.
Originality/value – The paper is among the first to give specific and concrete examples for lessons learned from Industry 4.0 implementation, directly obtained from industrial application.

Keywords Industry 4.0, Industrial Internet of Things, Digital transformation, Implementation, Qualitative research, German companies

Paper type Research paper

1. Introduction

The new manufacturing paradigm “Industry 4.0” which is internationally known as “Industrial Internet of Things” refers to digitized and connected industrial value creation (Ghobakhloo, 2018; Kagermann *et al.*, 2013). It is characterized by intelligently, horizontally and vertically connecting people, machines, objects and information and communication technology (ICT) systems. Thereby, future value creation is located in digitized, real-time capable, intelligent, connected and autonomous factories and production networks. Industry 4.0 is assumed to yield extensive industry-spanning opportunities, e.g., increases in efficiency, quality and flexibility. In sum, Industry 4.0 is considered to qualify for maintaining companies' competitiveness whilst ensuring future competitiveness (Kagermann *et al.*, 2013; Müller, Buliga and Voigt, 2018).

Before companies are able to exploit the opportunities yielded by Industry 4.0 and fully benefit from them, they need to implement Industry 4.0 in a targeted and adequate way. In management research, Industry 4.0, its implementation and its economic, environmental and social implications represent a comparably young research field (Kiel *et al.*, 2017; Müller, Kiel and Voigt, 2018). So far, there is little experience in corporate practice with respect to a purposeful and successful Industry 4.0 implementation.

Given the specific and complex nature of Industry 4.0, enterprises need to undertake appropriate implementation strategies tailored to the individual design of their institutional and process organization structure (Müller, Buliga and Voigt, 2018). Yet, up to now, literature provides corporate practice with general and highly aggregated recommendations that are difficult to grasp and usually disregard company-specific characteristics.

The goal of this paper is to provide purposeful guidelines and recommendations to design Industry 4.0 implementation process effectively, generating a deeper understanding of relevant implementation actions that need to be taken. The study at hand does not only provide concrete recommendations, but also enriches current research developing a conceptual model of an implementation process.

The paper is organized as follows. First, the term Industry 4.0 is defined, giving an overview of the current state of research regarding its implementation. Second, the research method is outlined. Third, empirical results are presented in seven areas to implement Industry 4.0 in corporate contexts. Fourth, results are discussed and compared with current literature, subsequently developed into a framework for Industry 4.0 implementation. Finally, limitations and further research areas are presented.

2. Theoretical background

2.1 Industry 4.0

Technological developments, progresses in the area of ICT systems, and the internet-based connection of entire value chains represent the fundament of Industry 4.0 (Kagermann *et al.*, 2013). Cyber-physical systems (CPS), comprising sensors, microprocessors and actuators constitute the technological core of Industry 4.0 and enable real-time data transfer (Müller, Buliga and Voigt, 2018).

Based on digitization, automation and interconnection, Industry 4.0 represents a paradigm change and is believed to be the next industrial revolution (Liao *et al.*, 2017). Its goal is to interconnect resources, information, objects and human beings in industrial value creation (Kagermann *et al.*, 2013).

Figure 1 illustrates the horizontal integration that is intended through Industry 4.0. This describes the digital interconnection of entire supply chains and customers in real-time. This approach leads to eased data exchange, and thereupon data analysis, which paves the way for numerous benefits for all supply chain partners, and the customer. For example, the better alignment of processes across the supply chain can lead to an increased resource efficiency in terms of material usage, energy consumption, and waste processes, resulting in cost reductions and productivity increases (Saberi and Yusuff, 2011; Müller, Kiel and Voigt, 2018). Besides, value creation processes across the supply chain can be more flexible and decision making is optimized. In addition, Industry 4.0 paves the way to develop and market highly customized innovative products and services. Further, innovation management itself undergoes fundamental changes, as data can flow back from product usage to product development directly (Yoo *et al.*, 2012). However, the exchange of data along the supply chain faces several technical challenges, accompanied by concerns that data might be transparent to competitors or third parties. As a result, especially SMEs are reluctant

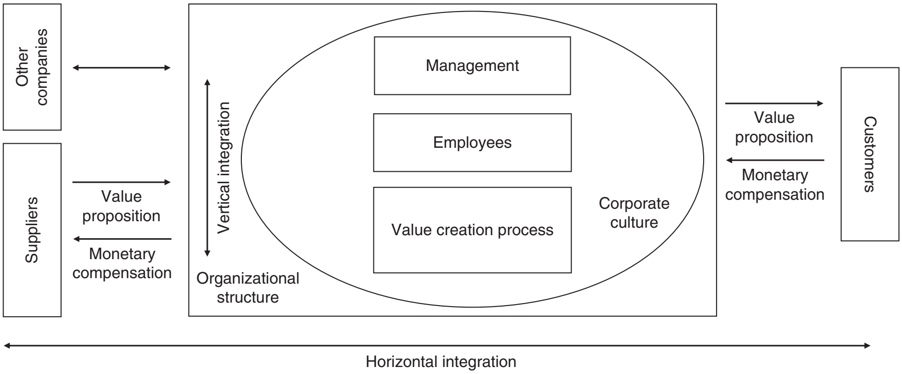


Figure 1.
Framework of
Industry 4.0
implementation

toward the Industry 4.0, as they fear losing bargaining power or to be replaced (Kiel *et al.*, 2017; Müller, Kiel and Voigt, 2018).

Additionally to horizontal integration, vertical integration within a company is intended through Industry 4.0. This means that separate departments grow together virtually, for instance from product development, operations management, to marketing and sales. However, such approaches require, among further, a different organizational change and culture, interdisciplinary thinking and the addressing of several social challenges, such as a loss of jobs or competencies within this transformation process (Kagermann *et al.*, 2013; Kiel *et al.*, 2017).

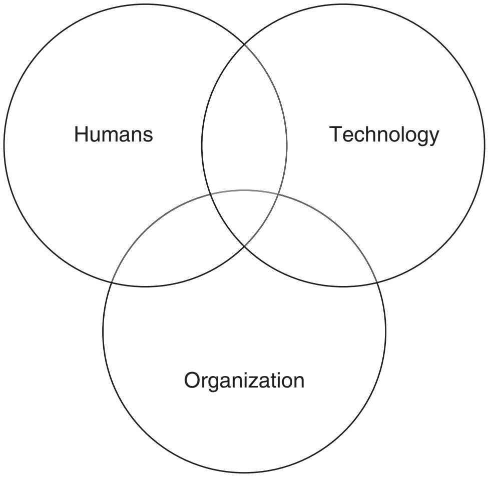
An effective Industry 4.0 realization is the goal of national economies all over the world. For instance, the "Industrial Internet Consortium" in the USA, the "Internet Plus Initative" within "Made in China 2025," among further (Liao *et al.*, 2017; Müller and Voigt, 2018).

2.2 Implementation of Industry 4.0

Besides technical challenges, Industry 4.0 implementation is described in literature as further encompassing organizational and social concerns (Kiel *et al.*, 2017; Thoben *et al.*, 2017). Therefore, the paper takes a socio-technical system approach (Coenen and López, 2010), as all dimensions as well as their overlapping have to be considered when implementing Industry 4.0. Oks *et al.* (2017) introduce an approach and state human, technological and technical aspects are to be considered when implementing industrial CPS. The paper extends the approach and transfers it to the context of Industry 4.0. In doing so, the paper adds that not only the single dimensions, but also their overlapping are of importance. Neglecting a single dimension could block the entire implementation progress. Thus, all dimensions including their respective interdependencies need to be considered and addressed during the implementation process as they are inter-related. Figure 2 illustrates the dimensions and their overlapping.

Table I gives an overview of the main topics regarding Industry 4.0 implementation economic research has dealt with so far.

In order to be able to work in smart factories, humans need to have several skills and competencies. The basis of working in the digital era is confidence in technology (Erol *et al.*, 2016). Further, humans need to have a fundamental understanding of ICT systems, automation technology, and data analysis. Additionally, being aware of issues concerning data abuse and ICT security is critical (Erol *et al.*, 2016; Schuh *et al.*, 2017). Humans should have interdisciplinary knowledge and an understanding of interconnected systems (Erol *et al.*, 2016; Kagermann *et al.*, 2013). The automation of processing steps increases planning and controlling tasks, which in turn asks for further decision-making competence of humans (Schuh *et al.*, 2017). These skills and competencies can be developed and improved by



Source: Oks *et al*. (2017)

Figure 2.
Humans, organization and technology model

Table I.
State of research on Industry 4.0 implementation with exemplary sources

Dimensions/interfaces	Key statements	Exemplary sources
Humans	Trainings and further education help to develop and improve vital competencies and know-how	Birkel *et al.* (2019), Darbanhosseiniamirkhiz and Ismail (2012), Erol *et al.* (2016), Kagermann *et al.* (2013), Schuh *et al.* (2017)
Humans technology	Assistance systems support humans in their value adding activities Training for humans regarding new technologies is required Matters of work safety become more important with increasing human–machine interactions	Block *et al.* (2015), Kagermann *et al.* (2013), Kamble *et al.* (2018), Tupa *et al.* (2017)
Technology	Technological developments like CPS, big data and cloud solutions enable future value creation in smart factories Close interaction with established concepts like lean management of just-in-time	Moktadir *et al.* (2018), Telukdarie *et al.* (2018), Tortorella and Fettermann (2018)
Technology–organization	Different hierarchical levels are connected in a vertical system integration Organization needs to be aligned according to technological developments Interactions between suppliers, customers, and partners are improved by a horizontal interconnection	Kagermann *et al.* (2013), Moktadir *et al.* (2018), Mosler (2017), Siepmann (2016)
Organization	Agile forms of organization (decentralized decision making, flat hierarchies) Inter-firm networks and strategic cooperation Changing business models	Hermann *et al.* (2015), Müller, Buliga and Voigt (2018), Schuh *et al.* (2017)
Organization–Humans	Cultural change (acceptance of changes, entrepreneurial spirit, failure tolerance, democratic style of leadership, open communication)	Burmeister *et al.* (2016), Davies *et al.* (2017), Moktadir *et al.* (2018), Saberi and Yusuff (2011), Schuh *et al.* (2017)

applying trainings and education programs, for instance, scenario-based or e-learning (Darbanhosseiniamirkhiz and Ismail, 2012; Erol *et al.*, 2016). All in all, companies should work closely together with schools and universities so that future staff can be provided with the skills and competencies required by new job profiles (Kiel *et al.*, 2017).

In smart factories humans and technology act complementarily. Assistance systems help employees to operate complex systems (Block *et al.*, 2015). On the one hand, these systems aim at physically and mentally relieving employees, automating transportation and handling processes and taking care of monotonous tasks (Kiel *et al.*, 2017). On the other hand, they serve as platforms providing necessary information (Kagermann *et al.*, 2013). Assistance systems are able to identify humans via identification and visualization technologies (Schuh *et al.*, 2017). Personal data can be collected to facilitate interactions and to design employee-focused workplaces (Block *et al.*, 2015). In this context, guaranteeing employees' safety in human–machine interactions at any time is essential (Kagermann *et al.*, 2013). Subsequently, humans need to be trained in order to be qualified for the new technologies housed under the term Industry 4.0 (Kamble *et al.*, 2018; Tupa *et al.*, 2017).

Technology is a key enabler of Industry 4.0. The usage of new technologies requires the preparation of existing systems. For instance, integrating further sensors and actuators into existing production systems and purposefully managing data is a prerequisite for CPS. Additionally, the systems need to be integrated into flexible transportation systems so that intelligent production systems can emerge (Kagermann *et al.*, 2013). Plug-and-produce solutions are designed to be quickly added to or removed from a process (Weyer *et al.*, 2015). Also, fast and stable broadband internet infrastructure is a prerequisite, requiring respective investments. A smart factory should rely on a well-developed internal data infrastructure, e.g., based on the Industrial Ethernet (Schuh *et al.*, 2017). Further, the existing technological developments, such as radio frequency identification (RFID), manufacturing execution systems (MES) and enterprise resource planning (ERP) systems need to be integrated within the Industry 4.0 concept. This also applies for approaches such as just-in-time or lean management (Moktadir *et al.*, 2018; Telukdarie *et al.*, 2018; Tortorella and Fettermann, 2018). Cloud systems are available to handle and process large datasets. Intrusion detection systems, honeypots and firewalls help to protect data and impede unauthorized people's intervention (Kagermann *et al.*, 2013).

Applying technologies and changing the organization paves the way to develop smart factories. Creating a digital image of the value stream is a fundamental step (Siepmann, 2016). Respective software tools can virtualize entire production networks comprehensively (Schuh *et al.*, 2017). This enables organizing the value creation process transparently and offers wide-ranging options for simulations and analyses (Hermann *et al.*, 2015; Siepmann, 2016). Apart from the implementation on production level, Industry 4.0 is characterized by an overall digital connection both vertically and horizontally. The vertical integration includes connecting all internal systems and interfaces as well as the data exchange between intra-firm hierarchical levels. For instance, ERP systems and MES need to be connected (Mosler, 2017). Horizontal integration means the inter-firm integration of customers', suppliers' and external service providers' systems into a company's system landscape (Siepmann, 2016). In order to realize the connection between internal systems and external partners, standardized interfaces, data types and communication protocols are necessary that can be managed in a reference architecture model (Mosler, 2017). The reference architecture model integrates many perspectives by preferring incremental bottom-up as opposed to top-down approaches (Kagermann *et al.*, 2013). In the same regard, the existing organization with its hierarchical structure needs to be aligned according to technological developments (Moktadir *et al.*, 2018).

A company's organization structure should support the goals of Industry 4.0. Employees face frequent and regular changes of tasks as well as changing affiliations to teams. In the digital era, employees should be organized in communities, which match their competencies to work on a common task for a certain period of time (Schuh *et al.*, 2017). CPS provides the technical basis for decentralized decision making as they provide decision makers at the operational level with purposeful information (Hermann *et al.*, 2015). Flat hierarchies and uncomplicated, less formal structures further support decentralized and optimized decision making in smart factories (Hirsch-Kreinsen, 2014; Saberi and Yusuff, 2011). Consequently, management should adapt to unclear or changing demands by using agile management methods, e.g., the scrum approach, that are characterized by early prototypes and frequent feedback cycles with stakeholders (Schuh *et al.*, 2017). Companies should increasingly focus on their core competencies, outsource value creation processes and cooperate with partners (Block *et al.*, 2015; Müller, Buliga and Voigt, 2018). Cooperation with external partners is to be organized in networks or flexible marketplaces (Schuh *et al.*, 2017). Additionally, new value propositions, such as "product-as-a-service" and "everything-as-a-service," can be offered, which comprise product and service solutions along the entire product lifecycle (Kiel *et al.*, 2017). Beyond that, using different revenue models, e.g., pay-per-use contracts, change the way of making money (Müller, Buliga and Voigt, 2018).

The ability of a company to act agilely on a market strongly depends on the organization and on the human-centered corporate culture (Schuh *et al.*, 2017). For this reason, several changes are required in future value creation. Established companies should have an entrepreneurial spirit, so that they have a flexible, open mentality similar to start-ups (Burmeister *et al.*, 2016). An open communication aims at the free exchange of knowledge across all hierarchical positions and departments, enabling the acceleration of learning processes and focus on a common vision. Employees should have the willingness to continuously improve things and learn new content. Responsible managers should apply a democratic leadership style, value employees' skills, view them as part of a community and have a failure tolerance (Schuh *et al.*, 2017). Concrete approaches to trigger corporate cultural changes include, e.g., workshops and the introduction of think tanks (Burmeister *et al.*, 2016). In the same regard, interdisciplinary cooperation across hierarchical levels needs to be established (Davies *et al.*, 2017; Moktadir *et al.*, 2018).

Overall, current literature is mainly focused on specific topics within Industry 4.0 implementation and is mostly based on conceptual or visionary basis. Only few empirical papers can be found, that are mostly based on single case studies from pilot applications of Industry 4.0. However, such papers do not investigate the broad implication of Industry 4.0 and cannot provide a holistic overview of challenges and best practice examples. Therefore, this paper aims to close this research gap, providing an overview of best practice examples regarding the implementation of Industry 4.0. With this approach, the paper aims to present insights that are relevant, easy to grasp and supportive for a wide range of industrial enterprises.

3. Research design

The goal of this study is to develop a conceptual framework comprising recommendations for effective Industry 4.0 implementation and to provide managers with purposeful guidelines in this context. To achieve this goal, a qualitative empirical research design is used. This approach is particularly appropriate as current research lacks a comprehensive and systematic investigation of guidelines for Industry 4.0 implementation.

In line with the works of Edmondson and McManus (2007) as well as Eisenhardt and Graebner (2007), the paper uses inductively analyzed in-depth expert interviews. Qualitative research provides profound and deep-rooted information and help to answer "how" and "why" research questions. Further, a qualitative approach is widely used in contexts of complex, novel, evolving and contemporary phenomena to be studied within their real-life, social and organizational environment, which is true for Industry 4.0 and its implementation (Yin, 2009). The study at hand relies on multiple cases, increasing accuracy, robustness, reliability and generalizability of results (Eisenhardt and Graebner, 2007; Yin, 2009). Semi-structured expert interviews serve as primary source of data. This kind of interview allows collecting data in a structured way, yet maintaining an adequate and necessary level of openness to allow unexpected and novel knowledge to emerge (Yin, 2009).

In total, 13 managers from Industry 4.0-experienced German manufacturing companies of different industry sectors and firm sizes were interviewed between April and June 2016. The German economy is particularly suitable because of its representative character for a developed and industrialized nation, its economic importance for the European Union, and its advanced experiences in Industry 4.0 implementation. The sample comprises electrical engineering ($n = 6$), machine and plant engineering ($n = 5$) and automotive supply industry ($n = 2$). These industry sectors have leading roles in implementing Industry 4.0 and contribute significantly to the German economy in terms of the gross domestic product (Müller, Buliga and Voigt, 2018). Five enterprises have below 5,000 employees, six enterprises have up to 50,000 employees and two enterprises have above 50,000 employees.

Maintaining heterogeneity and different perspectives in the sample enables us to better generalize the results and counteract potential negative effects of sample biases (Yin, 2009). All experts have management positions, are closely involved in or responsible for Industry 4.0 implementation projects, and know the relevant markets and their company's strategic orientation. Consequently, the reliability of recalled issues is strengthened (Huber and Power, 1985). The interviews lasted between 48 and 70 min. They were conducted in German, the native language of the interviewees and interviewers, to avoid any language or cultural barriers and to ensure comparability.

The development of the interview guideline was informed by literature but followed the principle of openness and flexibility to allow unexpected and novel topics to emerge, corresponding to the exploratory nature of this study (Kasabov, 2015). A pretest was conducted with three participants of the study. The guideline consists of two parts. The first part deals with personal facts such as career, job position and profile, company tenure and industry experience to verify the interviewees' level of knowledge. The second part focuses on questions about relevant aspects as for Industry 4.0 implementation. Among others, the paper broaches initiators and goals of Industry 4.0 implementation, the actual implementation process, accompanying challenges and risks and also effects for the organization and the value creation process. All interviews slightly deviated from the original interview guideline, mostly as for the depth of single questions, in order to use the nature of the methodology to go deeper into some aspects and reveal further information.

All interviews were audio recorded and transcribed, resulting in more than 200 pages of text material, which was examined applying qualitative content analysis (Miles and Huberman, 1994). Whenever possible and for triangulation purposes, the expert interviews were verified using secondary data, e.g., annual reports and company websites (Yin, 2009).

During the qualitative content analysis, the developed categories were partly informed by extant literature, but followed an inductive coding procedure (Gioia *et al.*, 2013; Krippendorff, 2013) in order to allow new concepts to emerge rather than being restricted by predefined hypotheses. Likewise, inductive coding allows contributing to theory building (Edmondson and McManus, 2007) by identifying consistencies and common patterns in the collected data. Procedures followed Gioia *et al.* (2013): in an initial step, first-order (informant-centric) categories were developed. Second, these categories were synthesized into second-order themes. Third, these were distilled into the dimensions of corporate culture and communication, personnel, company organization, safety and security, preparing the implementation of Industry 4.0 solutions, handling and integrating Industry 4.0 solutions and financial feasibility. The entire process was conducted in a research team comprising the four authors of this paper to increase validity and objectivity of the coding procedure (Weston *et al.*, 2001). First, all team members separately suggested coding categories. Using them, the authors calculated inter-coder reliability that resulted in a high value following Holsti (1969). Later on, the authors compared and carefully discussed individual coding, rethought and if necessary revised it, and lastly consolidated them into the final scheme. Coding in a team allowed to discuss, constantly check and where appropriate revise the coding procedure. The illustration of first-order concepts, second-order themes and the aggregate dimensions in the data structure (see Table II) increases the methodological rigor of qualitative research design (Gioia *et al.*, 2013).

Additionally, potential key informant and retrospective biases were addressed by random selection of interviewees whilst ensuring expertise in the field and assuring all interviewees of full anonymity. Further, secondary data were used for triangulation reasons (Eisenhardt and Graebner, 2007; Yin, 2009) in order to further increase the robustness of results.

4. Empirical findings

The empirical results based on the expert interview reveal several aspects as for the implementation of Industry 4.0. The single expert statements were paraphrased, transferred into categories, and later on consolidated into second-order themes and aggregated dimensions. Consolidating and aggregating the dimensions included the interpretation of the research team following the widely appreciated procedure of Gioia *et al.* (2013).

The study indicates seven dimensions, which need to be considered when implementing Industry 4.0. Table II gives an overview of the dimensions and categories derived from the case material, underlined with exemplary interviewee statements. It also allocates them to the dimensions and its overlapping presented in the theoretical concept in Section 3 based on the work of Oks *et al.* (2017).

4.1 Corporate culture and communication

Implementing and using Industry 4.0 requires changing the corporate culture. In order to conduct cultural changes, the interviewees recommend applying a rather systematic approach. They state management should top-down initiate cultural changes and serve as a role model, leading by example and providing an unambiguous vision. They add corporate culture should rather be changed incrementally than radically in order to reduce the probability of internal resistances. Characteristics of an Industry 4.0-adequate corporate culture are manifold: for example, high level of willingness to learn, openness to new things, promotion of creativity and idea generation, entrepreneurial mindset and democratic leadership. In this context, the experts comment that the corporate culture should always focus on the customer and his demand.

Changing the communication culture is another key for Industry 4.0 implementation as information is highly valuable in future value creation. The results indicate three different ways of establishing an effective communication. Among others, online communication tools, such as news feeds, webcasts and information platforms can provide employees with purposeful information. In addition, the interviewees emphasize the importance to allow an open exchange of information and open discussions to aim at smoothly exchanging knowledge. This can be realized by platforms, informal personal exchange and interdisciplinary workshops. The communication and sharing of information may be integrated in daily business so it becomes self-evident for those affected.

4.2 Personnel

Industry 4.0-related changes result in the modification of work content, work conditions and workplace design, which in turn influence personnel planning. Due to an increasing automation, work content changes. Following the interviewees, monotonous and physically

Table II. Empirical findings and data structure

Aggregate dimensions	Second-order themes	First-order concepts/categories	Exemplary expert statements	Dimensions
Corporate culture and communication	Corporate culture (28)	Systematic change approach lead by management (15) Development of entrepreneurial spirit, failure tolerance, and creative environment (13) Consequent customer focus (6)	"You need a particular start-up mentality. […] With a traditional, rigid corporate culture we will not be successful in the future." (E13)	Human and Organization
	Communication (14)	Allowance of open information exchange and open discussions (9) Usage of specific tools to provide employees with accurate and relevant information (5)	"We actively take measures to improve communication […], such as discussion forums, discussion groups, and various forms of trainings." (E10)	
Personnel	Personnel planning (23)	Adaption of workplace structure and characteristics (19) Considering work content changes and consequently adapting task descriptions (3) Creation of favorable work conditions (3)	"For instance, working in virtual teams is a prerequisite within Industry 4.0 that will, for sure, change the way our employees work." (E9)	Human
	Skills and competencies (27)	IT competencies (9) Interdisciplinary competencies (13) Personality traits, e.g., openness to change and willingness to learn (5)	"I need employees, who cannot only concentrate on one specific topic, but who are capable of controlling many complex topics." (E2)	
	Education and training (11)	Workshops (8) Trainings (5) Learning by doing (3) E-learning (2) Mentoring (2)	"There are trainings, projects, and research projects […], and we teach employees by making them part of projects." (E12)	
Company organization	Intra-firm (17)	Establishment of a flexible and agile organization (8) Usage of a targeted form of project	"We have founded a new division to implement Industry 4.0 […]. In any case, that is something that needs to be separated from daily business. Otherwise it will not work." (E5)	Organization/ Organization and technology

(*continued*)

Table II.

Aggregate dimensions	Second-order themes	First-order concepts/categories	Exemplary expert statements	Dimensions
		organization to roll out Industry 4.0 (9)		
	Inter-firm (42)	Implementation of different types of cooperation (33) Horizontal and vertical connection of the value chain (7)	"We need a community of all suppliers to pool our strengths and to agree on how to provide our common end customers with value." (E13)	
Safety and security	Data security (31)	Data storage in clouds (5) Protection of data interfaces (4) Employment of ICT experts (4)	"In our system, there is a router, which assigns a fixed IP address […], the machine itself has a firewall, we set up a Virtual Private Network tunnel with another firewall." (E4)	Technology / Human and technology
	Work safety (19)	Taking work safety actions that go beyond legislation (6) Establishment of an institution that takes care of work safety (2)	"Safety at work is our first priority at all times, which has to be maintained in Industry 4.0" (E8)	
Preparing the implementation of Industry 4.0 solutions	Knowledge development (12)	Generation of experiences and lessons learned within the company (9) Usage of external sources of information (4)	"We analyzed different approaches and best practices very carefully […]. Thereof, we have derived the best path for our purposes." (E5)	Human, technology, and organization
	Project teams (17)	Bringing together various disciplines and knowledge (14) Creation of agile project teams (6)	"When it comes to disciplines in project teams to implement Industry 4.0, one must say that the more diverse they are, the better and the more effective." (E7)	
	Planning (15)	Systematic approaches (8) enriched by flexible application of trial-and-error principles (9)	"We have learned fast from our mistakes, and to take the chance to continue quickly and better." (E7)	
Handling and integrating Industry 4.0 solutions	Technical preparation (14)	Digital connection of processes (10) Implementation of hardware elements (6) Modeling interfaces (4)	"We had to install new sensors and new evaluation systems. […] The generated data goes into a cloud […], where an analysis tool reuses it." (E8)	Technology
	Retrofit of established	Adaption of existing infrastructure and production systems to Industry 4.0 ("retrofitting") (16)	"We do not change a machine but adapt our systems, while they are running. […] Never touch a running system!" (E7)	

(*continued*)

Aggregate dimensions	Second-order themes	First-order concepts/categories	Exemplary expert statements	Dimensions
	infrastructure and systems (19)	Development of a catalogue of measures (3)		
Financial feasibility	Financing (18)	Project-specific financing (12) Usage of fixed budgets (7)	"Before making a big hit, we set up pilot projects. […] In doing so, we are able to assess the costs and benefits quickly. Of course, that helps us, because it keeps costs under control." (E11)	Human, technology, and organization
	Performance measurement (18)	Profitability (7) Efficiency (6) Time (7)	"In our company, a very important aspect is to reduce the time-to-market." (E8)	

Table II.

demanding tasks are undertaken by assistance systems, leading to increasing requirements with regard to employees' mental activities and decisions. Consequently, the interviewees state employees should be provided with higher decision-making power allowing them to tap their creative and problem solving potential. In addition, the form of compensation may encourage these aspects. The experts had positive experiences with flexible workplaces that support the exchange of knowledge and skills of employees. Virtual teams across geographical locations and divisions do promise a similar effect. Based on the technological opportunities of connected remote control and augmented or virtual reality devices, employees do not necessarily have to control machines constantly, which enables flexible working time models. A purposeful exploitation of data and technological developments helps to tailor and specifically adapt future workplaces to employees' individual necessities. Nevertheless, as personal data are required for this purpose, the experts add data security plays a crucial role.

Industry 4.0 requires further employee skills and competencies, such as ICT know-how, interdisciplinary competencies and special personality traits. Given its digital basis, knowledge and skills in ICT are mandatory according to the interviewees' statements. In this context, technical and economic aspects, processes and methods seem to be relevant as well. With regard to personality traits, the results indicate employees should be open to changes. Furthermore, failure tolerance and a willingness to learn from mistakes, and creativity are essential. Finally, according to the experts' experiences, social and communication competencies facilitate interdisciplinary collaboration, teamwork and information exchange.

In order to develop these competencies, education and trainings have proven to be helpful in the sample cases. Among others, adequate measures were trainings of all kinds, e.g., workshops, scenario-based learning, learning by doing and e-learning approaches. A further expedient measure was mentoring that is a mixed form of education and training, where mentors from various disciplines help to get relevant knowledge. The interviewees highlight that training programs should be interlinked with practice and tailored to the employees' specific task, as doing so increases learning success. Additionally, a close collaboration with universities and schools ensures that future employees acquire relevant skills. An intuitive design of Industry 4.0 technologies and production equipment, however, decreases the necessity of specific trainings in the sample cases.

4.3 Company organization

The results also show that companies should revise their organizational structure to lay down an adequate foundation for Industry 4.0. Flat, weak defined hierarchies, flexible structures and processes, and decentralized settings may form an agile organization. This form allows faster decision making and promotes an entrepreneurial spirit. In the sample cases, organizational agility is further driven by a smooth data flow based on interconnected intra-firm and inter-firm systems. In this context, the experts used contemporary management methods, e.g., lean and agile project management. In case, it was not possible to create an organizational structure that fulfilled the requirements within the established corporate structure, some companies successfully spun off Industry 4.0-affected company parts into independent, specialized business units. By this means, employees working in the new business unit could act in a more agile and entrepreneurial way, as communication and decision making are simplified.

Additionally, in the sample cases Industry 4.0 implementation was advanced in individual projects, requiring a specific project organization. First, pilot projects were used to test and evaluate several implementation approaches. In doing so, know-how and information could be generated centrally. Subsequently, the development of a global rollout roadmap standardized the implementation steps that were to be taken and enabled transferring them to other application scenarios and contexts. This approach helped the sample companies to conduct transparent and comparable procedures to implement Industry 4.0 technologies in their subsidiaries. Given a projects' unique characteristics, heterogeneous teams were formed for a distinct period and for a certain purpose.

Connecting the value chain horizontally and vertically offered the companies the opportunities to develop new, strongly service-oriented business models. In the sample cases, the focus has started to turn to the end customers during all stages of the value adding process. In order to foster R&D activities, partnerships with research institutes and other companies were arranged. These changes allow novel value propositions and intensifying customer relationships to evolve.

Further, the experts mentioned manifold forms of cooperation. Temporary forms on a project level helped to bundle necessary resources for a while. Company networks allowed sharing data via web communities and cloud-based platforms so that key issues could be discussed in inter-firm meetings. For instance, cross-sectoral alliances positively influenced the companies' businesses as well as coopetition, which pools resources and know-how of competitors. The interviewees concluded that the selection of the most purposeful form of cooperation depends on the company's and respective partners' goals.

4.4 Safety and security

The use of ICT systems and digital interconnection is in need of protection against external interferences and other issues of data security. The experts stated that the most critical interfaces are those to, e.g., external partners and customers. Security can be increased by applying specific security systems, e.g., fixed IP addresses, firewalls and Virtual Private Network tunnels. Comprehensive surveillance and intrusion detection systems prevent unauthorized people from data access in the sample cases. Highly qualified ICT security experts are familiar with security technologies and, following the interviewees' experiences, should have leading IT positions within future smart factories. In order to constantly check the security of all systems, so-called "white hackers" can be employed who continuously search for existing security leaks. Some sample companies use "honeypots" that attract cyber-attacks while distracting hackers from intervening in core systems. Cloud computing represents a secure method to store data. Nevertheless, the interviewees admit issues as for data security should not lead to excessive isolation. Instead, according to their experiences, a healthy balance between security and openness should be maintained.

Some experts point out that the interaction between employees and machines calls for taking care of work safety. Strict regulations and laws may already stipulate work safety, but further efforts are important with regard to on-going technological developments and increasing human–machineinteractions. Some interviewees add that the design of new systems and machines must consider aspects of work safety.

4.5 Preparing the implementation of Industry 4.0 solutions

The interviewees' companies develop knowledge and expertise about Industry 4.0 solutions, using both internal and external sources of information. External sources are, for instance, best practice examples of other companies and academic literature as well as publications of research institutions and branch associations. Internal sources are R&D activities and learning from mistakes. It has proven to be best if employees are involved in the process as they are the ones to apply new technologies and to operate the machines.

Forming project teams was helpful to develop and implement Industry 4.0 solutions in the sample companies. The experts' experiences suggest that these teams comprise different disciplines, as knowledge and expertise from different fields are mandatory. Software developers and ICT experts were involved since software plays a vital role in Industry 4.0. Additionally, employees with a technical background, such as mechanical engineers, were part of them as well. Experts in sales, marketing and business development complemented the project teams, because they were familiar with customer needs and product or service marketing. Further, people with project management knowledge were necessary. Given the variety of members, coordinating these teams was of utmost importance. In the sample cases, these teams consisted of few members in order to enable short decision making processes and agility in the beginning. With implementation progress, the teams were expanded gradually, given their increasing responsibilities and tasks.

The findings show that there are two approaches for planning Industry 4.0 implementation. First, some sample companies apply a systematic approach following a predefined action plan. It may describe objectives and processes, include a standardized approach, and provide the basis for a target-performance analysis. However, the respective experts concede, planning is limited, especially with regard to large and complex Industry 4.0 projects. Thus, and second, companies encourage flexibility using trial-and-error methods. For the sample companies, it was important to learn quickly from mistakes and to test new approaches flexibly in order to develop and offer an effective solution.

4.6 Integrating Industry 4.0 solutions

Following the results of the interviews, another key element of Industry 4.0 implementation is the actual technical integration. First, interviewees emphasize that a company should develop a proper understanding of new, Industry 4.0-related technologies. Second, additional hardware components were necessary, e.g., RFID, network connections, sensors, microprocessors and actuators, to collect machine data and to enable their analyses. Third, software adaptions were required in most cases. This included creating a standardized connection via Ethernet, digitally connecting all processes and systems and storing data in clouds. Last, the sample companies created secure and standardized interfaces so that data could be processed without information losses.

The integration of Industry 4.0 solutions into existing value creation processes required a retrofit of the sample companies' infrastructure and systems. Retrofit refers to the modernization or expansion of existing manufacturing facilities. In order to prepare their systems, the interviewees' companies conducted the following steps: first, they carefully examined the application context and properly defined their goals. Second, the data of existing production systems were collected, compressed, analyzed and managed. Last but not least, they integrated Industry 4.0 solutions.

4.7 Financial feasibility

The empirical findings show two basic models to finance R&D activities concerning Industry 4.0 and its implementation, i.e., the allocation of fixed budgets and project-specific financing. Some sample companies used fixed budgets that were assigned to a division or plant, where it is used for R&D activities and Industry 4.0 implementation. However, this approach was mostly chosen for basic R&D activities. In contrast, some companies implemented Industry 4.0 by employing small projects. In the latter case, individually financing projects has proven to be appropriate. Some experts used cost-benefit analyses in their companies to determine the project-specific budget, and concrete information about costs and potentials were obtained from pilot projects.

After the implementation, the projects' performance can be measured and evaluated by using three different types of measures according to the results. Profitability indicators are appropriate to monetarily evaluate projects. Return on investment was the most common way of assessment, but cost savings were equally appropriate. Further, in some sample cases efficiency indicators were useful to measure project-specific goals, e.g., scrap rates, energy and resource efficiency and maintenance effort. Last, time indicators were purposeful as Industry 4.0 aims at increasing process speed along the entire value chain. In this context, time-to-market represents one key indicator for several experts. However, not only the overall time-to-market, but also specific elements of it are used as an indicator, e.g., lead-time, delivery time and turnaround time.

5. Discussion

The results reveal several insights and best practices regarding an effective Industry 4.0 implementation. In the following, the most important similarities are discussed and compared with the current state of research by applying the humans, organization and technology model of Oks *et al.* (2017).

As far as humans are concerned, both existing literature and the results indicate an increasing importance of ICT competencies (Erol *et al.*, 2016; Schuh *et al.*, 2017). Both show that interdisciplinary knowledge is perceived to be more important than exclusive ICT competencies. In the same regard, adequate training of the existing workforce, especially concerning IT competencies, is required (Kamble *et al.*, 2018; Tupa *et al.*, 2017). In accordance with Darbanhosseiniamirkhiz and Ismail (2012), the findings also show that companies frequently employ on-the-job measures to train their employees. Further, new forms of learning methods, e.g., e-learning methods, are still not in wide use. Training is frequently perceived as a responsibility of educational institutions (Kagermann *et al.*, 2013), whereas the study at hand discloses further forms of cooperation in this context, e.g., joint projects, consultations and funding. Further, distinct personality traits are required, e.g., willingness to change and communication skills. Despite their relevance, personality traits have not been addressed by literature so far.

Having a closer look at the interplay between humans and technology reveals further insights. Work safety is already discussed in literature but rather generally (Kagermann *et al.*, 2013). The findings underline the need for implementing a process of work safety that goes far beyond established legal regulations.

Current research comprehensively deals with technologies and illustrates their applicability. This basis is extended by providing approaches for the implementation of these technologies. In addition, it is shown that retrofitting of existing production systems and equipment is a critical challenge in the context of Industry 4.0 implementation. This insight can be combined with the findings or, e.g., Tortorella and Fettermann (2018), finding that Industry 4.0 must be embedded within existing concept and technologies, such as just-in-time or lean management approaches. Further, the data security has to be ensured in order to prevent unauthorized third parties from data access (Schuh *et al.*, 2017; Kagermann *et al.*, 2013).

Regarding the interplay between technology and organization, on the company level, the results show that flat hierarchies, flexible structures and processes and decentralized settings form an agile organization that is important when implementing Industry 4.0. These findings complement the recommendations of Moktadir *et al.* (2018) that advise an adequate organizational structure. Further, not only the organizational structure, but also smooth data flow contributes to agility. Minimizing technical barriers in a company's systems guarantees data flow in this context. On an inter-firm level, it is shown that digitally interconnecting suppliers and customers helps optimizing the global value chain. This requires both the adoption of new technologies and preparation of company-specific systems, such as proper handling of interfaces and the usage of common data types. Inter-firm communication can be facilitated by using, for example, web communities and cloud-based platforms. Finally, the importance of using a reference architecture model can be confirmed.

Theoretical findings about organizational aspects of Industry 4.0 implementation have already found their way into practice. One the one hand, the findings of this study emphasize the importance of an agile organizational structure, constituted by flat hierarchies and decentralized decision making to implement Industry 4.0 in corporate practice (Burmeister *et al.*, 2016; Saberi and Yusuff, 2011).

On the other hand, however, it may make sense to consolidate power, know-how about Industry 4.0 and capacity in one centralized organizational institution, or even a central position within the supply chain. In this way, companies could create an organizational team that has enough organizational decision power, all relevant knowledge and sufficient capacity at its disposal. Implementing Industry 4.0 could thereby become easier and faster, that may reveal a competitive advantage. This idea has not been discussed in literature so far and could offer several potentials. However, especially SMEs might be reluctant regarding this idea if this leads to even more influence of large enterprises (Müller, Kiel and Voigt, 2018).

Research on humans and organization widely discusses work design, work content and relationships. The results confirm findings regarding, e.g., assistance systems and the elimination of monotonous activities (Kiel *et al.*, 2017). Further, the importance of fault tolerance can be confirmed (Schuh *et al.*, 2017). In addition, the empirical findings reveal the necessity of an adequate cultural change by using a top-down approach (Moktadir *et al.*, 2018). In this context, open communication plays a central role (Schuh *et al.*, 2017).

So far, research has not dealt with the interplay between humans, organization and technology (Oks *et al.*, 2017). The article at hand extends current research by several aspects subject of the discussion, which belong to all dimensions. The article reveals insights about how to prepare the implementation of Industry 4.0 solutions. For instance, the paper deals with aspects about how to generate Industry 4.0-relevant knowledge, how to adequately set up project teams and how to reshape future planning activities. Further, aspects with respect to financing Industry 4.0 implementation as well as are presented, requiring the use of different performance measurement systems. By doing so, the study contributes to research and helps to understand how to implement Industry 4.0 effectively.

6. Implications

6.1 Managerial implications

Extending the introduction to Industry 4.0 in Section 2, the paper uses the presented framework to explain the implementation processes in detail depicted by Figure 3. The framework consolidates and summarizes the recommendations for Industry 4.0 implementation in practice. The company represents the center of the framework being surrounded by partners and market players, with whom frequent exchanges and communication exist. The entire pool and ecosystem of these players is critical for Industry 4.0 implementation.

In sum, the following Industry 4.0 implementation principles are recommended:

- First, the future tasks of employees require further competencies. Knowledge about ICT technologies as well as interdisciplinary knowledge should be conveyed, e.g., via trainings, workshops and further education programs. Apart from traditional training methods, emphasis should be placed on e-learning and scenario-based learning. Companies should also cooperate with educational institutions of all sorts in order to be involved in the development and design of educational programs tailored to the specific qualification needs of Industry 4.0.
- Second, Industry 4.0-relevant knowledge should be developed by utilizing research results, experiences and recommendations of branch associations and internal experiences. Sharing knowledge with, e.g., research institutions, should be a reciprocal process.
- Third, organizational changes are vital to provide an appropriate basis for Industry 4.0. The organizational structure should be characterized by a flat hierarchy and decentralized decision making in order to promote agility. In some cases, it is

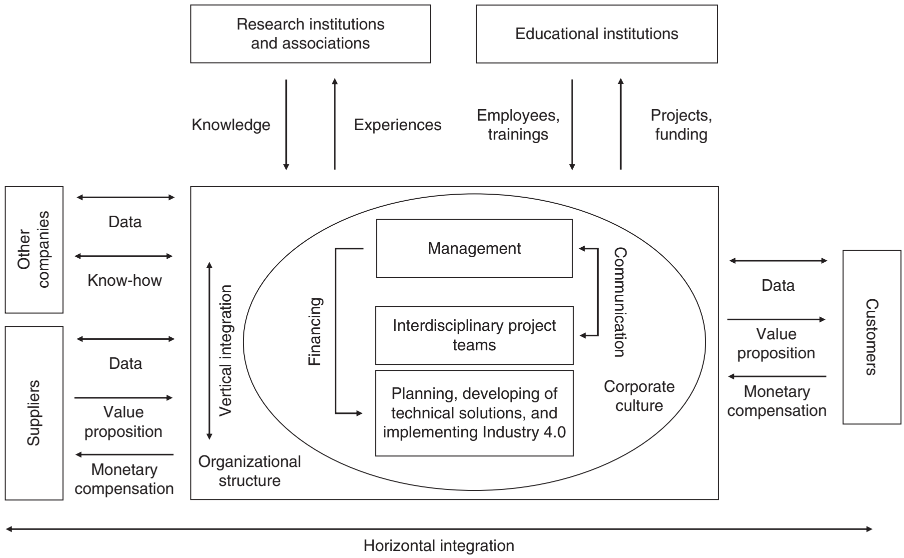


Figure 3.
Framework of Industry 4.0 implementation with empirical findings

necessary to spin-off business units to put them into an entrepreneurial environment. Furthermore, interdisciplinary project teams should be formed, which consist of software developers, engineers and experts from the areas of sales and business development. Project organization, working time models and compensation should encourage creativity, problem solving and decision making.

- Fourth, corporate culture and the way communication is set up should support Industry 4.0 without constraints. Among others, corporate culture should be characterized by flexibility, openness, willingness to learn and an entrepreneurial mindset. Changes of the corporate culture should be initiated and exemplified by top management in an incremental and top-down process. Communication is to be opened up so that employees are able to freely communicate and discuss across both hierarchical levels and organizational borders.
- Fifth, companies can start to horizontally connect the value chain. In order to optimize processes across the entire value chain, data exchange from customers to suppliers and vice versa should be allowed. The principles of openness and trust are essential in cross-company cooperation. Depending on the specific case, temporary cooperation, networks, strategic alliances or coopetition may be adequate. These can be used to develop new business models based on novel value propositions and intensified customer relationships.
- Sixth, Industry 4.0 implementation process needs to be planned and technical solutions need to be developed and implemented. Pilot projects and use cases pave the way to build up knowledge centrally and later on allow transferring Industry 4.0 to other application contexts and scenarios. Both systematic approaches and trial-and-error methods help to develop goal-oriented solutions. The new Industry 4.0 technologies and solutions should be integrated into existing machinery and production systems. In this context, key elements are integrating additional hardware and software as well as managing data interfaces in order to properly retrofit established manufacturing equipment and to digitally connect all processes

and systems. This vertical interconnection should follow an incremental bottom-up approach. Therefore, uniform interface standards, data types and communication protocols are required. Last, data security and work safety are of utmost importance when implementing Industry 4.0.

6.2 Limitations and suggestions for future research

Given the exploratory and qualitative nature, the study at hand faces some limitations. Qualitative research serves illustrate complex topics in a detailed way, which in turn makes general theoretical contributions difficult. Yet, to be able to derive theoretical implications, detailed data are compressed while maintaining the relevant informational content. In the method section, various biases are discussed, e.g., key informant and retrospective bias. Several measures are applied to reduce their impact and to achieve more reliable results. Another limitation is the focus on German companies. Even though this choice serves the purpose of this study, this limitation should be kept in mind when generalizing the results and transferring them to different countries or cultural contexts. First, different economic environments and cultural backgrounds may be the reason why implications differ. Second, transferring results and implications to other industry sectors might be difficult due to different market environments and overall conditions. Third, solely manufacturing companies are examined. Thus, the results should not to be directly applied to, for example, service companies.

On-going research can help to shed light on further aspects of Industry 4.0 implementation. Using different company samples, e.g., in terms of nationalities and industry sectors, contributes to verifying the results and to revealing differences across countries and industries. Due to the limited explanatory power of this study, the authors recommend further differentiated analyses regarding varying company sizes, value chain positions, strategic goals and implementation states.

Despite the presented limitations, this study reveals valuable insights and implications that serve both research and practice to better understand the process and relevant aspects of Industry 4.0 implementation.

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Appendix. Interview guideline

Part I: introduction

(1) What is your current position and function in the company?

(2) Please describe your responsibilities and your role in the company.

(3) Could you please briefly describe your career path?

(4) Since when do you hold your current position? When did you start working for the company?

(5) How much industry experience do you have in total?

Part II: implementing Industry 4.0

(1) What were the first steps to implement Industry 4.0 and what were your experiences?

(2) How is your organizational structure set up? How about communication processes?

(3) Which qualifications do employees need in the context of Industry 4.0? What changes are required in human resource management?

(4) Which financial resources does your company require for the implementation and how are those provided?

(5) How do you integrate Industry 4.0 applications into existing systems? What adjustments do you have to make in order to integrate Industry 4.0 solutions?

(6) How do you asses the success of Industry 4.0 applications and how do you measure it?

(7) How does your company deal with issues of safety and security?

(8) What impact does Industry 4.0 implementation have on your corporate culture?

(9) Do you try to implement Industry 4.0 across various stages of the value chain and across company boundaries? If so, how do you ensure a smooth cooperation?

(10) Is there anything that has not been discussed in the interview so far, but is important to you as for implementing Industry 4.0?

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