RESEARCH ARTICLE

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

Erwin Rauch1,* and Andrew R. Vickery2

1Faculty of Science and Technology, Free University of Bozen-Bolzano, Universitätsplatz 5, 39100 Bolzano, Italy
and 2Faculty of Mechanical Engineering, Worcester Polytechnic Institute, 100 Institute Road, Worcester, 01609 MA, USA

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*Corresponding author. E-mail: erwin.rauch@unibz.it
http://orcid.org/0000-0002-2033-4265

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 (4.0) (Kagermann, Wahlster, & Helbig, 2013; Sendler, 2013) or smart manufacturing (Kang et al., 2016). 4.0 is the fourth industry emerging from an industrial revolution, which is led by intelligent manufacturing. The concept of 4.0 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 4.0 vary greatly, and a fundamental, generally accepted definition of 4.0 does not exist (Bauer, Schlund, Marrenbach, & Ganschar, 2014). The focus of 4.0 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, 2013; 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
respond to expectations and requirements of its customer is not easy and requires agile and flexible manufacturing systems with rapid design (Zawadzki & Zywicki, 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 (Spaath 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, Törrgren, & 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, & Hämerl, 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 (Spaath 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, & Fracaroli, 2016). SMEs are the backbone of the EU and many other economies (Federal Ministry of Education & Research, 2013). European SMEs provide 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 of 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.

Thus, research consortia 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
Systematic analysis of needs and requirements for the design of smart manufacturing systems in SMEs

Customer-facing techniques (Eppinger & Ulrich, 1995). The research team did not feel conducting a survey to be appropriate. Due to the novelty of 4.0, 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 4.0 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 4.0, then presenting of some practical applications and best practice examples in SMEs. This should help raise awareness that 4.0 will be an important topic for SMEs in the future and prove that even smaller companies can implement 4.0. Afterwards the participants were asked to express their needs and requirements to introduce 4.0 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 4.0. 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.
(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, forecast 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, & Ghernaqi, 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
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 2—Smart Logistics | 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 were 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 DPs 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 suitable 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 | x    |
| PV           | Process variables | 1            | 0.45  | x    |

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 FRs. 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$_{RES}$)                                      |
|----|--------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| 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                                           | 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 4.0, 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                                |
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 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 represents 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 FRres (obtained from DPs and PVs using the previously explained RE approach) were consolidated, and redundancies removed by combining similar FRs and FRres 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 delivered.

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 4.0 technologies                                                                                                                        |
|                          | 29 | Measure the impact of 4.0 on the company’s sustainable success                                                                                                                              |
|                          | 30 | Provide an overview of existing 4.0 instruments and their suitability for SMEs or industry sectors                                                                                                 |
| Inspection               | 31 | Gain access to knowledge needed to implement 4.0                                                                                                                                              |
|                          | 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 | 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                                                                                                                                       |
| Production planning and  | 44 | Manage internal knowledge and staff development for Industry 4.0                                                                                                                             |
| control                  |    | 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 Preventive and predictive     |    | Forecast demand changes quickly and interact with systems for planning, control, and logistics                                               |
| maintenance                      |    | Ensure maintenance costs are minimized while maximizing value added time of machines                                                        |
| 47 Real time status              |    | Proactively maintain to ensure availability and decrease down time of machines                                                               |
| 48                              |    | Predict data-based probability of machine stops or machine down time                                                                        |
| 49                              |    | Digitize feedback system, and infrastructure, which monitors status of production, storage, shipping, risk, and crisis management             |
| 50                              |    | Gather real-time status and visualize this data for operators and management                                                                   |
| 51 Remote control                |    | Enable location independent control of maintenance, facilities and products                                                                    |
| 52 Resource management           |    | Monitor (data driven) material and process capability for all relevant resources                                                              |
| 53                              |    | Ensure machines are capable for prospective jobs, and are able to be repurposed for a variety of other jobs                                      |
| 54                              |    | Reduce time investment for I4.0 implementation and throughout life cycle                                                                        |
| 55 Safety                        |    | Provide workers with ergonomic workplace                                                                                                |
| 56                              |    | Provide safe working environment                                                                                                           |
| 57 Sustainability                |    | Reduce energy consumption and environmental cost                                                                                           |
| 58                              |    | Measure and optimize energy, material, and time usage on processes                                                                         |
| 59 Tracking and tracing          |    | Track products easily from origin through the value chain                                                                                     |
| 60                              |    | Trace and locate products digitally along the supply chain                                                                                     |
| 61 Transport                     |    | Transport material inside the plant easily and without the need of a worker                                                                   |
| 62 Upgrade                       |    | Reuse and upgrade of existing manufacturing equipment                                                                                        |
| 63 Virtual reality               |    | Allow user friendly ‘smart’ representation of systems for production, maintenance, design, and service                                         |
| 64                              |    | 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  | People    | Lack of employee acceptance of new operational processes and technologies                                                                     |
| 3  | Implementation | Company needs a well-entrenched top down culture which allows continual improvement and mitigation of silo syndrome                           |
| 4  | Resource management | 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  | Security  | Lack of visibility of I4.0 among professionals who would otherwise champion the implementation of I4.0                                      |
| 6  | Strategy  | 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  | Resource management | SMEs lack access to the financial, informational, digital, physical, and educational resources to ensure I4.0 is fully realized.            |
| 9  | Strategy  | Lack of easy access to thought leaders and talent (relative to multinational companies)                                                      |
| 10 | Resource management | Buildings are not designed for automating internal transports or processes or for new manufacturing technologies                               |
| 11 | Security  | High financial barrier to new manufacturing technologies                                                                                     |
| 12 | Strategy  | Lack of knowledge transfer from experts to SMEs for the implementation of I4.0                                                               |
| 13 | Strategy  | 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-
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 (\( I = -\log_2 P \)) (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 4.0 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 4.0 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 4.0.

Further research will start with a decomposition of the implementation of 4.0 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 4.0. It is believed that this will deliver a suite of tools for SMEs to take full advantage of 4.0 such that they do not lose their competitive advantage. The capabilities of 14.0 is explored and exploited to ensure the competitive survival of SMEs as 14.0 comes to the foreground of industry.

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Conflict of interest statement

Declarations of interest: none.

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