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Status of the Implementation of Industry 4.0 in SMEs and Framework for Smart Manufacturing

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1.1 Introduction

Since the term Industry 4.0 was first mentioned at the Hannover Messe in 2011 (BMBF 2012), 10 years have passed. The accompanying Fourth Industrial Revolution has almost turned both research and industrial practice upside down and led to a multitude of technological innovations and the digitalization of production (Kagermann et al. 2013). A lot has happened in these 10 years. After the discussions around

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Industry 4.0 were initially still very much limited to Germany and later Europe, a look at the publications on this topic shows that the term was discussed worldwide, especially from 2016 onwards. The first years were largely dominated by discussing what the collective term Industry 4.0 means, how it can be defined and which core technologies support the fourth industrial revolution. From 2015 onwards, the first initiatives and national plans for the implementation and introduction of Industry 4.0 in industrial practice emerged, particularly in Europe. Such plans were mostly linked to financial support or tax relief in order to also prepare a financial incentive for companies to invest in new technologies (Matt and Rauch 2020). At the same time as the national plans and initiatives, competence centers, research laboratories or demo-labs for the transfer of advanced technologies from research to practice have also been established in many cases.

"Smart Manufacturing" or "Smart Factory" are often used as synonyms for Industry 4.0. In particular, Industry 4.0 in combination with digitalization has ultimately also contributed to the formation of the term Digital Transformation (Deloitte 2015). While Industry 4.0 refers primarily to the manufacturing industry, the concepts of digital transformation also apply to non-industrial sectors and contribute to the introduction of digital technologies and digital business models there. In recent years, the basic concepts of Industry 4.0 and digital transformation have also been transferred to many other areas. In 2016, for example, the term Society 5.0 was created with the overarching goal of increasing the well-being of society in the long term by means of new and advanced technologies and thus transferring many of the technologies into everyday life (Fukuda 2020). Furthermore, many cities and regions have been working on digitalization strategies for several years in order to increase efficiency in the public sector and sustainability (Safiullin et al. 2019). With the pressure to introduce Industry 4.0 technologies in companies, there is also a shortage of skilled workers with appropriate knowledge in these technologies. This has led most education systems to adapt their curricula and content to these new developments. Such developments have often been referred to as Education 4.0 (Hussin 2018) or, for the engineering sector, Engineering Education 4.0 (Morandell et al. 2019). The latest trend that has been emerging for a few years is the introduction of artificial intelligence in companies. In the field of manufacturing, too, opportunities are currently being sought to introduce established AI methods for the optimization of production processes and to explore the range of possible applications (Woschank et al. 2020; WMF 2020).

In this now ten-year development around Industry 4.0, research on the introduction of Industry 4.0 in SMEs has also increased significantly. Especially from 2017 onwards, partly due to the launch of an important EU H2020 MSCA RISE project entitled “SME 4.0 - Industry 4.0 for SMEs” (Rauch et al. 2018), the research work regarding SMEs has significantly increased year by year. In these years, a lot of research has been done on which technologies are particularly suitable for SMEs (Prause 2019), which prerequisites and limitations SMEs have when introducing Industry 4.0 (Masood and Sonntag 2020), and which tools facilitate a successful introduction (Matt et al. 2018; Rauch et al. 2020a). One objective of this chapter is to determine the status of Industry 4.0 implementation in SMEs. This will provide an overview of how far the implementation of Industry 4.0 has progressed and which empirical or case study-based studies exist to date that report on the impact and effects of Industry 4.0 on the performance of SMEs. Based on this and previous research by the authors, a modular framework model is created to facilitate SME manufacturers to introduce smart manufacturing in their companies. The presented framework is accompanied by a stage model that supports the step-by-step implementation in SMEs. Finally, future developments will be addressed to prepare SMEs for the challenges of the future. For this purpose, the term “Industry 4.0+” is introduced, which describes the next level of Industry 4.0 for the next five to ten years.

Based on the objectives described above, the following research questions are defined for this chapter:

RQ1: *What is the status of the application and implementation of Industry 4.0 in SMEs?*

RQ2: *What frameworks and guidelines can SMEs use to successfully implement smart manufacturing?*

RQ3: What are the medium and long-term challenges SMEs will have to face in the future?

The chapter is structured as follows. After the introduction to the topic in Sect. 1.1, Section 1.2 describes the status of the introduction of Industry 4.0 in SMEs based on literature research. Section 1.3 then shows the modular framework model for SME manufacturers. Finally, Sect. 1.4 gives an outlook on the future challenges in the context of Industry 4.0+.

1.2 Status of Industry 4.0 Implementation in SMEs

1.2.1 Review of Literature on Industry 4.0 Implementation in SMEs

In order to investigate the current state of adoption of Industry 4.0 technologies in SMEs, a literature review was conducted based on scientific papers. For the search, the database Scopus was used and the following keywords in title, abstract and keywords were searched: ("SME" OR "small and medium-sized" OR "small and medium-sized") AND (implementation OR adoption OR introduction) AND "industry 4.0". Afterwards the identified works were reduced to papers from the last two years 2019–2020 and screened for relevant papers for this research.

Table 1.1 summarizes the results of various studies on the application of Industry 4.0 technologies in SMEs. The search in literature has been conducted at the end of December 2020 (20 December 2020) therefore the search includes mostly all published works in these two years. The results of the evaluation of the individual technologies in the studies have different evaluation scales and were therefore classified by the authors for this comparison as follows: low (low application), medium (medium application), and high (high application).

Ghobakhloo and Ching (2019) conducted a study in Iranian and Malaysian SMEs to investigate the adoption of Industry 4.0 technologies. According to them, the most widely adopted Industry 4.0 technologies in SMEs are the following. First, the use of cloud data and storage by

Table 1.1 Adoption of Industry 4.0 technologies in SMEs based on surveys in different countries/regions

Technology	Ghobakhloo and Ching (2019) Iran-Malaysia	Cimini et al. (2020) Italy	Rauch et al. (2020a) Italy-Austria	Ko et al. (2020) Korea	Kilimis et al. (2019) Germany	Yu and Schweisfurth (2020) Denmark-Germany	Pech and Vrchota (2020) Czech Republic	Gergin et al. (2019) Turkey	Türkes et al. (2019) Romania	Ingaldi and Ulewicz (2020) Poland	Overall rating
Advanced Automation and Robotics	Medium	Medium	Medium	High	Medium	Medium	Medium	High	High	Medium	**Medium**
Additive Manufacturing (AM)	Low	/	Low	/	/	Low	Low	Low	Low	Medium	**Low**
Simulation	Medium	Medium	Medium	/	Medium	Medium	/	Medium	Medium	/	**Medium**
Virtual/Augmented Reality (VR/AR)	Low	Low	Low	/	/	low	Low	Low	Low	/	**Low**
Horizontal/Vertical Data Integration	High	/	High	High	High	High	High	/	High	High	**High**
Industrial Internet of Things (IIoT)	High	High	Low	High	Medium	Low	Medium	Medium	Medium	High	**Medium to high**
Cloud Computing	High	/	High	/	/	High	Medium	/	Low	/	**High**
Cybersecurity	Medium	Low	Medium	/	/	High	/	Medium	Medium	High	**Medium**
Big Data Analytics	Medium	High	Medium	Medium	/	Low	High	Low	High		**Medium to high**
Artificial Intelligence (AI)	Low	/	Low	Low	/	/	/	/	Low	Low	**Low**

changing inhouse software as well as data storage in cloud-based services. Secondly, many SMEs invested already in horizontal/vertical data integration by introducing basically Enterprise Resource Planning (ERP) systems for the management of data on the business process level. Many of them have already started also to introduce Manufacturing Execution Systems (MES) for production planning and control. The third technology mostly adopted by SMEs is Industrial Internet of Things (IIoT) equipping legacy machines with actuators and sensors for data collection and introducing machine and process control systems like programmable logic controllers (PLC) or supervisory control and data acquisition (SCADA). This allows SMEs to monitor the status of manufacturing systems in real-time. According to their study many SMEs are already on a good way to adopt advanced automation and robotics like mobile and collaborative robots. The same is for cybersecurity, data analytics and simulation. SMEs are already using the basic technologies available on the market (e.g. firewall, antivirus, virtual private network, etc.) to protect their businesses from cyberattacks. Further, they are moving toward data analytics although in most of the cases based on simple and commercially available data monitoring and analysis tools, while the use of machine learning or more complex artificial intelligence technologies is still in its infancy in SMEs. For simulation, two kinds of simulation need to be differentiated. While SMEs are already using advanced computer-aided design and engineering software (CAD and CAE) for doing simulations with digital models of parts and products they still do not yet use simulation software for manufacturing or logistics purposes (e.g., discrete event simulation) as they are cost-expensive. According to the authors, in addition to artificial intelligence there are other two technologies not yet exploited well by SMEs: additive manufacturing and virtual and augmented reality (VR/AR). The reason therefore might be that additive manufacturing of metal materials is still very cost-expensive while additive manufacturing of plastic materials (not rapid prototyping) is not of such great importance for many producing SMEs. The low rate of adoption of VR/AR is surprising as VR/AR headsets are available for an affordable price. The reason might be related to missing qualifications of the staff in SMEs in order to use or develop VR and AR models/environments. Further, the authors observed that implementers of AI, VR/AR, autonomous robots believe these applications provide them with organizational improvement and productivity. Results, however, showed that perceived costs have a significant negative influence on SMIDT adoption. It was observed that higher perceived cost has resulted in non-adoption of complex Industry 4.0 technologies including VR/AR, AI, additive manufacturing, ERP, industrial sensors, and machine and process controllers. This finding is in line with the majority of prior literature introducing the implementation costs as a major barrier to Industry 4.0 adoption by SMEs.

Cimini et al. (2020) conducted a study in several Italian SMEs. In their study, they include only a limited number of Industry 4.0 technologies. Basically, it is confirmed that Industrial IoT is already implemented by most of the SMEs. Different to the previous reference, the use of big data analytics is rated as high. It is further confirmed that the level of the use of advanced automation and robotics solutions and simulation can be rated as medium. It is also confirmed that VR and AR are only implemented at a very low level. In contrast to the aforementioned reference, cybersecurity is classified as low.

The authors itself conducted an assessment of Industry 4.0 in 13 SMEs from the Italy-Austrian border region (Rauch et al. 2020a). Data integration (ERP and MES) as well as cloud computing are reported as highly adopted Industry 4.0 technologies. Advanced automation and robotics, simulation, big data analytics and cybersecurity have been assessed as medium-level adopted technologies. VR/AR, additive manufacturing and artificial intelligence are (similar to other studies) technologies with a low adoption in SMEs. Further also IIoT is assessed as not widely adopted technology different to most of the other studies summarized in Table 1.1.

Ko et al. (2020) conducted a survey with responses from 113 Korean SMEs. According to their results, advanced automation and robotics like autonomous robots are highly adopted. The same is for horizontal/vertical data integration through ERP and MES systems for production planning and control and for IIoT based on tracking and tracing of products. Data analytics in sense of predictive maintenance is adopted at a medium level while artificial intelligence is at a very low level in SMEs.

Kilimis et al. (2019) describe in their work the results of a study in German SMEs. The most adopted technology is related to horizontal/vertical data integration in sense of the introduction of ERP or other advanced IT systems for production planning and control. Advanced automation and robotics, manufacturing simulation as well as digitalization technologies (IIoT) are adopted at a medium level.

Yu and Schweisfurth (2020) investigated the adoption of Industry 4.0 technologies in the Danish-German border region. The interests in additive manufacturing, VR/AR, big data analytics and IIoT are relatively low. A moderate number of SMEs use simulation and advanced robots. Those technologies, which have reached a high degree of implementation in the sample are data integration, cloud computing and cybersecurity.

Pech and Vrchota (2020) conducted a comprehensive questionnaire-based study on Industry 4.0 adoption in 186 SMEs. According to their results the introduction of ERP and MES software systems as well as data analysis are adopted in most of the SMEs. Advanced automation and robotics are implemented at a medium level. The same is for the introduction of IIoT and cloud computing. Additive manufacturing and VR/AR were implemented only on a low level in the participating companies.

Gergin et al. (2019) implemented a survey in 588 SMEs in Turkey. Advanced automation and robotics technologies in sense of automation are implemented by many SMEs (high level). Simulation, IIoT and cybersecurity are implemented at a medium level. Additive manufacturing, big data analytics and VR/AR are implemented only by a few companies and are therefore at a low level.

Türkeș et al. (2019) conducted a survey with 176 participating SMEs from Romania. Advanced automation and robotics, horizontal/vertical data integration and big data analytics are the most adopted technologies. Many companies (medium level) adopt simulation, IIoT and cybersecurity. The lowest level of adoption is reported for additive manufacturing, VR/AR, cloud computing and artificial intelligence. While the others are in line with what has been reported in other studies, there is a different opinion regarding cloud computing technologies.

Ingaldi and Ulewicz (2020) describe the results of a survey conducted in 187 SMEs from Poland. Data integration, IIoT and cybersecurity are identified as widely adopted technologies in SMEs, while advanced automation and additive manufacturing are at a medium level of adoption. As reported in many other studies, artificial intelligence is implemented only in a few SMEs.

1.2.2 Summary on the Adoption of Industry 4.0 Technologies in SMEs

Based on the results of the literature-based comparison of ten different studies on the adoption of Industry 4.0 technologies, we can summarize the following results:

- **High:** horizontal/vertical data integration, cloud computing,
- **Medium to High:** industrial internet of things, big data analytics,
- **Medium:** advanced automation and robotics, simulation, cybersecurity,
- **Low:** additive manufacturing, virtual and augmented reality, artificial intelligence.

However, with respect to this analysis, the following limitations must be considered. The presented studies in Table 1.1. were mainly conducted in European countries, while no clear data were available on other major economic powers such as China, United States, Canada, Brazil or Southeast Asia. In addition, the categorization of SMEs and their differentiation from large companies differ in some cases in the individual studies.

Nevertheless, the comparison carried out gives a good picture of the current situation with regard to the introduction of Industry 4.0 technologies in SMEs. Based on this overview, it becomes clear where SMEs have already successfully embarked on a good path and which technologies currently still need time for successful implementation. This includes advanced IT systems for data integration such as ERP systems, supply chain management systems, MES software and other technologies like RFID or new sensors that enable a seamless data flow. Cloud computing solutions are also already established and consolidated technologies that have been used at all levels of the enterprise for several years due to their ease of implementation and cost-saving potentials.

There could be identified two technologies with a great potential for SMEs. These are IIoT and big data analytics. With the use of already available data in the company, these technologies can help to achieve real-time monitoring of the status of machines and entire manufacturing systems and also uncover optimization potential using data analytics methods and thus drive data-driven innovation. Due to the current dynamics and constantly new providers of software and services in this area, it is also becoming easier for SMEs to introduce these technologies.

Furthermore, there is the group with a medium level of implementation such as advanced automation and robotics, simulation and cybersecurity. In the field of advanced automation and robotics, mobile and collaborative robots will increase in the near future, as they offer ideal conditions for SME-typical flexible production. In the area of simulation, a distinction must be made between simulation systems for production and those for product development. While there is currently already a wide range of inexpensive or free software for CAE, this range is still much smaller in the area of factory planning and production system planning software. In the future, it is expected that open or less expensive software will also enable the creation of digital twins for SMEs. Cybersecurity seems to be implemented at a very good level. It can be assumed that increasing digitization will lead to even more risks and that SMEs, together with their external IT partners, will have to constantly rethink and adapt their cybersecurity situation.

With regard to those technologies that currently have a low level of application, different arguments can be made. Based on the articles read and our own experience from research with SMEs, it is assumed that additive manufacturing will only play a greater role for SMEs once the investment costs for manufacturing equipment for additive manufacturing of metals drops significantly. Virtual and augmented reality seem to be of little interest to SMEs despite favorable hardware prices. Artificial intelligence, on the other hand, promises great potential for SMEs as well, but still requires several years of research to make the leap into broad industrial application.

Further, Masood and Sonntag (2020) conducted a survey-based study to identify benefits and complexity-based challenges related to Industry 4.0 technologies introduced in SMEs. According to their study, the following technologies provide a high benefit although linked to a high effort and complexity in introducing them: (1) data integration (like ERP/MES), (2) big data and analytics, (3) artificial intelligence (machine learning and deep learning) and (4) advanced robotics. The following technologies also provide a high benefit while complexity is low ("low hanging fruits"): (5) cyber-physical and embedded systems, (6) simulation, (7) predictive maintenance, (8) additive manufacturing and (9) sensors. Further, the following listed technologies provide a limited benefit and are easy to implement: (10) IIoT and (11) cloud computing.

Based on these findings and previous research of the authors, the following Sect. 1.3 provides guidelines and a modular framework for introducing highly adaptable and smart manufacturing systems in SMEs.

1.3 Framework and Guidelines for Smart Manufacturing in SMEs

1.3.1 Axiomatic Design Guidelines for Implementing Industry 4.0 in SMEs

Based on previous research reported in Rauch et al. (2020b), the authors developed and adapted a set of coarse design guidelines for implementing smart manufacturing in SMEs by using an Axiomatic Design based top-down approach (Brown 2020). In the following, this set of guidelines are broken down indicating also the most promising Industry 4.0 technologies. On the highest level (Level 0), the following functional requirement (FR) and design parameter (DP) have been defined:

FR_0 Create a smart and highly adaptable manufacturing system for SMEs

DP_0 Design guidelines for a smart and highly adaptable manufacturing system for SMEs

The abovementioned highest-level FR-DP pair can be further decomposed into the following top-level FR-DP pairs (Level 1).

FR_1 Adapt the manufacturing system very quickly in a flexible way
DP_1 Changeable and responsive manufacturing system
FR_2 Make the manufacturing system smarter
DP_2 Industry 4.0 technologies and concepts

The top-level FR-DP pairs, describing the main goals in sense of a highly adaptive and a more intelligent manufacturing system, can again be further decomposed into a set of FR-DP pairs on Level 2.

For FR_1/DP_1 (adaptability of the manufacturing system), the decomposition is as follows.

$FR_{1.1}$ Change and reconfigure the system with low effort
$DP_{1.1}$ Flexible and changeable SME manufacturing system **(advanced and autonomous robotics, additive manufacturing)**
$FR_{2.1}$ React immediately to changes
$DP_{2.1}$ Responsive SME manufacturing system **(computer vision)**

For FR_2/DP_2 (smartness of the manufacturing system), the decomposition is as follows

$FR_{2.1}$ Create data in manufacturing systems
$DP_{2.1}$ Multi-sensor data fusion **(sensor technologies)**
$FR_{2.2}$ Store and manage data in manufacturing systems
$DP_{2.2}$ Innovative storage systems with capabilities for big data **(cloud computing)**
$FR_{2.3}$ Connect all elements in the system to get real-time data
$DP_{2.3}$ Connectivity and interoperability to exchange data **(IIoT, horizontal/vertical data integration)**
$FR_{2.4}$ Take advantage of data in the manufacturing system
$DP_{2.4}$ Smart data analysis **(big data analytics, artificial intelligence)**
$FR_{2.5}$ Create digital models to test, monitor and control manufacturing systems

$DP_{2.5}$ Digital twin of products and manufacturing systems **(simulation)**
$FR_{2.6}$ Interact as human with the cyber-physical world
$DP_{2.6}$ Multimodal Human-machine interaction **(virtual and augmented reality)**
$FR_{2.7}$ Provide appropriate protection against cyberattacks
$DP_{2.7}$ Cybersecurity solutions for SMEs **(cybersecurity)**

1.3.2 Framework for Highly Adaptable and Smart Manufacturing in SMEs

Based on the design guidelines from the previous section, a framework is presented to help SMEs make their manufacturing systems highly adaptable and smart (see Fig. 1.1). The framework is divided into a part that represents the physical world. This means the physical manufacturing system with its machines, which must be designed to be as flexible and changeable as possible in order to meet the need for increasing individualization and thus the trend toward mass customization. On the other hand, it is divided into a cyber-world that is driven by the digital transformation and aims to achieve a smart manufacturing system. In between

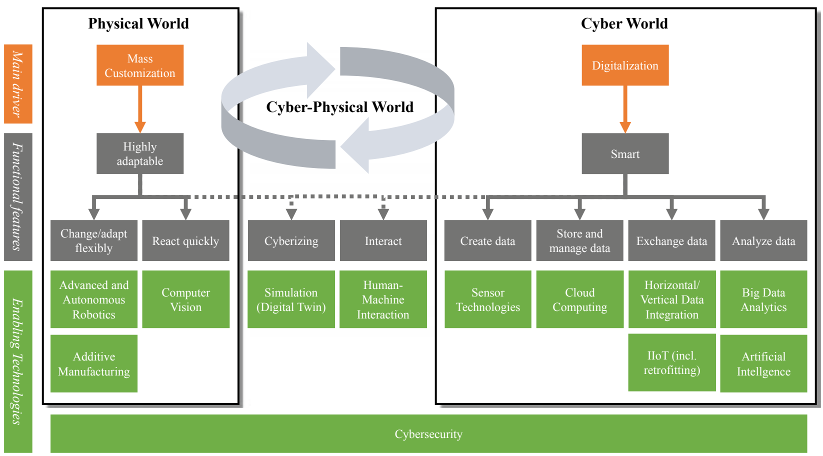

Fig. 1.1 Framework for highly adaptable and smart manufacturing systems

lies what we also call cyber-physical production systems. For all three, the framework identifies functional features of future SME manufacturing systems. They should be flexible and responsive, able to cyberize the physical allowing human interaction as well as creating, managing, exchanging and analyzing data to improve manufacturing processes.

For each functional feature, the framework indicates the most promising and enabling technologies. In the physical world, autonomous mobile and collaborative robots fulfill the requirement to adapt manufacturing processes easily to a changing environment or changing products or variants (advanced and autonomous robotics). In addition, additive manufacturing provides a possibility to produce customized and complex geometries on demand. Computer vision technologies enable context awareness as well as scene understanding capabilities in order to identify changes in the production environment immediately and therefore react with high response.

In the cyber-physical world, simulation and advanced CAE technologies provide the basis for cyberizing the physical and thus create a digital twin of products, manufacturing systems and entire factories. The human can interact with such digital models by using multimodal human-machine interaction technologies like virtual and augmented reality.

In the cyber-world, data can be created by using sensor technologies and multi-sensor data fusion combining information from different sensors and thus providing a robust picture of the environment. Such kind of smart machines equipped with sensors create a huge amount of data that needs to be stored and managed. Cloud computing solutions provide the necessary data storage capabilities as well as the needed computing power for managing big data. This data needs to be exchanged with other machines in the manufacturing system as well as integrated with other higher-level advanced IT systems and databases. Here IIoT provides the necessary connectivity and interoperability while data integration systems allow a seamless data exchange from the business level systems (ERP or MES) to the machine level. Once data is created, stored and the ability for data exchange is available this data can be used to gather useful information for decision making and improvements. Big data analysis techniques can be applied to analyze the data and artificial intelligence can be used to perform predictive analysis.

Due to connectivity and digitization, the entire smart manufacturing system must be adequately protected against cyberattacks. For this reason, cybersecurity is one of the fundamental enabling technologies for implementing Industry 4.0 in SMEs.

Many references repeatedly point out the limitation of SMEs due to financial resources (Orzes et al. 2018; Masood and Sonntag 2020). This means that most SMEs cannot completely renew their machinery in the short or medium term. In order to still be able to use Industry 4.0 technologies and in particular the advantage of a connected factory, SMEs are dependent on making legacy machines "Industry 4.0 ready". This is also referred to as "retrofitting" in the relevant literature. Digital retrofit is a process responsible for updating existing equipment by adding new software, hardware, or protocol-related components, allowing the system to extend its capabilities and meet new requirements. From an economic aspect, it avoids the incurring of large investments associated with the redesign or purchase of new equipment. In addition, the retrofit technique can assess the complete (or partial) migration to new technologies without compromising the integrity of the traditional methods employed by the company (García et al. 2020). Therefore, the need for retrofitting is also considered in the proposed framework as part of IIoT.

1.3.3 Three-Stage Model for Implementing Industry 4.0 in SMEs

To implement the presented framework, it is recommended to use a three-stage model as shown in Fig. 1.2. This model is divided into 3 stages: (i) design level, (ii) implementation level and (iii) operational level.

The design level comprises the previously presented design guidelines and the framework and supports the system designer in this design phase.

The implementation level is divided into initial pilot projects and the subsequent roll-out of the concept and technologies. In previously defined pilot projects, the technologies are initially tested and evaluated

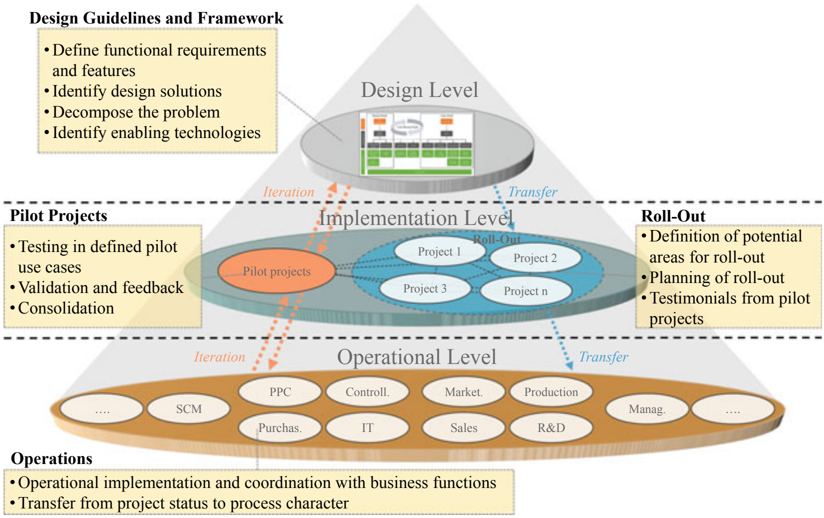

Fig. 1.2 Three-stage model for implementing Industry 4.0 in SMEs

for their suitability for operation and application. Based on the feedback, further work is then carried out to consolidate the implementation of the technologies. This is followed by the roll-out, in which the areas with the greatest potential are first planned and the timeline is prioritized. The roll-out is then completed with the support of testimonials from the pilot projects.

The operational level deals with the integration and coordination with the functional departments in the company. For both the pilot phase and the roll-out, it is necessary to involve the individual departments and thus to initiate the transfer from the project to the business process. With regard to knowledge transfer, on the one hand, new knowledge and new technologies are transferred to the operational areas in the company. On the other hand, the guidelines and framework defined at the design level are also put to the test by feedback from the operational level in an iterative process and adapted if necessary.

1.4 Industry 4.0+: An Outlook on Future Challenges for SMEs

After ten years of a continuing hype of Industry 4.0 and the effort to introduce Industry 4.0 also in SMEs we should take a look in the future to identify what kind of challenges SMEs will face in the forthcoming next ten years. Several researchers already discuss if there would be the beginning of a new industrial revolution or "Industry 5.0" (Özdemir and Hekim 2018) with a strong focus on the introduction of artificial intelligence in manufacturing. Taking a closer look to the original goals of Industry 4.0 from the beginning (Kagermann et al. 2013), we can understand that they have not yet been achieved completely. While initial objectives like cyber-physical systems, smart and connected factories, IoT and data integration are already well-researched topics ready for implementation, other objectives like intelligent manufacturing systems or self-optimizing factories are in its infancy and need still more research. Therefore, we do not see the beginning of a completely new industrial revolution but the completion of something that stared roughly ten years ago.

In this regard, we propose a concept called "Industry 4.0+" describing a next level of Industry 4.0 with new challenges for the next decade. Figure 1.3 shows the classic picture of the four industrial revolutions with the extension of Industry 4.0 by the next level of Industry 4.0+. The first level aims at achieving a smart and connected factory, while the next and future level of Industry 4.0 aims to achieve an intelligent and self-optimizing factory. The first level of Industry 4.0 is characterized by technology-driven innovation, which is also the prerequisite for the next level. In this last decade, we developed technologies making it possible to create data, collect and manage data and process large amount of data. The second level of Industry 4.0 is characterized by data and intelligence-driven innovation. This next decade of Industry 4.0 will be dominated by making sense of data and utilizing such data for not only optimizing our factories, but to bring them to a level of self-regulation and self-optimization. Going this way toward intelligent factories, we can exploit the capabilities from artificial intelligence as well as bio-inspired intelligence (Rauch 2020).

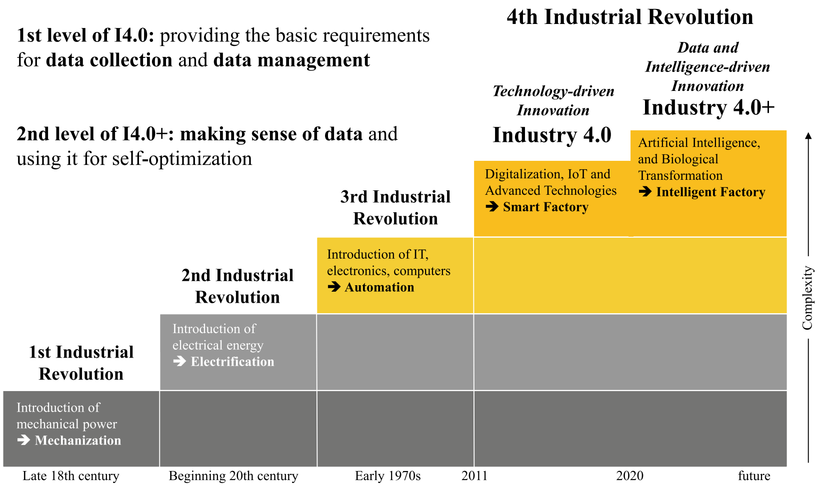

Fig. 1.3 Industry 4.0+ as the next level of Industry 4.0 (Rauch 2020)

First, we should clearly define what we mean with Industry 4.0 by differentiating the two terms "smart factory" and "intelligent factory". While a smart factory can be understood as a manufacturing system, which is capable to apply previously acquired knowledge an intelligent factory may be seen as a factory, which can autonomously acquire new knowledge and apply it for self-optimization purposes. To achieve this goal, the results from the first era of Industry 4.0 play an important role, as digitalization, connectivity and advanced manufacturing technologies are a prerequisite for this next level of Industry 4.0. In the coming years, the goal will be to fully realize the Industry 4.0 vision by equipping our manufacturing systems with intelligence using nature as an inspiration and profit from the latest advances in artificial intelligence. (Rauch 2020).

An intelligent and self-optimizing manufacturing system can be realized by using artificial intelligence (including **machine learning** and with increasing amount and complexity of data especially **deep learning**). Possibilities for the application of artificial intelligence in manufacturing are expected in automated or assisted engineering design, manufacturing system reconfiguration, production planning, predictive maintenance, quality inspection as well as in supply chain management

(Rauch 2020). The introduction of artificial intelligence in manufacturing enables manufacturing systems to become self-aware, self-comparing, self-predicting, self-optimizing and thus more resilient as traditional manufacturing systems (Lee et al. 2018).

Resilience is also one of the central characteristics of many biological systems. From a biological point of view, resilience is a property that enables a system to maintain its functions against internal and external disturbances (Van Brussel and Valckenaers 2017). Increasing technical capabilities in information processing and computer capacities have enabled a growing understanding of biological processes in our environment in recent years. It is to be expected that biology and information technology will grow closer together in the future. Therefore, biological transformation is also seen as a parallel process to digital transformation (Dieckhoff et al. 2018). According to (Miehe et al. 2018), biological transformation can be transferred in three levels to industrial production:

- **Bio-inspired manufacturing:** involves the imitation or transfer of phenomena from nature to complex technical problems.
- **Bio-integrated manufacturing:** means the integration of technological and biological processes into industrial value-added processes.
- **Bio-intelligent manufacturing:** as the combination of technical, informatics and biological systems creating robust and self-sufficient value creation systems.

This results in completely new potentials in the use of nature as a source of inspiration by not only imitating biological effects but by intelligently transferring principles from nature to various fields of application, such as manufacturing. It can be seen as a process that interacts symbiotically with digital transformation. While the first two levels of biological transformation mentioned above have already been applied in the past and present, the third level represents a groundbreaking innovation that will be able to fully unfold its full potential shortly based on the latest Industry 4.0 technologies and enhanced by the progress in artificial intelligence (Rauch 2020).

These new challenges are currently a long way off for SMEs in particular, as artificial intelligence and especially bio intelligence are topics that small companies are currently not or hardly concerned with. In the medium to long term, however, SMEs must be prepared for this future development, the necessary qualification programs must be provided and it must be identified how SMEs can best profit from this new development. This means driving forward the implementation of Industry 4.0 (see proposed framework) as the proposed enabling technologies are also the basis for the next level of Industry 4.0+. In the future, however, it will also be necessary to adapt Industry 4.0+ approaches, applications and tools to the needs of smaller companies.

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