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SME Requirements and Guidelines for the Design of Smart and Highly Adaptable Manufacturing Systems

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2.1 Introduction

The industrial environment has undergone a radical change with the introduction of new technologies and concepts based on the fourth industrial revolution, also known as Industry 4.0 (I4.0) (Sendler 2013), the Fourth Industrial Revolution (Kagermann et al. 2013) or Smart

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Manufacturing (Kang et al. 2016). The concept of I4.0 is building on the integration of information and communication technologies and advanced industrial technologies in so-called Cyber-Physical Systems (CPS) to realize a digital, intelligent, and sustainable factory (Zhou et al. 2015). The basic meaning of I4.0 lies in connecting products, machines, and people with the environment and combining production, information technology, and the internet (Kagermann et al. 2013). Industry, especially in high-wage countries, must introduce these types of smart production strategies to maintain the current competitive advantage in the long-term competing on a global market (Manhart 2017). To remain competitive, lead times, flexibility, and the ability to produce many individual kinds of products in low batch sizes or batch sizes of one, must improve (Spath et al. 2013; Matt and Rauch 2013a). In a mass customization and “design for x” environment, more functionality and customization options have to be provided to the client and more flexibility, transparency, and globalization for the supply chain (Baum 2013). On the other hand, this also leads to a more difficult and complex situation for manufacturing companies. Quickly responding to the expectations and requirements of customers is not easy and requires agile and highly adaptable manufacturing systems (Zawadzki and Żywicki 2016). The introduction of I4.0 in manufacturing companies contributes exactly to tackling these global challenges for strengthening competitiveness of high-wage countries (Kagermann et al. 2013).

Manufacturing companies, and especially SMEs, struggle with the introduction of I4.0 and to gain from its potential to increase productivity on the shop floor (Matt et al. 2014). Very often, they do not know how to face the challenge of I4.0 or how to start introducing and implementing I4.0 concepts (Ganzarain and Errasti 2016). A recent 2017 study (Wuest et al. 2018) conducted with manufacturing SMEs in West Virginia, USA, confirmed the struggle for SMEs to adopt Smart Manufacturing (Mittal et al. 2018). According to their literature review, only a few studies specifically focus on supporting SMEs’ evolutionary path and paradigm shift toward “Smart Manufacturing (SM)” or “Industry 4.0”. SMEs often face complications in such innovative processes due to the continuous development of innovations and technologies. Therefore, further research is needed to provide specific

instruments and models for SMEs introducing I4.0 in their companies and production shop floors. In addition, policy makers should propose strategies with the aim of supporting SMEs to invest in these technologies and make them more competitive in the marketplace (Zambon et al. 2019).

The objective of this chapter is to analyze and evaluate the specific needs and requirements of SMEs with the aim of defining guidelines for the design of highly adaptable and smart manufacturing systems for SMEs in a dynamic environment using I4.0. After a brief introduction on I4.0 and its impact for SMEs, Sect. 2.2 summarizes the state of the art in I4.0 and its transfer to SMEs based on a literature review. The following Sect. 2.3 gives an overview of the problem formulation and the system limits of this research. Section 2.4 illustrates the research methodology, which is grounded in Axiomatic Design (AD) theory to transform user needs into functional requirements and finally into design guidelines for highly adaptable manufacturing systems. Section 2.5 describes in detail the analysis of the user needs of SMEs to introduce I4.0 in their factories. The collection of these user needs is based on an explorative study, while the derivation of functional requirements and design parameters is based on AD theory. Results of this main section are a final list of SME requirements as well as constraints to introducing I4.0 in manufacturing and a set of coarse design parameters for their implementation. In Sect. 2.6, there follows a critical discussion of the obtained results and in Sect. 2.7, the conclusion and outlook for further necessary research are presented.

2.2 Background and Literature Review

2.2.1 Industry 4.0—The Fourth Industrial Revolution

The term I4.0 was introduced in 2011 by a German group of scientists during the Hannover Fair, which symbolized the beginning of the fourth industrial revolution (Lee 2013). After mechanization, electrification, and computerization, the fourth stage of industrialization aims to introduce concepts like CPS, Internet of Things (IoT), Automation,

and Human–Machine Interaction (HMI) as well as Advanced Manufacturing Technologies in a factory environment (Zhou et al. 2015). Since then, the term I4.0 has become one of the most popular manufacturing topics among industry and academia in the world and has been considered the fourth industrial revolution with its impact on future manufacturing (Kagermann et al. 2013; Qin et al. 2016). Based on the principle of I4.0, traditional structures can be replaced, which are based on centralized decision-making mechanisms and rigid limits on individual value added steps. These structures are replaced by highly adaptable and agile manufacturing systems, offering interactive, collaborative decision-making mechanisms (Spath et al. 2013).

A key element in I4.0 for manufacturing companies is CPS with capabilities for self-organization and self-control. CPS are computers with networks of small sensors and actuators installed as embedded systems in materials, equipment and machine parts and connected via the Internet (Kagermann et al. 2013; Broy and Geisberger 2012; VDI/VDE 2013). CPSs positively affect manufacturing in the form of Cyber-Physical Production Systems (CPPS) in process automation and control (Monostori 2014). There is still a need for further research on CPS (Wang et al. 2015). In the future, CPS and networks of CPS, better known as CPPS, as well as all the technologies behind them, may act as enablers for new business models, which have the potential to be disruptive (Rauch et al. 2016).

Furthermore, the “Internet of Things” (IoT) is also one key element of I4.0, when the physical and the digital world are combined (Federal Ministry of Education and Research 2013). In its origins, the IoT means an intelligent connectivity of anything, anytime, anywhere (Atzori et al. 2010). IoT has developed into the combination and integration of information and physical world addresses to create the “4Cs” (Connection, Communication, Computing, and Control) (Tao et al. 2014). Production data are provided in a new way with real-time information on production processes, through sensors, and continuous integration of intelligent objects (Spath et al. 2013; Gneuss 2014). With connected production technologies, individualized production at low costs will become possible (Kraemer-Eis and Passaris 2015).

The potential benefits from the successful implementation of IoT in the context of I4.0 are immense and research is still important.

Other key elements of I4.0 are Automation, HMI, and Advanced Manufacturing. Automation needs to become more flexible allowing manufacturing processes to be automated with changing products or volumes (Rüßmann et al. 2015). To achieve a symbiosis between automation and operators, HMI plays a major role in providing adequate technological assistance as well as intelligent user interfaces (Gorecky 2014). Advanced manufacturing technologies like high-precision machining, reconfigurable manufacturing units, additive manufacturing, and others are changing production strategies, but also processes and manufacturing systems (Chen et al. 2018; Frank et al. 2019). A prominent example of such advanced technologies in Additive Manufacturing (AM), also known as 3D printing (Rauch et al. 2018). It is defined by the American Society for Testing and Materials (ASTM) as “the process of joining materials to make objects from 3D-model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM 2013).

2.2.2 State of the Art in the Introduction of Smart and Highly Adaptable Manufacturing Systems in SMEs

However, challenges arise for companies due to the immense financial resources required to acquire new I4.0 technologies, which makes it difficult for SMEs to introduce I4.0 (Erol et al. 2016). Despite these difficulties, SMEs will not be able to ignore the trend toward I4.0 and therefore, it will be a major challenge for them in the near future (Matt et al. 2018). I4.0 is particularly interesting for these companies, as this term promises the enabling of intelligent automation toward batch size one (Matt et al. 2016). SMEs are the backbone of the EU and many other economies (Federal Ministry of Education and Research 2013). European SMEs provide around 45% of the value added by manufacturing while they provide around 59% of manufacturing employment (Vidosav 2014). In the United States, SMEs account for nearly

two-thirds of net new private sector jobs (USTR 2017). Programs like the European Horizon 2020 research and innovation program actively support SMEs by providing direct financial support and indirect support to increase their innovation capacity, although, the number of publications and research activities related to I4.0 for SMEs is still limited (Mittal et al. 2018). New technologies and ideas related to I4.0 need to be further researched and adapted to make it possible to use them in SMEs (Nowotarski and Paslawski 2017).

According to a survey, many SMEs struggle with increasing product variety and individualization in a mass customization environment. Price competition, high quality requirements, and short delivery times are becoming increasingly important (Spena et al. 2016). Due to their flexibility, entrepreneurial spirit, and innovation capabilities, SMEs have proved to be more robust than large and multinational enterprises, as the previous financial and economic crisis showed (Matt 2007). SMEs are not only adaptive and innovative in terms of their products, but also in their manufacturing practices. Recognizing rising competitive pressure, small organizations are becoming proactive in improving their business operations (Boughton and Arokiam 2000), which is a good starting point for introducing new concepts of I4.0 like smart and highly adaptable manufacturing systems.

Successful implementation of such intelligent manufacturing systems must take place not only in large enterprises but also in SMEs (Sommer 2015). Various studies point out relevant changes and potential for SMEs in the context of I4.0 (Rickmann 2017). I4.0 technologies offer opportunities for SMEs to enhance their competitiveness. The integration of ICT and CPS with production, logistics, and services in current industrial practices would transform today's SME factories into smarter and more adaptable factories with significant economic potential (Lee and Lapira 2013). Previous works have shown a limited but positive impact of Industry 4.0 in SME operational performance, with little investment and little expertise when it relates to cloud computing (Radziwon et al. 2014).

The introduction of new technologies and practices is always risky in SMEs (Moeuf et al. 2017) and represents a big challenge for them. SMEs are only partly ready to adapt to I4.0 concepts due to their current

organizational capabilities. The smaller the SME, the greater the risk that they will not be able to benefit from this revolution. Many SMEs are not prepared to implement I4.0 concepts. This opens the need for further research and action plans to support SMEs in introducing I4.0 concepts (Sommer 2015) like smart and highly adaptable manufacturing systems.

Only a few works address the specific requirements of SMEs for introducing such intelligent manufacturing systems and most of them do not provide a complete list of them. In the work of Rauch et al. (2019) the authors present a study regarding requirements for the design of flexible and agile manufacturing systems for SMEs. This work does not consider the introduction of I4.0 concepts, but highlights the need for research into SME specific I4.0 solutions. The work of Mittal et al. (2018) is one of the only works that provides a list of SME requirements regarding the design of smart manufacturing systems by introducing I4.0. The work is based on literature research as well as a survey-based study with US SME companies. According to this work, the main SME requirements for I4.0 in manufacturing are (a) the need for financial resources, (b) the need for advanced manufacturing technologies, (c) the need for industrial standards, (d) the need to include I4.0 in the organizational culture, (e) the need to develop and include employees in I4.0 related changes, (f) the need for alliances with universities and research institutions, and (g) the need for collaboration with customers and suppliers. Although the results show a good starting point for further considerations, they are formulated very generally, they do not address the specific requirements for designing an SME manufacturing system and most of them are typical requirements of any kind of companies introducing I4.0. Therefore, we conclude that there is still a need to investigate the specific requirements of SMEs for smart manufacturing system design.

2.3 Problem Formulation

As previously identified in the literature review, there is a need for research and investigations for the implementation of I4.0 technologies and concepts in SME manufacturing. The authors compare these

challenges with the introduction of Lean Management in small- and medium-sized enterprises over the past 20 years. While most large companies have introduced or integrated Lean, at least in part, into their corporate strategy, most SMEs have gradually addressed this topic. Carrying out an analysis in Scopus with the keywords “lean” and “SME,” for example, shows research on this topic was carried out from 2001 onwards. There are several papers recommending specific strategies for the introduction of lean (Medbo et al. 2013) and specific lean methods for SMEs (Dombrowski et al. 2010; Matt and Rauch 2013b). As a result, Lean has now been implemented in many SMEs in practice. A similar approach is therefore also expected for SME manufacturing companies introducing I4.0, even as large companies have already addressed this goal.

As with the introduction of Lean, the success rate for introducing I4.0 in SME manufacturing can be increased by developing SME-customized implementation strategies, SME-adapted concepts and technologically feasible solutions. Otherwise, the current efforts for awareness-building of SMEs for I4.0 are at risk of failing to achieve the expected results and benefits. As mentioned in the conclusion of the literature review in Sect. 2.2, we can state that there is still a lack of scientific literature regarding detailed analysis of the needs and requirements of smart SME factories for a better understanding of the necessities and problems involved in the introduction of I4.0 in SME manufacturing. In addition, there are already no clear design guidelines available about how SMEs can implement I4.0 in their manufacturing facilities and processes. Another important question is what kind of limitations or barriers could hinder the successful implementation of I4.0 in manufacturing. Knowing these barriers, SMEs can better define the constraints for I4.0 implementation strategies and actions.

For this reason, we define the aim of our research with the following research questions:

- What are the current needs of SMEs when I4.0 is being introduced into manufacturing?
- What are the functional requirements of SMEs based on their specific user needs for smart manufacturing?

- What are coarse design guidelines to facilitate the introduction of I4.0 in SME manufacturing systems?
- What are the possible limitations and barriers for SMEs introducing I4.0 in manufacturing?

2.4 Research Methodology

In order to obtain direct input from the beneficiaries of smart manufacturing systems, we selected a primary research approach to collect specific user needs by interviewing SMEs. Another approach to get this information could also be to conduct a survey like in the work of Mittal et al. (2018). Due to the novelty of I4.0, many SMEs have not yet dealt with the topic at all or only to a limited extent, thus a survey might not produce any usable results. Therefore, the approach of an explorative field study (see also Becker et al. 2009; Wölfel et al. 2012) based on SME workshops was chosen, which allowed direct contact to be made with SMEs in order to better understand their real requirements. In the exploratory study, the researchers preferred discussion in smaller workshop groups. Such workshops allow a common exchange of experiences and stimulate discussion among the participants, thus creating a more creative atmosphere.

The workshops themselves were structured as follows. A total of four SME workshops were held in Europe (Italy and Austria), USA (Massachusetts), and Asia (Thailand) to investigate specific requirements for SME (see Fig. 2.1). The implementation of SME workshops in different countries/continents should also help to identify cultural or country-specific differences, thus avoiding local needs having a strong influence on the final design guidelines for the introduction of I4.0 in SMEs. A limit of 10–12 participating companies (owner, general manager, operations manager) facilitated a productive interaction in the workshops. The workshops had a standardized structure starting with an initial introduction and overview of I4.0, then presenting some practical applications and best practice examples in SMEs. This should help raise awareness that I4.0 will be an important topic for SMEs in the future and prove that even smaller companies can implement I4.0. Afterward,



Fig. 2.1 Explorative field study through SME workshops (Map reproduced from D-maps.com: https://d-maps.com/carte.php?num_car=3267&lang=en)

the participants were asked to express their needs and requirements for introducing I4.0 concepts in their companies and share their experiences with the other participants. They were then asked about the main barriers and limitations for the implementation of I4.0. The inputs were collected in the form of sticky-notes on pinboards and categorized by topic. Before starting the evaluation of the collected inputs, several company visits were carried out at participating SMEs to gain a better practical understanding of the requirements and barriers on site.

For the evaluation of the collected inputs from the SME workshops, the research team applied Axiomatic Design (AD) theory (see also Fig. 2.2). AD is a method used for the systematic design of complex systems (Suh 2001). In AD so-called Customer Needs (CNs) are translated into Functional Requirements (FRs) because not all customer “wishes” can be considered as functional. In addition, some of the CNs are translated into Constraints (Cs) as some of them limit design space. Once the needs and requirements have been determined, the next step starts with a decomposition and mapping process selecting appropriate solutions or Design Parameters (DPs) for individually fulfilling each FR. So-called Process Variables (PVs) are then the real process parameters

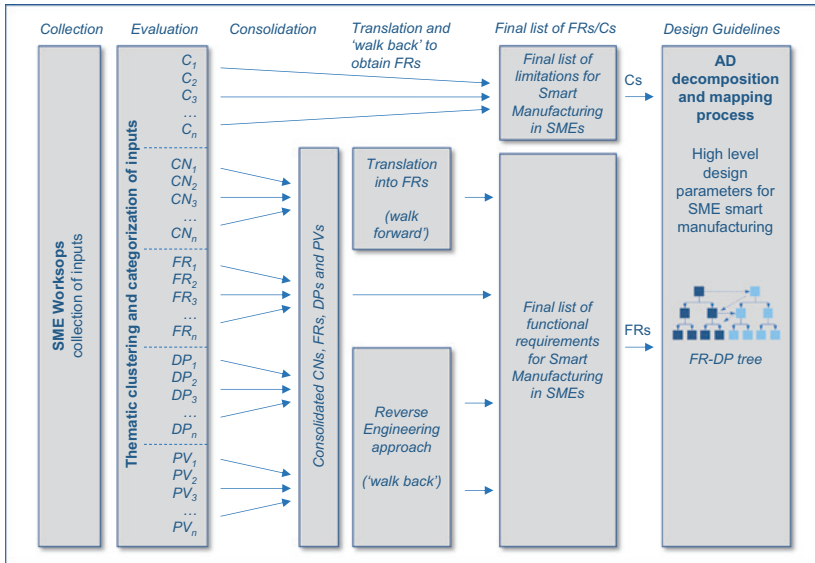


Fig. 2.2 Axiomatic Design based methodology for the analysis of SME requirements and design guidelines for smart manufacturing

in the phase of realization of the DPs. Chapter 6 gives a detailed overview about the AD methodology used in this chapter and explains the application of AD for the design of complex products, processes, and systems.

Although people in the workshop were asked about their needs and requirements for introducing I4.0, the experience of the authors showed that, often, people do not express their thoughts in the form of solution-neutral CNs or FRs, but rather in the form of physical solutions in the sense of DPs or PVs. Thus, the research team categorized the inputs from the SME workshops into Cs, CNs, FRs, DPs, and PVs. Cs are collected and build a final list of constraints that must be considered when realizing a smart manufacturing system in SMEs. The other inputs had to be further processed and interpreted to create a final list of solution-neutral FRs as a basis for the later definition of DPs. CNs were translated into FRs by analyzing the expressed needs and deriving the functional requirements by which the needs can be fulfilled.

FRs were added directly to the final list of FRs. DPs and PVs needed to be further processed to create “true FRs.” Users had most difficulties expressing solution-neutral CNs or FRs, proposing partial physical solutions, rather than basic needs. According to Girgenti et al. (2016), such a mixing of CNs and FRs with DPs or PVs can introduce personal bias, forestall creative thinking, and further complicate and constrain the design process. Therefore, we applied a Reverse Engineering (RE) approach, which starts from DPs/PVs from the SME workshops to derive solution-neutral FRs and CNs. This idea of using reverse engineering to solve this problem is based on previous research (Girgenti et al. 2016; Sadeghi et al. 2013). More details on the application of the RE approach is shown in Sect. 2.5. To build the final list of FRs, a consolidation of the identified FRs was needed as many of the inputs deal with the same requirement and could be merged together. In the last step, the final list of FRs was used as input for the top-down decomposition and mapping process in AD to derive coarse design guidelines for the design of smart manufacturing systems for SMEs.

2.5 Analysis of Requirements for SME 4.0 Manufacturing Systems and Coarse Design Guidelines

2.5.1 Collection of User Needs Through an Explorative Study

As explained in the previous section, the research team conducted four SME workshops in Italy, Austria, USA, and Thailand in order to collect inputs for the analysis of needs and requirements of SMEs regarding the introduction of I4.0. To ensure a uniform collection of requirements, a standardized procedure, and presentation for the conduct of the workshops were defined in advance. Table 2.1 illustrates the standardized structure of the workshops, where inputs for smart manufacturing were collected in three categories defined previously by the research team: (i) adaptable manufacturing system design, (ii) smart manufacturing

through ICT and CPS, and (iii) automation and man-machine interaction. In each brainstorming round, participants were also asked to express the main barriers and difficulties of introducing I4.0 concepts in manufacturing, which they had experienced, or foresaw experiencing as they planned on implementing I4.0 within their firms.

Table 2.1 Structure of SME workshops

No	Agenda point	Duration	Objective	Method
1	Introduce project presentation	15 min	Explanation of the project and research objectives	Opening presentation
2	Concept and origin of I4.0	30 min	Introduction to I4.0 for a common understanding	Opening presentation
3	Best practice examples	20 min	Awareness raising for implementation	Case studies, pictures, videos
4	Overview AD	15 min	Understanding of the research method and of the difference of CNs, FRs, DPs	Introductory presentation, examples
5	Introduction brainstorming session	10 min	Understanding of the brainstorming method	Introductory presentation
6	Brainstorming "adaptable manufacturing systems design"	30 min	Creative brainstorming with sticky-notes and subsequent discussion	Sticky-notes method
7	Brainstorming "smart manufacturing through ICT and CPS"	30 min	Creative brainstorming with sticky-notes and subsequent discussion	Sticky-notes method
8	Brainstorming "automation and man-machine interaction"	30 min	Creative brainstorming with sticky-notes and subsequent discussion	Sticky-notes method
9	Discussion and closure	30 min	Summary and closure	Open discussion

Table 2.2 Categories used in the workshop brainstorming sessions

No	Category	Brainstorming session	Sticky-notes
1	Adaptable manufacturing systems design	Session 1—smart manufacturing	58
2	Smart manufacturing through ICT and CPS	Session 1—smart manufacturing	64
3	Automation and man-machine interaction	Session 1—smart manufacturing	41
4	Main barriers and difficulties for SMEs—manufacturing	Session 1—smart manufacturing	60
Sum			223

Participants of the SME workshops who could speak well to the needs of SMEs in the manufacturing sector were invited through contact databases of the research team and professional associations. To allow an open discussion, the number of participants was limited to around a dozen companies in each workshop. Only owners, general managers, and production or logistics managers were invited. A total of 67 people from 37 SME companies attended and contributed to collect 163 user needs and 60 inputs regarding barriers/difficulties in the form of sticky-notes (see Table 2.2). Participants came from a variety of fabrication backgrounds, such as metal fabricators, wood processors, and many other industries.

2.5.2 Thematic Clustering and Categorization of Inputs

The workshop results built the basis for the definition of FRs and a subsequent AD decomposition and mapping process to derive DPs for the design of smart manufacturing systems for SMEs. The evaluation of the workshop results showed that the participants did not always write down Cs, CNs, or FRs as desired, but replied partly in the form of DPs or PVs. As this is a common behavior of people when they are asked to express their basic needs and requirements, the research team categorized all sticky-note responses.

The results were interpreted using the following procedure to define the AD domain:

- Each category was discussed during the brainstorming session and notes were taken to ensure the intent of the inputs when final collation of data was to be done after the workshop. The open discussion of participants' feedback on post-its ensures a correct interpretation of the statements. The moderator needed to check if the respondents understood the concepts of I4.0 correctly and used them in a correct way according to what they intended to express. In addition, this confirmed the alignment between their understanding and the interpretation of the research team.
- After the workshop, inputs, and notes were collected in an Excel spreadsheet and inputs were categorized into thematic "clusters" (see Table 2.3), which were used to identify subjects of interest for several categories.
- Each piece of input was then categorized as a C, CN, FR, DP, or PV based on AD grammar, notes, and interpreted design space.

Table 2.3 Thematic clustering of workshop inputs

No	Cluster	Sticky-notes	No	Cluster	Sticky-notes
1	Agility	23	15	Production planning and control	10
2	Automation	16	16	Preventive and predictive maintenance	5
3	Connectivity	12	17	Real-time status	10
4	Culture	14	18	Remote control	3
5	Design for manufacturing	4	19	Resource management	14
6	Digitization	22	20	Safety	2
7	Ease of use	8	21	Security	4
8	Implementation	12	22	Strategy	2
9	Inspection	5	23	Sustainability	4
10	Lean	8	24	Tracking and tracing	5
11	Machine learning	3	25	Transport	1
12	Mass customization	9	26	Upgrade	3
13	Network	4	27	Warehouse management	1
14	People	16	28	Virtual reality	3

Table 2.4 Breakdown of categorization of workshop outputs

Abbreviation	AD domain	Sticky-notes	%	Check
C	Constraints	47	21.08	✓
CN	Customer Needs	65	29.15	✓
FR	Functional Requirements	34	15.25	✓
DP	Design Parameters	76	34.08	✗
PV	Process Variables	1	0.45	✗

Table 2.4 summarizes the result of the categorization. 21.08% of the inputs were constraints. In particular, the inputs regarding limitations and barriers for the introduction of I4.0 were good sources for the collection of constraints. Overall, 29.15% of the inputs were categorized as CNs and another 15.25% as FRs. CNs could be translated by the research team and companies into real FRs. However, nearly 35% of the inputs were categorized as DP and PVs and need a reverse engineering interpretation to be used for further AD design studies.

2.5.3 Reverse Engineering of Inputs Categorized as DPs and PVs

DPs and PVs were derived to functional requirements (see Table 2.5) applying the reverse engineering approach (hereinafter called FR_{RES}). Through logical regression, the research team then “walked back” each input to make it a functional requirement. For this purpose, these were analyzed in detail and discussed together with companies from the workshops in order to identify the real needs.

The grammatical rules of AD were applied for this “walk back.” A look at the first example will show that “automate a current manual loading...” is a physical solution, and that the true FR would be to “mitigate highly repetitive tasks.” This gives a larger solution space as the design team is no longer constrained to using automation, but whatever solution is deemed best by the design team and customer.

Table 2.5 shows an excerpt of the complete list of 43 derived FR_{RES} . Due to repetition of similar DPs in the various workshops, many DPs have been consolidated into single inputs to make reading the FR list easier to digest. This means that the original 77 non-satisfactory inputs from sticky-notes have been reduced to 43 FR_{RES} .

Table 2.5 Excerpt from the list of the reverse engineering approach

No	Inputs (DPs and PVs)	Reverse engineered FR (FR _{RES})
1	Automate a current manual loading process using a robot to load and process	Mitigate highly repetitive manual tasks
2	Augmented reality in service, maintenance and after sales, augmented reality for information provision at assembly	Allow user-friendly “smart” representation of information for production, maintenance, design, and service
3	Machine driven SPC and adaptive tool path generation	Identify and adjust parameter deviations in the manufacturing process influenced by environmental variance
4	Automation for billing, order management for correct priorities, and workflow optimization	Automate and digitize internal workflows and report generation
5	Simulation of components before production	Avoid cost and time for physical prototyping
6	Data acquisition of machines, workstations, warehouses, and buildings	Collect real-time data of machines, warehouses, and facilities to keep production under control
7	Optimal utilization of space thanks to flexible working systems, with shortened distances through flexible workstations	Create compact production lines and work stations
8	Automated time recording of staff presence	Create data-driven resource and process capability monitoring system for all relevant resources
9	Computational design and engineering as well as simulation for products can save cost and test process, etc.	Create data-driven system for product development, improvement, and management
10	Use of sensors on the machine for data acquisition, real-time data collection, machine reports capacity usage, digital feedback of work steps	Create a digital feedback system, and infrastructure, which monitors real-time status of production

A limitation of the reverse engineering approach is a possible misunderstanding of the user input by the research team. However, the risk of making a misjudgment through the reverse engineering approach is lower than the limitation one would accept if one continued to work with inputs that are not solution-neutral. Furthermore, as the case study in this research confirms, many user inputs can be categorized often as

DPs or PVs (in the described case study nearly 35%). Therefore, simply ignoring these inputs is not a recommended way forward. Thus, the presented reverse engineering approach represented a good possibility to transfer “false CNs” into useful requirements for further design studies.

2.5.4 Final List of Functional Requirements and Constraints Regarding the Introduction of Industry 4.0 in SMEs

FRs (directly collected in the workshops or translated from CNs) and FR_{REs} (obtained from DPs and PVs using the previously explained RE approach) were consolidated, and redundancies removed by combining similar FRs and FR_{REs} and merging them into one. Due to the high number of inputs from SME workshops and many similar inputs from different workshops, this was necessary and reasonable to make the document and the final FR list more workable and useful. The same was also done for the identified constraints to achieve a list of the main limitations and barriers that SMEs are facing to introducing I4.0 in their companies. This final FR list, together with the final list of Cs is used in a next step to derive coarse design guidelines for the design of smart manufacturing systems for SMEs (see also Sect. 2.5.5).

Table 2.6 shows the consolidated list of functional requirements for SMEs based on the procedure discussed throughout Sect. 2.4 of this chapter.

In addition, Table 2.7 shows the consolidated list of the main limitations and barriers (deduced from the identified Cs) for SMEs introducing I4.0. This list serves as a starting point for measures to minimize the listed barriers or also to set SME specific limits in the design of smart manufacturing systems.

2.5.5 Derivation of Coarse Design Guidelines for Smart Manufacturing in SMEs

The consolidated final list of FRs builds the basis for the next step to derive coarse design guidelines for the design of smart manufacturing systems. According to AD, this can be achieved through a top-down

Table 2.6 Final list of SME functional requirements for smart manufacturing

Cluster	No	(Functional) Requirements for the design of smart manufacturing systems in SMEs
Agility	1	Build or improve production lines and work stations to be more compact
	2	Ensure flexible, scalable, customizable production systems
	3	Minimize set up time for new configurations
	4	Enable the ability to produce a wide variety of products and a wide range of volumes without significant reconfiguration of costs and time
	5	Create self-adjusting processes
	6	Enable easy to use and change systems of new manufacturing technologies
	7	Take advantage of rapid prototyping technologies to make product development easier, and reduce requirements for stock
Automation	8	Mitigate repetitive tasks with quick payback time
	9	Enable on demand customizable packaging
	10	Reduce labor and cost of all production and logistics processes
Connectivity	11	Implement self-maintaining processes
	12	Ensure the ability to easily and efficiently communicate on a sufficiently real-time basis with internal and external customers
	13	Standardize and simplify security and interoperability of information and communication technologies
	14	Create standardized easy to use systems for connectivity, communication, and transparency
	15	Enable internal and external information connectivity to enable better forecasting, inventory management, current demand measuring, internal material requirements, etc.
Culture	16	Understand the culture of customers to interpret preferences for cost and quality
Design for manufacturing	17	Enable the use of advanced manufacturing technologies in the design phase
Digitization	18	Implement automation and digitization of internal workflows and report generation
	19	Avoid cost of physical prototyping
	20	Implement clear data gathering, management, analysis, and visualization to both internal and external customers

(continued)

Table 2.6 (continued)

Cluster	No	(Functional) Requirements for the design of smart manufacturing systems in SMEs
	21	Collect real-time data of machines, warehouses, and facilities to keep production under control
	22	Enable data flow to be consistent through the whole product life cycle and in the whole supply chain
	23	Enable fast measurement on-site and immediate delivery of data to production facility
	24	Provide and visualize information everywhere and every time to reduce waiting times and unnecessary delays
Ease of use	25	Simplify maintenance of newly adopted manufacturing technologies
	26	Minimize informational barrier, complexity of entry to new manufacturing technologies
	27	Enable user-friendly robot programming for "normal" workers
Implementation	28	Manage legal and bureaucratic hurdles for introducing I4.0 technologies
	29	Measure the impact of I4.0 on the company's sustainable success
	30	Provide an overview of existing I4.0 instruments and their suitability for SMEs or industry sectors
Inspection	31	Gain access to knowledge needed to implement I4.0
	32	Identify a defect as early as possible with little to no worker intervention needed
	33	Mitigate the human element in otherwise tedious or low information content tasks, such as delicate maintenance, equipment calibration, etc.
	34	Identify defects through in line inspection of process and material to avoid non-quality at the customer side
Lean	35	Eliminate non-value adding activities in production and logistics
	36	Produce on demand and deliver just in time
	37	Move product individualization as late as possible in the value chain
Machine learning	38	Automatically identify and adjust parameter deviations in the manufacturing process influenced by environmental variance
	39	Implement fast and automated design-based generation of tool path, part processing plan, and quotation
Mass customization	40	Gain the ability to produce small lot sizes (lot size 1) without losing efficiency

(continued)

Table 2.6 (continued)

Cluster	No	(Functional) Requirements for the design of smart manufacturing systems in SMEs
Network	41	Ensure that SME has a culture which includes the needs of the customer and workers through discourse and communication to enable full and productive integration of SME 4.0
	42	Gain the ability to communicate and/or share capacity, materials, infrastructure, and information with internal and external customers, and suppliers
People	43	Enable ergonomic support for physically difficult tasks
	44	Manage internal knowledge and staff development for Industry 4.0
Production planning and control	45	Enable a decentralized and highly reactive production planning and control
	46	Create system which can forecast demand changes quickly and interact with systems for planning, control, and logistics
Preventive and predictive maintenance	47	Ensure maintenance costs are minimized while maximizing value added time of machines
	48	Proactively maintain to ensure availability and decrease downtime of machines
	49	Predict data-based probability of machine stops or machine downtime
Real-time status	50	Create digital feedback system, and infrastructure, which monitors status of production, storage, shipping, risk, and crisis management
	51	Gather real-time status and visualize these data for operators and management
Remote control	52	Enable location independent control of maintenance, facilities, and products
Resource management	53	Create data-driven material, and process capability monitoring system for all relevant resources
	54	Ensure machines are capable for prospective jobs, and are able to be repurposed for a variety of other jobs
	55	Minimize time investment for I4.0 implementation and throughout life cycle
Safety	56	Provide workers with ergonomic workplace
	57	Provide safe working environment
Sustainability	58	Minimize energy consumption and environmental cost
	59	Measure and optimize energy, material, and time usage on processes

(continued)

Table 2.6 (continued)

Cluster	No	(Functional) Requirements for the design of smart manufacturing systems in SMEs
Tracking and tracing	60	Implement easy tracking of products from origin through the value chain
	61	Ensure supply chain has capability to digitally trace, and allow localization of systems
Transport	62	Create easy to use, worker independent material transport system for inside plant
Upgrade	63	Reuse and upgrade of existing manufacturing equipment
Virtual reality	64	Allow user-friendly “smart” representation of systems for production, maintenance, design, and service
	65	Create data-driven system for product development, improvement, management, and security to ensure product is more profitable for SME and customer through product life

decomposition and mapping approach of FR-DP pairs applied to decompose first level FR-DP pairs from an initially abstract level toward more tangible design guidelines (see also Fig. 2.3). To conduct such a decomposition, the two basic Axioms of AD will be considered (see also Chapter 13 in the Appendix). The application of the first Axiom, the Independence Axiom, favors DPs which are independent of FRs other than the one they were selected to fulfill. The second Axiom, the Information Axiom, ensures that in case of alternative solutions (alternative DPs), the best DP has the lowest information content, or greatest probability of success (Suh 2001):

- Axiom 1—Independence Axiom: the design of a system is considered ideal if all functional requirements are independent of the others to avoid any kind of interaction among them. Each defined design parameter is only related to one functional requirement and has no influence on other functional requirements.
- Axiom 2—Information Axiom: The Information Axiom helps the designer to choose among multiple possible solutions. The design parameter should be part of the physical domain with the smallest information content, to ensure a higher probability to satisfy a requirement. The aim is to minimize the information content or complexity of the design.

Table 2.7 Constraints (limitations and barriers) of SMEs introducing smart manufacturing

No	Cluster	Limitations and barriers for the design of smart manufacturing systems in SMEs
1	Culture	Lack of cooperation, openness, and trust between firms
2		Lack of employee acceptance of new operational processes and technologies
3		Company needs a well-entrenched top-down culture which allows continual improvement and mitigation of silo syndrome
4		Regulations and culture of the sphere within which the SME and parent organization functions must be such that proliferation of I4.0 is enabled, rather than disabled
5		Lack of visibility of I4.0 among professionals who would otherwise champion the implementation of I4.0
6	Implementation	Lack of experience in project management and budgeting for implementation of I4.0
7	People	Lack of training and qualification of personnel for systems to encourage communication, flexibility, education of I4.0, and soft skills
8		SMEs lack access to the financial, informational, digital, physical, and educational resources to ensure I4.0 is fully realized
9	Resource management	Lack of easy access to thought leaders and talent (relative to multinational companies)
10		Buildings are not designed for automating internal transports or processes or for new manufacturing technologies
11		High financial barrier to new manufacturing technologies
12	Security	Lack of and need for better, data security for operations such that potentially unforeseen dangers can be mitigated or blocked entirely
13	Strategy	Current lack of knowledge transfer from experts to SMEs for the implementation of I4.0
14		Lack of risk management tools for investments in new processes

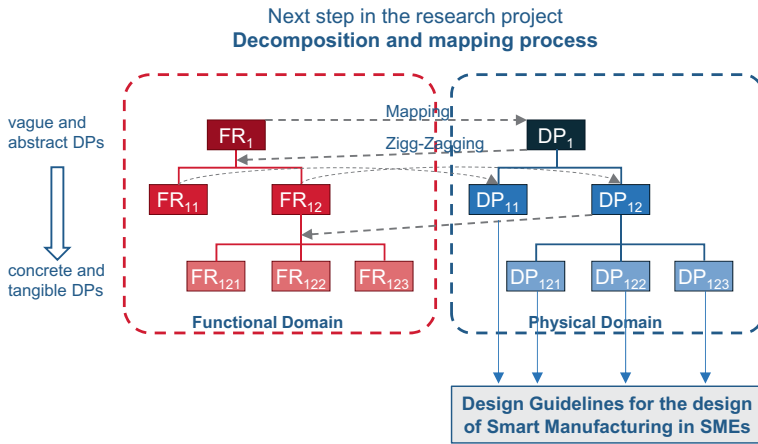


Fig. 2.3 AD approach to deduce design parameters for smart manufacturing in SMEs

By using the previously explained Axiomatic Design approach and examining the final list of FRs in Table 2.6, we identified the following top-level (Level 0 and Level 1) and upper-level FRs as well as their related design solutions (DPs).

- FR₀ Create a smart and highly adaptable manufacturing system for SMEs
- DP₀ Design guidelines for a smart and highly adaptable manufacturing system for SMEs

The abovementioned highest level FR-DP pair (Level 0) can be further decomposed into the following top-level FR-DP pairs.

- FR₁ Adapt the manufacturing system very quickly in a flexible way
- DP₁ Changeable and responsive manufacturing system
- FR₂ Make the manufacturing system smarter
- DP₂ 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 upper-level FR-DP pairs.

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
- $DP_{1.1}$ Changeable SME manufacturing system
- $FR_{2.1}$ React immediately to changes
- $DP_{2.1}$ Responsive SME manufacturing system

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

- $FR_{2.1}$ Enable the manufacturing system for Industry 4.0
- $DP_{2.1}$ Digitalization, Smart Sensors, and Cyber-Physical Systems
- $FR_{2.2}$ Connect all elements in the system to get real-time data
- $DP_{2.2}$ Connectivity and Interoperability in SME Cyber-Physical Production Systems
- $FR_{2.3}$ Take advantage of available data in the system
- $DP_{2.3}$ SME-adapted Big Data Analytics and Artificial Intelligence
- $FR_{2.4}$ Make automation in SME manufacturing easier
- $DP_{2.4}$ SME Automation and Human–Machine Interaction
- $FR_{2.5}$ Prepare typically low qualified people in SMEs for Industry 4.0
- $DP_{2.5}$ SME specific Industry 4.0 qualification programs
- $FR_{2.6}$ Provide appropriate protection against cyber attacks
- $DP_{2.6}$ Cyber Security systems for SMEs
- $FR_{2.7}$ Reduce ecological impact of manufacturing
- $DP_{2.7}$ Sustainable and Green Manufacturing for SMEs

Once the decomposition and mapping process is finalized, the lowest level DPs of every branch in the FR-DP tree build a list of coarse guidelines for the design of smart manufacturing systems for SMEs. This final list of design guidelines will support researchers to develop specific I4.0 implementation strategies and solutions for SMEs and should guide practitioners from SMEs in their work to design smart manufacturing systems.

2.6 Discussion

The derivation procedure described previously in this chapter and the results summarized in Tables 2.6 and 2.7 give a good overall list of needs and constraints for SMEs to introduce I4.0. In the following, we try to use all these inputs to describe a picture of a smart SME manufacturing firm using the concepts of I4.0.

The needs discussed by the SME workshop participants desire a rapidly evolving manufacturing facility, where machines are easy to set up, and quick to adhere to the steps of ever-changing product configurations. These processes track themselves such that the personnel running the facility can concentrate on progressive improvement and upgrades to the system rather than acting as firefighters keeping the production working from day to day. Furthermore, these processes nondestructively inspect themselves. This would give operators the ability to be the first line of defense in quality control by giving them the tools to understand what the implications of process variations are, to lower their workload and increase the efficiency of the firm. Such an SME facility is also highly digitized with the ability for workplace user interfaces to be connected vertically and laterally within the organization. This allows for the destruction of silo syndrome through meaningful connectivity both within and without the organization and interoperability between single machines or processes. This allows the SME to better communicate within itself to ensure the manufacturing floor is always pushing the edge of productivity and adaptability. In addition, there is also the possibility for SMEs to achieve higher efficiency in higher-level supply chain management by connecting the company with suppliers and customers. The management in such a smart SME manufacturing firm has real-time numbers on the outputs of different machines, problems on the shop floor, potential upcoming costs, through predictive maintenance, or tracking the manufacturing environment and resources needed to ensure that all the needs of the floor workers are met, enabling increases in profitability. Furthermore, the leaders of these firms have access to experts, thought leaders as well as cognitive assistance systems that can give guidance on decisions which would otherwise have lasting costs. These leaders also engender an empowered workforce

which is highly encouraged to bring possible improvements of the process to the fore, even when everything is working as expected.

These needs were not found to change much from culture to culture, or sector to sector, which lead us to believe that SMEs worldwide and from different sectors face similar challenges and problems. The lists in Tables 2.6 and 2.7 are general needs and constraints for most small- and medium-sized companies. The authors believe that these final list of FRs and Cs do give a good initial list of subjects to be pursued for implementation in SMEs throughout the world, due to the repetition of similar needs across these multinational workshops.

Possible limitations of this research include that the derived requirements and constraints using the reverse engineering approach are subject to the interpretation of the authors, as well as the initial company leaders, who communicated these needs. The authors attempted to hedge against this by taking notes on the intent behind the inputs, as well as diversifying the backgrounds, and geographical locations, of the participants of the workshops and by intensive discussions with SMEs during the phase of evaluation of the workshop results. It is believed by the authors that this did mitigate possible misinterpretations of needs, as well as incomplete needs for SMEs for implementing I4.0.

A current limitation of the presented decomposition of FRs into DPs is the fact that the design guidelines derived describe coarse design parameters. Manufacturing engineers receive a good basis for the appropriate design of their manufacturing system, but they do not yet find a very detailed, so-called “leaf-level” of design guidelines in order to be supported in the very detailed levels for machine design or the design of single processes. This would need a much more detailed investigation regarding the low-level decomposition of FRs and DPs defined in this work.

2.7 Conclusions

In this chapter, a comprehensive list of SME specific requirements and limitations regarding the introduction and implementation of I4.0 was proposed using an explorative field study as well as Axiomatic

Design theory. These lists are based on multinational workshops, which brought together leaders from manufacturing organizations from a variety of manufacturing spaces. To better organize the inputs of these workshops, they were broken down according to the subject matter of the session being discussed, then broken down further by “Clusters.” These clusters allowed for an efficient manner for categorizing and further refining the requirements and constraints.

Upon initial processing of the content from the international workshops, the authors found that almost 35% of the input given was not solution-neutral. With the use of AD, this is a requirement to ensure the best solution is reached. The authors thus concluded that the inputs would need refinement to derive the “true FRs” behind the input from the workshops. The FR derivation technique, which was discussed, is a good methodology to derive solution-neutral requirements from these organizational leaders. These requirements and constraints show the basis for further research on the subject matter, giving a starting point for researchers to begin investigating, developing, and delivering tools for SMEs to fully realize the advantages which I4.0 is believed to offer them.

The decomposition and mapping process was used to derive coarse design guidelines for manufacturing system designers implementing I4.0 in SMEs. Together with the list of requirements and constraints, these guidelines form the main result of this research and a useful tool set for practitioners to design manufacturing systems for SMEs that are not only flexible and reconfigurable, but also smart and innovative as described in the picture in the previous section.

Further research will be needed now to investigate lower-level design guidelines and to develop techniques, methods, tools, and techniques as well as organizational solutions for SMEs to satisfy the functional requirements and to apply the defined coarse design guidelines. It is believed that this will deliver a suite of instruments for SMEs to take full advantage of I4.0 such that they do not lose their competitive advantage to large enterprises.

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