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RESEARCH ARTICLE

Systematic analysis of needs and requirements for the design of smart manufacturing systems in SMEs☆

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Abstract

With the increasing trend of the Fourth Industrial Revolution, also known as Industry 4.0 or smart manufacturing, many companies are now facing the challenge of implementing Industry 4.0 methods and technologies. This is a challenge especially for small and medium-sized enterprises, as they have neither sufficient human nor financial resources to deal with the topic sufficiently. However, since small and medium-sized enterprises form the backbone of the economy, it is particularly important to support these companies in the introduction of Industry 4.0 and to develop appropriate tools. This work is intended to fill this gap and to enhance research on Industry 4.0 for small and medium-sized enterprises by presenting an exploratory study that has been used to systematically analyze and evaluate the needs and translate them into a final list of (functional) requirements and constraints using axiomatic design as scientific approach.

Keywords: industry 4.0; digitization; small and medium-sized enterprises; axiomatic design; smart manufacturing

1. Introduction and Motivation

In recent years, the industrial environment has undergone a radical change with the introduction of new theoretical models and technologies based on the fourth industrial revolution, also known as Industry 4.0 (I4.0) (Kagermann, Wahlster, & Helbig, 2013; Sendler, 2013) or smart manufacturing (Kang et al., 2016). I4.0 is the fourth industry emerging from an industrial revolution, which is led by intelligent manufacturing. The concept of I4.0 is based on the integration of information and communication technologies and advanced industrial technology and is dependent on building a cyber-physical system (CPS) to realize a digital and intelligent factory, to promote manufacturing to become more digital, information-led, customized, and sustainable (Dallasega, Rauch & Matt, 2015; Zhou, Liu & Zhou, 2015). The characterization and definition of I4.0 vary greatly, and a fundamental, generally accepted definition of I4.0 does not exist (Bauer, Schlund, Marrenbach, & Ganschar, 2014). The focus of I4.0 lies in connecting products, machines, and people with the environment and combining production, information technology, and the internet. Thus, the newest information and communication technologies are combined with classical industrial processes (Federal Ministry of Education & Research, 2013). Industry must introduce these types of production strategies to maintain the current competitive advantage in the long term (Manhart, 2017). To remain competitive, lead times, flexibility, and the ability to produce many versions of products in low batch sizes, must improve (Matt & Rauch, 2013a; Spath, Ganschar, Gerlach, Hämmerle, & Schlund, 2013). More functionality and customization options are provided to the client and more flexibility, transparency, and globalization for the supply chain (Baum, 2013). Enabling a company to quickly

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respond to expectations and requirements of its customer is not easy and requires agile and flexible manufacturing systems with rapid design (Zawadzki & Żywicki, 2016). Therefore, I4.0 should allow the return to uniqueness (Hartbrich, 2014). The development of I4.0 contributes to tackling global challenges, like achieving better resource and energy efficiency for strengthening competitiveness of high-wage countries (Kagermann et al., 2013).

Companies, and especially small and medium-sized enterprises (SMEs), struggle in realizing the ideas of I4.0 in concrete measures to implement and gain from its potential to increase productivity on the shop floor (Matt, Rauch & Dallasega, 2014). They do not know how to face the challenge of I4.0 or how to start introducing and implementing I4.0 concepts (Ganzarain & Errasti, 2016). The aim of this research is to analyze and evaluate the specific needs and requirements of SMEs with the objective to define guidelines for the design of smart manufacturing using I4.0. In this context, the authors define I4.0 in SMEs as the achievement of highly flexible and efficient production even at batch size 1 by combining the potentials of advanced manufacturing technologies and the connectivity of product, machine, human, and environment.

This work is structured as follows. After an introduction in the topic of I4.0 and its importance for SMEs, Section 2 provides an overview of the state of the art in I4.0 and its transfer to SMEs. Section 3 shows the research methodology used for this research, which grounds on axiomatic design (AD) theory developed by Nam Suh (Suh, 2001). Section 4 is dedicated to the analysis and evaluation of the needs of SMEs to introduce I4.0 in their environment. The collection of the needs is based on an explorative study, the derivation of functional requirements (FRs) for the design of smart manufacturing systems for SMEs is based on AD theory. This section provides the main result of this research in sense of a final list of SME requirements as well as constraints to introduce I4.0 in manufacturing. In Section 5, the results of this research are discussed and an overview is given how researchers will use this results in a next step to deduce design guidelines for smart manufacturing systems in SMEs. Finally, Section 6 summarizes the results of this research.

2. Literature Review

2.1. Industry 4.0 and digital transformation

In 2011 the term I4.0 was introduced 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 (IoTs), Automation, and Human–Machine Interaction as well as Advanced Manufacturing Technologies in a factory environment (Zouh et al., 2015). Since then, the term I4.0 is 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, Liu, & Grosvenor, 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 flexible, reconfigurable manufacturing systems, offering interactive, collaborative decision-making mechanisms (Spath et al., 2013).

One expected opportunity is the capabilities of CPS 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 & Geisberger, 2012; VDI/VDE, 2013). CPSs positively affect manufacturing in form of cyber-physical production systems in process automation and control (Monostori, 2014). The application potential of CPS in manufacturing, coupled with the lack of common understanding of CPS in manufacturing means there is a need for further research of CPS (Wang, Törngren, & Onori, 2015). In the future CPS and the technologies behind them may act as enablers for new business models which have the potential to be disruptive (Rauch, Seidenstricker, Dallasega, & Hämmerl, 2016).

When physical and digital are combined this is also called 'IoTs' (Gershenfeld, Krikorian, & Cohen, 2004; Federal Ministry of Education & Research, 2013). In its origins IoT means the intelligent connectivity of anything, anytime, anywhere (Atzori, Iera & Morabito, 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, Cheng, Da Xu, Zhang, & Li, 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 & Passaris, 2015). Summarizing, the potential benefits from the successful implementation of I4.0 are immense and research is still important.

Further technologies of I4.0 are automation and human–machine interaction (HMI). Automation needs to become more flexible allowing also to automate manufacturing processes with changing products or volumes (Rüßmann et al., 2015). To achieve a symbiosis between automation and operators, HMI plays a major role providing adequate technological assistance as well as intelligent user interfaces (Gorecky, Schmit, Loskyll, & Zühlke 2014).

Automation, HMI, and Advanced Manufacturing Technologies are mentioned as one of the key technologies for I4.0 (MISE, 2016). A prominent example of such technologies is additive manufacturing (AM), also known as 3D printing (Rauch, Unterhofer, & Dallasega, 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).

Many of these I4.0 technologies and concepts were transferred outside the production shop floor using the term "Digital Transformation". The introduction of digital technologies for business processes in the rest of the company is manifold. The concept of digital transformation—the use of digital technology to improve performance—is hyped as the Industrial Internet and is a hot topic of interest (Gilchrist, 2016). 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, Schumacher, & Sihn, 2016).

2.2. Transfer of I4.0 to SMEs

In the last decades lean management dominated the research in production aiming to improve the value for the customer and at the same time minimizing not-value adding time (Womack

& Jones, 1997). After the lean management wave, new concepts like I4.0 are major challenges for companies, especially SMEs (Matt, Rauch, & Riedl, 2018). I4.0 is particularly interesting for these companies, as this term promises the enabling of intelligent automation towards batch size 1 (Matt, Rauch, & Fraccaroli, 2016). SMEs are the backbone of the EU and many other economies (Federal Ministry of Education & 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). Recently, SMEs moved into the focus of many authors in their scientific work. Programmes like the European Horizon 2020 research and innovation programme actively support SMEs by providing direct financial support and indirect support to increase their innovation capacity. Publications related to I4.0 for SMEs is limited. Searching in the database Scopus for scientific literature with the key words "industry 4.0" and "small and medium-sized enterprises" the authors obtained only 161 documents, where most of the papers are from 2017 to 2019, while only 17 papers were published before this period. The authors believe new technologies and ideas related to this concept need to be further researched to make it possible to use them in SMEs (Nowotarski & Paslawski, 2017).

According to a survey, many SMEs struggle with increasing product variety and individualization. Price competition, high-quality requirements, and short delivery time are becoming increasingly important (Spena, Holzner, Rauch, Vidoni, & Matt, 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 worldwide financial and economic crisis showed (Matt, 2007). Typically, SMEs are adaptive and innovative not only in terms of their products, but in their manufacturing practices. Recognizing rising competitive pressure, small organizations are becoming proactive in improving their business operations (Boughton & Arokiam, 2000), which is a good starting point for introducing new concepts of I4.0.

Thus, successful implementation of an industrial revolution must take place not only in large enterprises but 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 factories with significant economic potential (Lee & Lapira, 2013).

However, I4.0 represents a challenge for SMEs. 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 (Sommer, 2015).

There is a lack of literature regarding detailed and comprehensive analysis of the needs and requirements of SMEs for a better understanding of the necessities and problems involved in the introduction of I4.0. For this reason, we define the goal for our research to collect the requirements of SMEs based on an explorative study and a subsequent systematic analysis. The results of this analysis should provide valuable inputs for the definition of guidelines for the design of smart manufacturing systems.

3. Research Method

3.1. Background and research context: the EU H2020 Research Project SME 4.0

As previously explained there is a need for research and investigations for the implementation of I4.0 technologies and concepts in SMEs. The authors compare these challenges with the introduction of lean management in SMEs over the past 20 years. While most large companies have introduced or integrated Lean, at least in part, into their corporate strategy, SMEs have addressed this topic a little later (Matt & Rauch, 2013b). Carrying out an analysis in Scopus with the keywords "lean" and "SME", e.g., shows research on this topic was carried out from 2001 onwards. There are several papers recommending specific strategies for the introduction of lean (Medbo, Carlsson, Stenvall, & Mellby, 2013; Matt & Rauch, 2014) and specific lean methods for SMEs (Dombrowski, Crespo, & Zahn, 2010; Matt & Rauch, 2013b). As a result, Lean has now been implemented in many SMEs. The same will be needed for SMEs to introduce I4.0, even as large companies have addressed this for several years.

As with the introduction of lean, the success rate for introducing I4.0 in SMEs 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.

Thus, a research consortium of European and international partners has formed to tackle this topic and is currently working together on the introduction of I4.0 in SMEs.

To overcome the gap in research the European Commission financed the research project titled 'SME 4.0–I4.0 for SMEs' with a grant of 783.000 Euro from Horizon 2020 research and innovation program. The international research network under the leadership of the Free University of Bolzano includes academic as well as industrial partners from Europe: Free University of Bolzano (Italy), Montanuniversität Leoben (Austria), Technical University of Kosice (Slovakia), the SME company Elcom s.r.o. (Slovakia), Massachusetts Institute of Technology (USA), Worcester Polytechnic Institute (USA), Chiang Mai University (Thailand), and SACS Engineering College (India).

The main research question in the project to be addressed are as follows:

- What are I4.0 requirements and suitable concepts for SMEs?
- How can promising I4.0 concepts be adapted to the needs of SMEs?
- What are suitable I4.0 implementation strategies and organization models for smart SMEs?

The research project is organized into three fields (see Fig. 1): (i) Smart Manufacturing in SMEs, (ii) Smart Logistics in SMEs, and (iii) Organization and Management Models for smart SMEs. These fields are further decomposed into nine topics that investigate specific concepts. As announced in the title of this paper, the focus in this work will lie on the first research field 'Smart Manufacturing' to analyze SME requirements and to develop guidelines for the design of smart manufacturing systems for SMEs.

3.2. Axiomatic design-based research methodology for the analysis of SMEs needs and requirements for introducing I4.0

The research team decided that the direct beneficiaries and users, the SMEs, must be interviewed in workshops by using

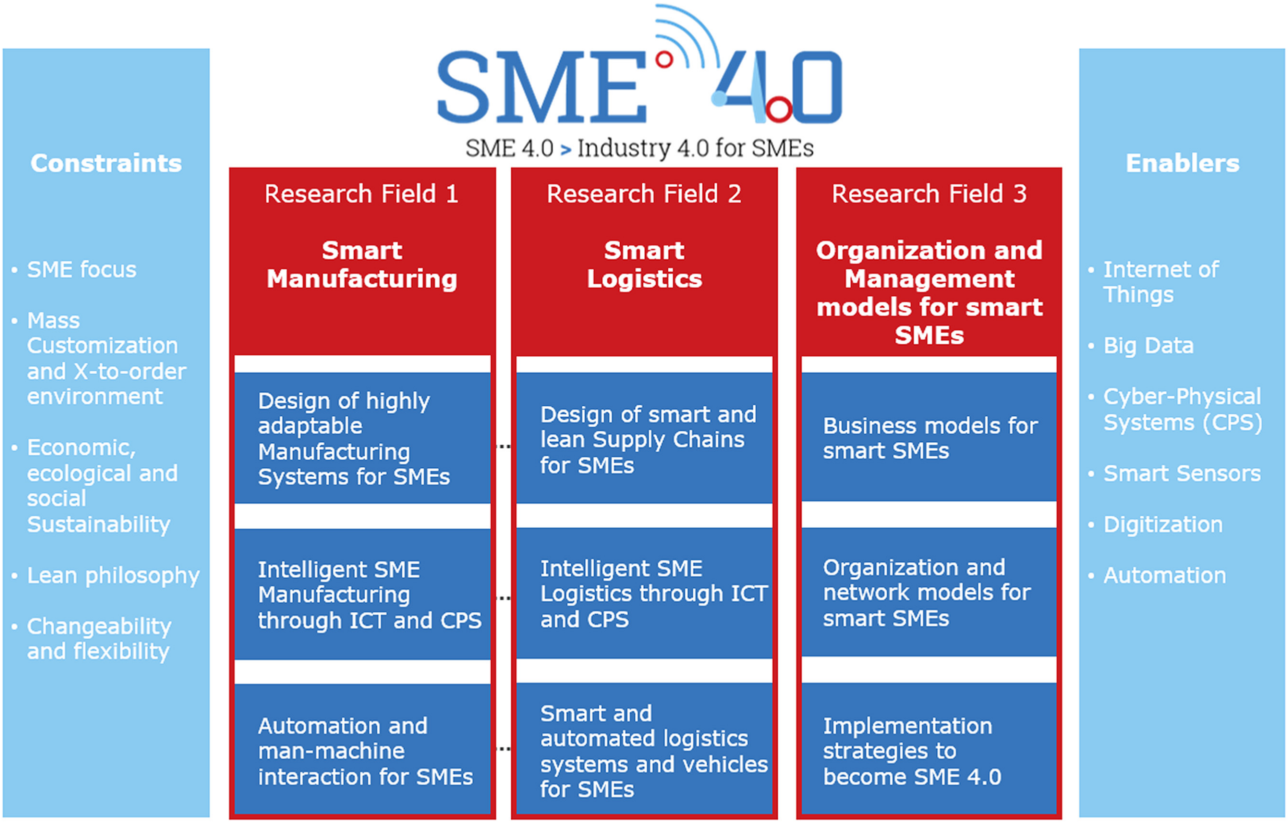

Figure 1: Research fields and topics of the project SME 4.0.

customer-facing techniques (Eppinger & Ulrich, 1995). The research team did not feel conducting a survey to be appropriate. 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, Beverungen, Matzner, & Müller 2009; Wölfel, Debitz, Krzywinski & Stelzer, 2012) based on SME workshops was chosen, which allows the research team to gain direct contact with SMEs and better understand their requirements. In the exploratory study, the researchers preferred discussion in smaller workshop groups. The 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 and to deduce ideas for SME specific methods and technologies (see Fig. 2). The implementation of SME workshops in different countries/continents should also help 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 (see Section 4 for details) starting with an initial introduction and overview of I4.0, then presenting of 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. Afterwards the participants were asked to express their needs and requirements to introduce I4.0 concepts in their company and share their experiences with the other participants. They were then asked the main barriers and limitations for the implementation of I4.0. The inputs were collected in the form of adhesive sticky notes on pin boards and categorized by topic (for details see Section 4). Before starting the evaluation of the collected inputs, several company visits were carried out by 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 applies AD (see Fig. 3). AD is a method used for the systematic design of complex systems (Suh, 2001). In AD so called customer needs (CNs) are translated into 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 starts the next step 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 in the phase of realization of the DPs. The following four domains form the base of the AD methodology (Suh, 2001):

(1) Customer domain: the customer domain defines the desires and needs of customer, usually defined as CNs.
(2) Functional domain: the functional domain focuses on the FRs of the system, which derive from CNs. System constraints (Cs) are also considered.
(3) Physical domain: the physical domain contains the DPs which satisfy the FRs.

Figure 2: Structure of SME workshops.

(4) Process domain: the process domain transforms the DPs into real PVs for realization of the system and makes them relevant for quality assurance and maintenance.

Although people in the workshop are asked regarding their needs and requirements for introducing I4.0 the experience of the researchers in the team and from literature (Girgenti, Pacifici, Ciappi, & Giorgetti, 2016) shows that, often, people do not express their thoughts in form of solution-neutral CNs or FRs, but rather in form of physical solutions in sense of DPs or PVs. Thus, the research team categorizes the inputs from the SME workshops into Cs, CNs, FRs, DPs, and PVs. In this work we consider only inputs regarding the research field 'Smart Manufacturing', while other research teams in the project will conduct a similar analysis for the other two research fields shown in Fig. 1. Cs are collected and built a final list of constraints that must be considered when realizing a system. The other inputs must be further processed and interpreted to create a final list of solution-neutral FRs as a basis for the later definition of DPs in a next step of this research project. CNs are translated into FRs by analyzing the expressed needs and deriving with which FR the need can be fulfilled. FRs can be added directly to the final list of FRs. DPs and PVs need to be further processed to create 'true FRs'. Users had 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 apply 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 RE to solve this problem is based on previous research (Sadeghi, Mathieu, Tricot, Al Bassit, & Ghemraoui, 2013; Girgenti et al., 2016). More details on the application of the RE approach is shown in Section 4. To build the final list of FRs a consolidation of the identified FRs is needed as many of the inputs deal with the same requirement and can be merged together consolidate FRs.

4. AD-based analysis and evaluation of sme needs and requirements to introduce I4.0

4.1. Results of the explorative research study based on SME workshops

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 conduction of the workshops was defined in advance. Table 1 illustrates the standardized structure of the workshops.

SME manufacturers who could speak well to the needs of SMEs in the manufacturing sector were invited to participate in the workshops through contact databases 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 545 inputs in the form of sticky note (see Table 2). Participants came from a variety of fabrication backgrounds, such as metal fabricators, wood processors, and many other industries.

According to the pre-defined work packages in the research project, the workshop used standardized categories (see Table 2) for the collection of CNs of SMEs for I4.0. In addition to the project work packages, participants were also asked the main

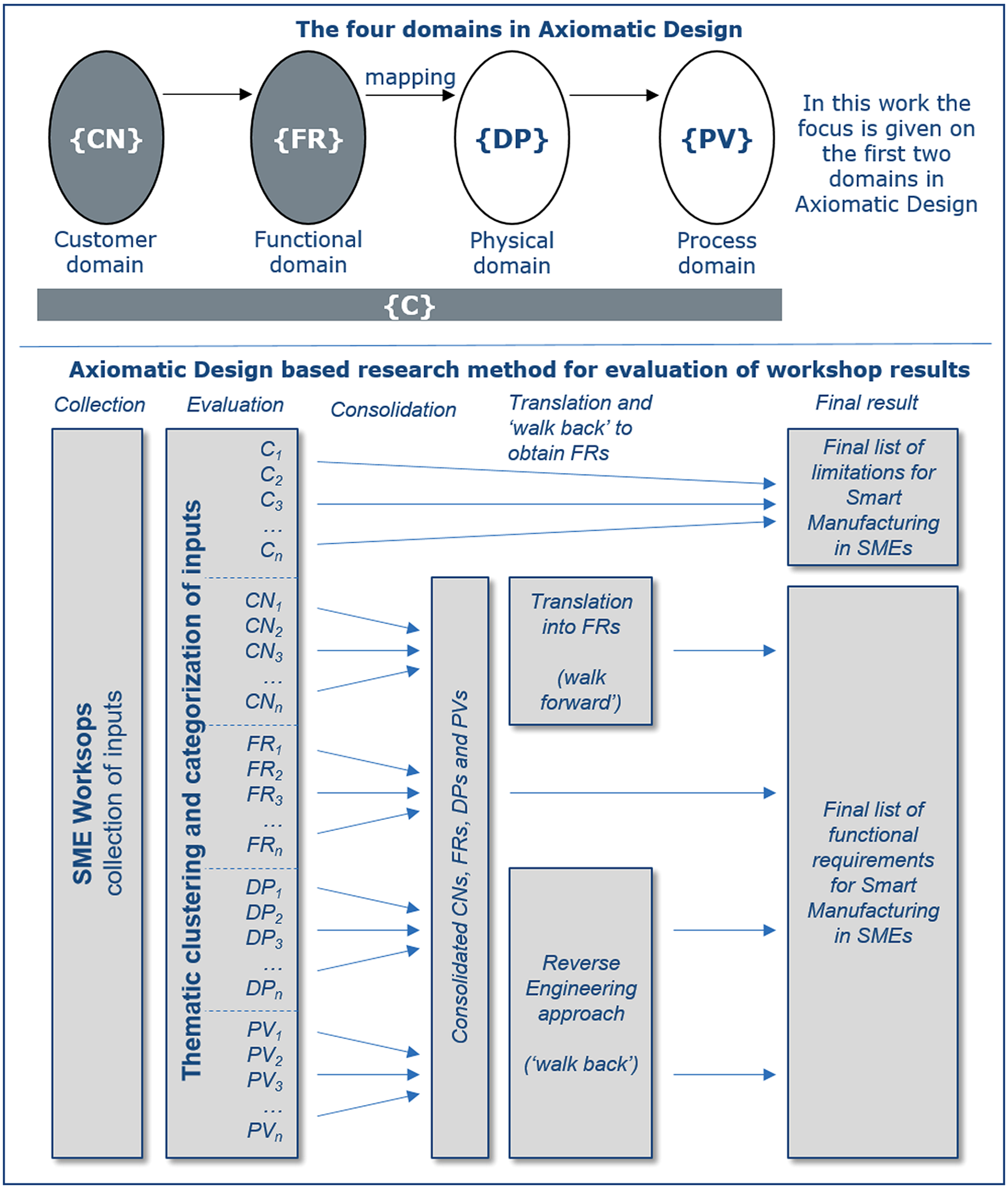

Figure 3: AD-based approach for evaluation of workshop inputs.

barriers and difficulties of introducing I4.0 concepts in manufacturing, logistics, and organization, which they had experienced, or foresaw experiencing as they planned on implementing I4.0 within their firms.

4.2. Interpretation and Categorization of Inputs from SME Workshops

The workshop results build 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, smart logistics systems and smart organization and management models 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.

For this paper, the authors will be concentrating on the inputs in Session 1 (Smart Manufacturing) from Table 2 as Session 2 (Smart Logistics) and Session 3 (Organization and Management models for smart SMEs) will be discussed in further papers by other researchers in the research project.

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 participant's feedback on sticky note ensures a correct interpretation of the statements. The moderator needed to check if the respondents understood

Table 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 in 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 ‘smart manufacturing’	90 min	Creative brainstorming with sticky notes and subsequent discussion	Sticky note method
7	Brainstorming ‘smart logistics’	90 min	Creative brainstorming with sticky notes and subsequent discussion	Sticky note method
8	Brainstorming ‘organization and management models for smart SMEs’	90 min	Creative brainstorming with sticky notes and subsequent discussion	Sticky note method
9	Discussion and closure	30 min	Summary and impression of the day	Open discussion

Table 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
5	Smart and lean supply chains	Session 2—Smart Logistics	51
6	Smart logistics through ICT and CPS	Session 2—Smart Logistics	53
7	Automation in storage and transport systems	Session 2—Smart Logistics	37
8	Main barriers and difficulties for SMEs—logistics	Session 2—Smart Logistics	29
9	New and innovative business models	Session 3—Organization and Management Models for Smart SMEs	43
10	Organization and network models	Session 3—Organization and Management Models for Smart SMEs	47
11	Implementation strategies for smart SMEs	Session 3—Organization and Management Models for Smart SMEs	31
12	Main barriers and difficulties for SMEs—organization	Session 3—Organization and Management Models for Smart SMEs	33
Sum			**547**

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 Microsoft Excel spreadsheet and inputs were categorized into thematic ‘clusters’ (see Table 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, additional notes and interpreted design space.

Table 4 shows an exemplary excerpt from the categorization of workshop inputs into Cs, CNs, FRs, DPs, and PVs. Cs can be directly adopted as such and serve the designer as important guidelines for system design. CNs can be transferred to FRs, which form the basis for subsequent AD decomposition and mapping. FRs can be used directly for AD design. DPs and PVs are not solution-neutral inputs and are converted into FRs by an RE approach explained afterwards in more detail (Thompson, 2013).

The domains of sticky note were designated based on the grammatical rules of AD. If a sticky note has an active verb it is an FR, however physical solutions were scrubbed to derive more solution neutral FR’s. Sticky notes which are describing DP’s or PV’s, according the decomposition rules of AD, are ‘walked back’ using RE as discussed in Section 3.2.

In order that the best solution can be found by the design team, simply converting the grammar of a DP or PV to that of an FR is insufficient. For the solution space set before the design to be suitably large to enable creativity and innovation, physical characteristics of the DP and PV must be scrubbed in order that the true base need of the DP and PV to be mined back out of them to form a satisfactory FR. This could be to examine the DP and find what the need/function of the DP is. This resulting need would be the final FR. The procedure which has been formed attempts to limit potential misinterpretation of the inputs by having sufficient initial input from workshop participants, ensuring full intent of the input is laid bare for the research team to correctly interpret the needs behind the inputs.

Table 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 4: Examples from the categorization of workshop inputs into AD domains.

Input (Post-It)	Notes	AD domain
People have intelligence, robots don't	Participant felt uneasy with automation due to complex nature of work flow relative to instructing a new worker	C
Create new adaptable process without programming machines/robots	Worker problem / skill gap in the production shop floor	CN
Collect data on machine and feedback for performance, maintenance and design	Data collection through life of product to next iteration for continual product improvement	FR
Automated material handling to reduce personal protective equipment requirements	Processes show efficiency losses due to personal protective equipment requirements	DP
3P (production, preparation, process) method	Applying lean techniques	PV

Table 5: 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 5 summarizes the result of the previously described categorization step. 21.08% of the inputs are constraints. Especially the inputs regarding limitations and barriers for the introduction of I4.0 were good sources for the collection of constraints. 29.15% of the inputs were categorized as CNs and other 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 an RE interpretation to be used for further AD design studies. The check column in Table 5 shows, which kind of input can be used in its original form by the research team for further studies and which kind of feedbacks need to be converted into FRs.

4.3. Reverse engineering of inputs categorized as DPs and PVs

Applying the RE approach, DPs and PVs are derived to FRs (see Table 6). Through logical regression, the research team then "walked back" each input to make it an FR. 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 us 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 6 is the complete list of derived FR_{RE}s. 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 for readers. This means that the original 77 non-satisfactory inputs have been reduced to 43.

A limitation of this approach is the fact that I4.0 is still an emerging topic and needs to be explained in workshops. In the beginning of the workshops, activities were focusing on the concepts of I4.0 and best practice examples. Of course, there is also a risk that these presentations do not introduce the principles and advantages of I4.0 in a completely solution independent way. Thus, it is a challenge to choose the right portion of examples needed to support the understanding of the I4.0 concept among the participants. Another limitation lies in the case of integral solutions that fulfill many functions. In this case, it might be difficult for a designer to identify all functions. Many of the functions might be easy to read from participant's feedback, while it is hard to identify those functions the participant indirectly was addressing in their statement.

However, the risk of making a misjudgment through the RE approach is lower than the limitation one would accept if one

Table 6: Complete list of RE approach.

No	Inputs (DPs and PVs)	Reverse engineered FR (FR_{RE}s)
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	Reduce 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	Reduce the size of production lines and work stations
8	Automated time recording of staff presence	Monitor (data driven) resource and process capability for all relevant resources
9	Computational design and engineering as well as simulation for products can save cost and test process, etc.	Digitize 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	Digitize feedback system, and infrastructure, which monitors real-time status of production
11	Implementation of SMED in SME 4.0	Change manufacturing lines and systems very quick in case of product changes
12	Automated Guided Vehicle (AGV) for the distribution of pre-prepared assembly material	Transport material inside the plant easily and without the need of a worker
13	RFID tools for parts-monitoring of in process job status; discreet marking on product that is low cost; interchangeable	Track products easily from origin through the value chain
14	Standardized process owners/roles; cross-qualification for flexible use of personnel	Encourage training and qualification of personnel such that system encourages communication, flexibility, education of I4.0, and soft skills
15	Machine reminds people of maintenance	Avoid unplanned machine stops maximizing value added time of machines
16	Digital traceability of products	Trace and locate products digitally along the supply chain
17	Automatic on-site measurements and electronic submission of order data	Enable fast measurement on-site and immediate delivery of data to production facility
18	Synchronizing work flows across networked machines to minimize down time, tool changes, and predictive maintenance	Enable synchronization and orchestration of work flows and machines
19	Design for manufacturing for new technologies and methods	Enable the use of advanced manufacturing technologies in the design phase
20	Adaptable tools	Reduce set up time for new configurations of tools
21	Standardized interfaces	Communicate on a sufficiently real time basis with internal and external customers
22	Event-based warning and early detection systems (to increase reactivity)	Identify a defect as early as possible with little to no worker intervention
23	Online maintenance, remote monitoring and trouble shooting at customer	Enable location independent control of maintenance, facilities, and products
24	Automatic/ programme 'on' and 'off' of heating and cooling elements; low battery' mode for equipment during 'down time'	Reduce energy consumption and environmental cost
25	Man–machine interaction improvements through additive manufacturing; program 'helper' for assistance in production systems	Ensure low informational barrier, complexity of entry to new manufacturing technologies
26	Flexible or automatic adjustment of energy or light to the situation (only if really needed)	Measure and optimize energy, material, and time usage on processes
27	Automating and eliminating non-value-added processes and secondary processes	Reduce non-value adding activities in production and logistics processes
28	Automated production of individual packaging (size, printing)	Customize packaging on demand
29	Condition based maintenance and decentralized maintenance	Enable predictive maintenance to ensure availability and decrease down time of machines.
30	Print product labels instead of sticking for late product individualization	Move product individualization as late as possible in the value chain
31	Production of components just in time for assembly	Produce components on demand and deliver just in time
32	Interactive terminals on work floor; output to mobile devices for instructions, quality control check lists, etc.; reduction of unneeded movement with information provision	Provide and visualize information everywhere and every time to reduce waiting times and unnecessary delays
33	Automation to optimize ergonomics	Provide workers with ergonomic workplace

Table 6: Continued

No	Inputs (DPs and PVs)	Reverse engineered FR (FR_{RE}s)
34	Automated material flow between workstations (conveyer belts); automated provision of material, automated preparation and processing of single or small batch orders for highly repetitive products	Reduce labor and cost of production and logistics processes
35	Adding sensors or automation to older machines, including network connectivity	Reuse and upgrade of existing manufacturing equipment
36	Parts inspection/detection, building digital thread for critical machine parts; 'smart' preventive maintenance and machine "health checks"; visual defect identification by machine	Enable robust and in-line identification of defects in process and material to avoid non-quality at the customer side
37	More automated material handling to reduce protective equipment requirements	Provide safe working environment
38	Automated setup; automatic adjustment of process parameters related to the age of products	Adapt and adjust processes autonomously
39	Investment in production system and human training (capital and time).	Gain access the financial, informational, digital, physical, and educational resources to ensure I4.0 is fully realized
40	Generic interfaces for robots for easy reprogramming; digital thread through integration of information technology, operational technology, communication technology, IoT data collection and exchange of info	Ensure standardization, simplification, security, and interoperability of information and communication technologies for robot programming and the use of modern machines
41	Forecasting based on consumer behavior data; automated control of material and resources for production; personnel deployment planning across departments; synchronized materials management	Forecast demand changes quickly and interact with systems for planning, control, and logistics
42	Automation of job setup tasks and CNC machining, additive manufacturing to enable adaptable tooling, using robots instead of fixtures for single/small unit manufacturing	Produce a wide variety of products and at wide range of volumes without significant re-configuration costs and time
43	3P (production, preparation, process) method	Reduce non-value adding activities and waste in production and logistics

continued to work with inputs that are not solution-neutral. Further, as the case study in this paper confirms, many customer 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. Thus, the presented RE approach represented a good possibility to transfer 'false CNs' into useful requirements for further design studies.

4.4. Final list of limitations and functional requirements regarding the introduction of industry 4.0 in SMEs

FRs (directly collected in the workshops or translated from CNs) and FR_{RE}s (obtained from DPs and PVs using the previously explained RE approach) were consolidated, and redundancies removed by combining similar FRs and FR_{RE}s 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 in order to achieve a list of the main limitations that SMEs are facing to introduce I4.0 in their companies. These final FR-list together with the final list of Cs builds the main result of this research and will be used in a further research step to derive design guidelines for the design of smart manufacturing systems for SMEs (see also Section 5.2).

Table 7 shows the consolidated list of FRs for SMEs based on the procedure discussed throughout Section 4 of this paper.

In addition, Table 8 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.

5. Discussion and Future Work

5.1. Discussion of the results

Through looking at results exposed by the needs derivation procedure shown previously in this paper and summarized in Tables 7 and 8, the authors feel that a good overall list of needs and constraints for SMEs to begin implementing I4.0 could be delivered.

In the following the authors try to summarize the main results painting a picture or vision of a future smart SME manufacturing system. 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 troubleshooters keeping the line working from day to day. Further, these processes non-destructively 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 work load and increase the efficiency of the firm. This facility is also highly digitized with the ability for work place user interfaces to be connected vertically and laterally within the organization. This allows for the destruction of silo

Table 7: Full consolidated 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	Reduce set-up time for new configurations
	4	Produce a wide variety of products and at wide range of volumes without significant re-configuration costs, and time
	5	Adapt and adjust processes autonomously
	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	Customize packaging on demand
	10	Reduce labor and cost of all production and logistics processes
	11	Implement self-maintaining processes
Connectivity	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	Reduce cost of physical prototyping
	20	Implement clear data gathering, management, analysis, and visualization to both internal and external customers
	21	Collect real-time data of machines, warehouses and facilities to keep production under control
	22	Enable data flow has 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	Lower 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
	31	Gain access to knowledge needed to implement I4.0
Inspection	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	Reduce 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
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	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

Table 7: Continued

Cluster	No	(Functional) Requirements for the design of smart manufacturing systems in SMEs
	46	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 down time of machines
	49	Predict data-based probability of machine stops or machine down time
Real time status	50	Digitize feedback system, and infrastructure, which monitors status of production, storage, shipping, risk, and crisis management
	51	Gather real-time status and visualize this data for operators and management
Remote control	52	Enable location independent control of maintenance, facilities and products
Resource management	53	Monitor (data driven) material and process capability 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	Reduce time investment for I4.0 implementation and throughout life cycle
Safety	56	Provide workers with ergonomic workplace
	57	Provide safe working environment
Sustainability	58	Reduce energy consumption and environmental cost
	59	Measure and optimize energy, material, and time usage on processes
Tracking and tracing	60	Track products easily from origin through the value chain
	61	Trace and locate products digitally along the supply chain
Transport	62	Transport material inside the plant easily and without the need of a worker
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	Digitize product development, improvement, management and security to ensure product is more profitable for SME and customer through product life

Table 8: 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, 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

syndrome (when people talk a lot inside their group or department, but they do not talk with people in other groups or departments) through meaningful connectivity both within and without the organization. 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 picture of this facility goes past the machines on the floor. The leadership (higher level management as well as shop floor management) in this organization has real time numbers on the outputs of different machines, problems on the shop floor, potential upcoming costs, through predictive main-

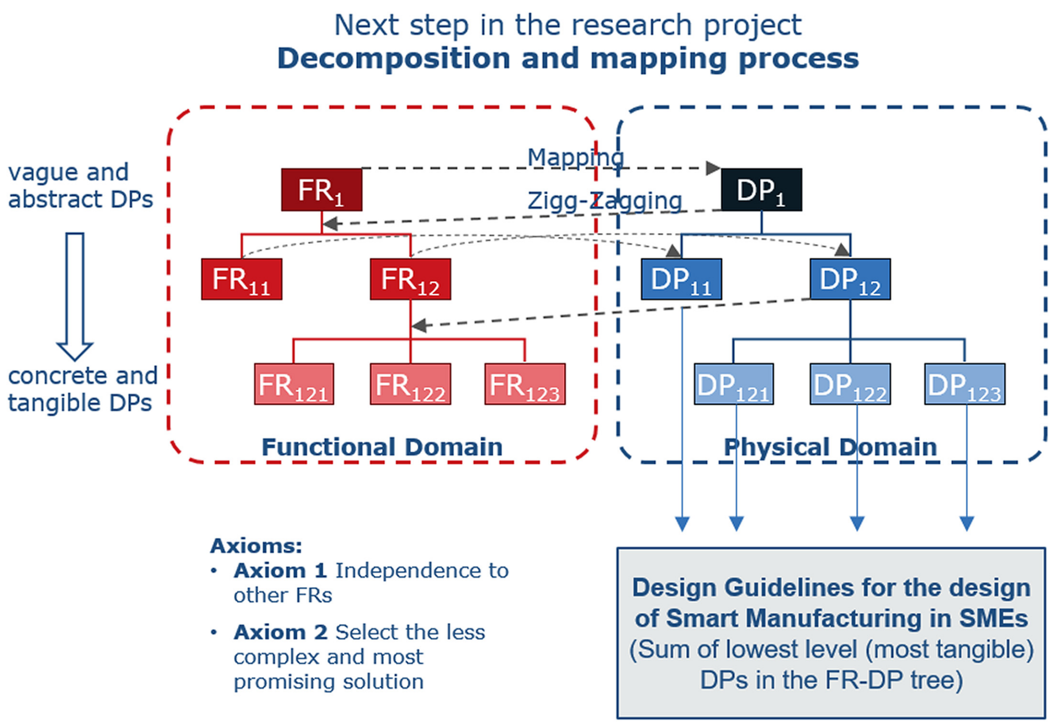

Figure 4: Axiomatic design approach to deduce DPs for smart manufacturing in SMEs.

tenance, or tracking the manufacturing environment and resources needed to ensure that all the needs of the floor workers are met, enabling increases in profitability. Further the leaders of these firms have access to experts, thought leaders as well as cognitive assistance systems that can give guidance to 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 (Ho, Cicmil, & Fung, 1995).

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 7 and 8 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.

5.2. Future work to deduce design guidelines for smart manufacturing in SMEs

The consolidated final list of FRs builds the basis for a next step in the overall research project to derive design guidelines for the design of smart manufacturing systems. According to AD this can be achieved through a top-down decomposition and mapping approach of FR–DP pairs applied to decompose first level FR–DP pairs from an initially abstract level towards more tangible design guidelines (see also Fig. 4). To conduct such a decomposition the two basic Axioms of AD will be considered. 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, assures, that in case of alternative solutions (alternative DPs), the best DP minimizes the 'information content of the design. In the following both Axioms are described more in detail (Suh, 1990, 2001):

- Axiom 1—Independence Axiom: the design of a system is considered ideal if all FRs are independent of the others to avoid any kind of interaction among them. Each defined DP is only related to one FR and has no influence on other FRs.
- Axiom 2—Information Axiom: The Information Axiom helps the designer to choose among multiple possible solutions. The DP should be part of the physical domain with the smallest information content, to ensure a higher probability to satisfy a requirement. Information content generally means complexity (El-Haik & Yang, 1999). The information content I is defined in terms of the probability P of satisfying a given FR and is the negative of the logarithm of success ($I = -\log 2P$) (Suh, 1990). According to complexity theory it is a measure of the probability of obtaining an FR in a certain "design range" (the tolerance expected by the user) with a DP in accordance with a certain "system range" (all the values effectively achieved by the system) and is described by a "common range". The ideal design is one in which the common range and the design range are the same, in other words the design range is "included" in the system range (Le Masson, Weil, & Hatchuel, 2017).

Once finalized the decomposition and mapping process the lowest level DPs of every branch in the FR–DP tree will build together a list of guidelines for the design of smart manufacturing systems for SMEs. Such a list of guidelines will support researchers in the SME 4.0 project to develop specific I4.0 solutions for SMEs and should guide practitioners in their work to design manufacturing systems in the SME environment.

6. Conclusion and Outlook

In this paper, a comprehensive list of specific requirements and limitations for SMEs regarding the introduction and implementation of I4.0 was proposed using and explorative field study as well as AD as research methodology. These lists are based on multinational workshops which brought together leaders from manufacturing organizations from a variety of manufacturing spaces as well as preliminary studies in Spena et al. (2016) to analyze the SMEs manufacturing field sector and their technological level and manufacturing practice. The inputs from these workshops were broken down by the subject matter of the session being discussed, then broken down further by 'Clusters'. These clusters allowed for an efficient manner to categorize and further refine the requirements and constraints set before the SMEs attending the workshop.

Upon initial processing of the content from the international workshops, the authors found that almost 35% of the input given was not solution neutral. This is important because non solution neutral inputs limit the design space and the creativity of the designer. 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, what the authors believe, 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.

Possible limitations of this research include that the derived requirements and constraints are subject to the interpretation of the authors, as well as the initial company leaders which 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.

Further research will start with a decomposition of the implementation of I4.0 in SMEs, as discussed in Section 5, with further input received from various organizational leaders of manufacturing SMEs to ensure the needs and techniques being explored are applicable to SMEs and to ensure they can use the tools developed for them.

After the problem has been broken down, a multinational group of researchers from various fields and countries has been assembled to answer each component of the needs of SMEs to implement I4.0. It is believed that this will deliver a suite of tools for SMEs to take full advantage of I4.0 such that they do not lose their competitive advantage. The capabilities of I4.0 is explored and exploited to ensure the competitive survival of SMEs as I4.0 comes to the foreground of industry.

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Conflict of interest statement

Declarations of interest: none.

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