Adopting additive manufacturing in SMEs: Exploring the challenges and solutions

Miia Martinsuo and Toni Luomaranta

Laboratory of Industrial and Information Management,

Tampere University of Technology, Tampere, Finland

Abstract

Purpose: Adopting additive manufacturing (AM) can be challenging, especially in small and medium-sized enterprises (SMEs) and as part of the supply chains of larger firms. The purpose of this study is to explore SMEs' perspectives on the adoption of additive manufacturing in their specific supply chain positions. The paper develops new knowledge on the challenges SMEs face across the supply chain and the actions they need to promote the adoption of AM.

Design/methodology/approach: An exploratory interview-based research design is used. Seventeen interviews were conducted and analyzed in four types of SMEs in their specific positions in AM supply chains. The challenges of adopting AM were mapped, and actions to promote AM adoption were identified.

Findings: SMEs in different supply chain positions experience different challenges when adopting AM. Strategic and operative actions are suggested as key solutions to overcome the challenges. The benefits of AM on a large scale will be achieved only if the broader supply chain adopts AM technology and experiences its benefits.

Research limitations/implications: The research is limited by its single-country context, its focus on SMEs, and the selection of early-phase AM adopter firms. The findings imply a need to understand AM adoption as a shared concern and systemic innovation in the supply chain, instead of just a firm-specific implementation task.

Practical implications: The findings offer a framework for categorizing AM adoption challenges and propose ways to overcome the challenges of adoption.

Originality/value: The study reveals that AM adoption is not only a technology issue, but an issue of strategic, organizational and operational challenges across the supply chain. It shows that when adopting AM, SMEs face particular challenges and require specific solutions according to their supply chain position.

Keywords: Additive manufacturing; Advanced manufacturing technology; Small and medium-sized enterprises (SMEs)

1. Introduction

Industrial competitiveness is no longer a single firm's concern, and requires multiple firms in the supply chain to interact—including small and medium-sized enterprises (SMEs). Additive manufacturing (AM) represents a topical innovation in manufacturing technologies, and it may significantly change value chains and business logics in manufacturing industries (Steenhuis and Pretorius, 2017). In contrast to more traditional digital manufacturing technologies that remove materials from the item being manufactured, AM technologies process materials by joining and adding to them, usually layer-by-layer (ASTM, 2012), to make an object from a digital model. AM technologies can be considered advanced manufacturing technologies (Arvanitis and Hollenstein, 2001), and they are also a means of rapid prototyping and manufacturing (Hopkinson et al., 2006; Mellor et al., 2014), particularly if intended for components or products for actual end use. The implementation of AM technologies is not currently widespread, and it may be slow. This paper explores SMEs' AM adoption, challenges, and requirements.

AM has attracted increasing attention in both technology-based firms and management research, largely because AM technology usage can have far-reaching implications for businesses (Oettmeier and Hofmann, 2016; Steenhuis and Pretorius, 2017). Companies are drawn to experiment with AM for a variety of reasons, including efficiency, flexibility, and innovation potential (Holmström et al., 2010; Weller et al., 2015). Despite growing interest in AM, its potential business applications are just now emerging (Oettmeier and Hofmann, 2017), and its broader adoption requires solving not only technology issues, but various issues in new kinds of supply chains. AM technologies and applications are evolving rapidly and continuously, thereby necessitating research to discover means for overcoming the barriers to technology transfer (Oettmeier and Hofmann, 2017; Flores Ituarte et al., 2016b) and to identify how and where to introduce AM (Niaki and Nonino, 2017; Ruffo et al., 2007).

This study focuses on the need to understand the role of SMEs in adopting AM to achieve supply chain-level changes in AM-related new businesses. SMEs may appear in many different positions in manufacturing supply chains, and they are presumably facing challenges in their attempts to adopt AM.

SMEs differ from large firms in many ways. Generally SMEs are thought to have a fewer available resources (Tovstiga and Birchall, 2008), less specific divisions of labor (Vossen, 1998), and less bureaucracy (Rothwell, 1989) than large firms, and these characteristics have implications for their development and innovation activities. More innovation-specific differences have also been pointed out, including SMEs' risk aversion in innovation activities (Lasagni, 2012), lack of systematic development procedures (Tovstiga and Birchall, 2008), and greater capacity to absorb new knowledge and technologies (Vossen, 1998). Understanding of the particular features of SMEs is pertinent to understanding how their AM adoption can be supported.

Most recent studies have shown that AM is used in niche applications alongside traditional large-scale manufacturing technologies (Ortt, 2016; Rylands et al., 2016). SMEs' role in the future of AM may be even larger than that of bigger global players (Rogers et al., 2016) because SMEs adopting AM may be capable of transforming themselves into direct digital supercenters (Sasson and Johnson, 2016). However, the adoption of AM in SMEs is currently poorly understood, as the majority of the literature focuses on large firms, or a mix of large firms and SMEs, and overlooks the supply chain positions of the firms. With limited resources and experience with technological innovation, SMEs require more effort to integrate AM into their existing systems (Oettmeier and Hofmann, 2016). There is a need to understand SMEs' perspectives on AM technology adoption in order to strengthen their position in modern manufacturing value chains.

This paper explores SMEs' perspectives on the adoption of AM in their supply chains. The goal is to identify the different types of challenges and requirements for adopting AM across different supply chain positions, and develop new knowledge on the practices that are needed to promote AM adoption. The focus is on the following research questions:

1. How do SMEs in different supply chain positions differ in their challenges in adopting AM?
2. How can SMEs overcome the challenges?

This paper adds to AM technology adoption literature that calls for more research on different industrial setups (e.g., Mellor et al., 2014; Oettmeier and Hofmann, 2017) by revealing the realities of SMEs. The research contributes to the discussion on AM adoption by identifying the key challenges experienced by different types of SMEs, and proposing means to overcome them. The focus is on different SMEs in company networks where AM is experienced as relevant (i.e., adoption of AM is topical), but not yet part of the mainstream, whereas the major application industries already deeply engaged in AM are excluded. We have purposefully excluded large firms as previous research has already covered their experiences.

We first review previous research on the forces driving AM adoption, experiences of adopting AM, and the barriers that have been identified so far. We then introduce the exploratory research design, covering interviews with managers in 17 SMEs considering adopting AM in their businesses. We map the challenges that the interviewees have experienced in adopting AM, and propose solutions. Finally, we draw conclusions about AM adoption in SMEs, discuss actions to promote broader AM adoption in the supply chains of SMEs, and suggest pathways for further research.

2. Literature review

2.1 Additive manufacturing: Drivers and benefits

Additive manufacturing may drive radical changes in how manufacturing industries and societies operate (Ortt, 2016). AM is not a single technology, but a set of several—all at different stages of development—enabling the use of various materials and different levels of output quality (Ford et al., 2016). Different AM technologies exist; they all are relevant manufacturing innovations, and all require that firms exert effort for their adoption to be useful for businesses. Although AM technology has existed for almost three decades, academic research on it from the perspective of business and supply chains has only begun recently and is still in an emerging, exploratory phase (Ortt, 2016).

Previous research has emphasized various benefits of using AM technologies, including design freedom, efficiency and speed, customization of products, enabling of small batches, flexibility, adaptability, simplification of supply chains, and reduction of waste (Berman, 2012; Holmström et al., 2010; Flores Ituarte et al., 2016b; Niaki and Nonino, 2017; Weller et al., 2015). Sometimes, AM is compared with traditional advanced manufacturing technologies and the benefits of achieving flexibility and complexity “for free” are emphasized (Weller et al., 2015). The main benefits for SMEs are suggested to be the high level of customization, flexibility, possibilities in logistics management, and potential for production cost savings (Mellor et al., 2014).

By adopting AM technologies, companies may reap a variety of strategic rewards. For example, small- and medium-batch production could be transferred back from low-wage to high-wage countries, since AM may reduce the need for manual labor (Berman, 2012). The economic benefits have been emphasized, potentially because of the inventory turnover decrease stemming from on-demand manufacturing, flexible use of manufacturing equipment, and energy savings (Niaki and Nonino, 2017). AM can provide a competitive advantage, especially if the market is uncertain and demands a great variety of products and adaptability to varying customer needs (Weller et al., 2015), along with a shorter time to market (Niaki and Nonino, 2017). Some AM applications have the potential to enhance productivity when manufacturing on a large scale (Flores Ituarte et al., 2016b). AM may additionally offer novel innovation possibilities both in products and processes (Niaki and Nonino, 2017), thereby helping to reach new customers (Mellor et al., 2014) and creating products that were not possible with other manufacturing technologies (Mellor et al., 2014; Niaki and Nonino, 2017).

For customers, the flexibility and adaptability AM technologies enable can offer useful outcomes. Customers ordering AM components may benefit from the higher service levels, as production may be decentralized and located closer to customers (Khajavi et al., 2014). AM can potentially integrate customers better into the value creation process and mitigate the problems in economies of scale and product variety (Oettmeier and Hofmann, 2016; Rylands et al., 2016). Customer needs can be met better by creating products that fulfill their requirements, as AM offers almost unlimited freedom of design (Diegel et al., 2010), making real mass-customization of products possible (Deradjat and Minshall, 2017; Niaki and Nonino, 2017).

2.2 Adopting AM in different firms

At the industry level, the pace of AM technology diffusion depends on how different firms bring the technologies into use and develop commercialized solutions based on them. Some previous research covers the overall process through which AM is adopted in firms (Rylands et al., 2016; Oettmeier and Hofmann, 2017), in line with earlier research on technology adoption and diffusion (Davis et al., 1989; Rogers, 1962, 2003). An initial approach would require the piloting of low-volume production using AM as a new manufacturing opportunity (Flores Ituarte et al., 2016b).

To convert the use of AM technologies into profitable business, companies need to manage complex innovation and socio-technical processes. Paying attention to technical and economic issues only is insufficient when adopting AM (Farooq and O'Brien, 2012); it is likely that strategic production plan changes are needed (Oettmeier and Hofmann, 2016). Manufacturing firms should consider the potential effects of AM on their supply chains, processes, and management when deciding whether to adopt AM technologies in their industrial parts production (Oettmeier and Hofmann, 2016).

Companies have two different options when engaging in the field of AM: they can source ready-made AM parts (contract manufacturing or service), or invest in machinery and source required materials (Oettmeier and Hofmann, 2016). In both cases, there are a variety of factors that may influence a firm's intent to adopt AM technology, including: technology-related, firm-related, market structure-related, and supply chain-related factors (Oettmeier and Hofmann (2017). Mellor et al. (2014) formed a conceptual framework of the socio-technical factors relevant in AM implementation, including strategic, technological, organizational, operational, supply chain-related, and external factors. They found that both external forces and internal strategies are driving AM adoption in the context of a rapid prototyping company converting to rapid manufacturing, and proposed that the framework be used in future studies in other contexts and scenarios.

The size of an organization has been identified as critical to understanding the process of adopting new manufacturing technologies. A number of scholars have suggested that small businesses cannot be considered as scaled-down larger businesses, and the theories proven using large enterprises may not apply to them (Federici, 2009; Thong et al., 1996). Studies covering SMEs' adoption of traditional advanced manufacturing technologies show that SMEs have a short planning horizon: they tend to use reactive mechanisms to keep customers satisfied by fulfilling existing orders, thereby overlooking long-term and strategic planning (Fulton and Hon, 2010). SMEs are often unaware of the benefits of new manufacturing technologies (Fulton and Hon, 2010), and they may lack management commitment as well as financial and human resources for technology investments (Thomas et al., 2008). Due to their limited bargaining power, it is possible that SMEs do not easily get support from manufacturing technology suppliers, and they may lack long-term relationships with major customers (Mishra, 2016). Furthermore, even within the sector of manufacturing SMEs, company profiles are very heterogeneous and they can differ in their technology-intensity, innovativeness, and ambitions for growth (Thomas et al., 2008). Since AM utilizes digital models, it is not just manufacturing firms, but also industrial design SMEs that need to adopt AM. Previous studies have recognized inadequate inter-organizational information systems and the strong dependency of SMEs on the supply chain partners as factors possibly hindering the adoption of digital supply chain innovations (Archer et al., 2008). Also the lack of standards can be a challenge in adopting digital model-driven engineering (Peltola et al., 2011). To conclude, an SME's approach to AM adoption is likely to be different from that of a large multinational company (Mellor et al., 2014). Previous research has to some extent covered SMEs' views on AM adoption, as shown in Table 1.

Table 1. Overview of empirical studies on AM adoption, partly covering the views of SMEs.

Source	Method and context	Findings	Gap justifying this study
Mellor et al., 2014	Single case study. European SME industrial goods manufacturer, both plastic and metal parts in-house. Parts for different industrial sectors. AM application: end-use components.	Conceptual framework of important factors in AM implementation created and tested.	Single case; framework should be tested further in different industry scenarios.
Flores Ituarte et al., 2016b	Single case study. Global consumer electronics manufacturer, focus on plastic parts, in-house AM prototyping, outsourced AM manufacturing. AM application: prototypes and end-use components.	AM technology has not yet penetrated the current supply chain structure, considerable barriers exist in transferring AM to engineering applications.	Single case study in a large firm; emphasizes the importance of supply chains regarding AM adoption, encourages further research from technical, organizational, and managerial standpoints in different industry scenarios.
Oettmeier and Hofmann, 2016	Two-case study. European large and medium hearing aid system manufacturers. Plastic AM in-house. AM application: end-use products.	AM affects internal processes, management activities, and supply chain processes.	Two cases, of which one is medium-sized; further research needed on engineer-to-order environment, procurement of ready-made AM parts, interaction between purchasing firm and contract manufacturer, and different industry scenarios.
Rylands et al., 2016	Two-case study. European SME manufacturers: industrial and commercial. AM application: Production process (tooling).	AM adoption process and business impact model. Implementation of AM causes a shift in value proposition, AM complements traditional manufacturing.	Two cases; model requires further evidence and additional research on how AM adapts to suit new industries.
Deradjat and Minshall, 2017	Multiple case study of 6 firms. Large and SME dental and medical implant manufacturers. AM application: metal end-use implants.	Implementation of AM faces different considerations depending on the stage of implementation and maturity of technologies, as well as company size.	Future research to study other applications for AM in mass customization.
Niaki and Nonino, 2017	Exploratory study with 16 firms. Large and SME manufacturing companies in Italy and US. Various industries. AM application: various technologies and various applications not specified.	Implementation of AM has boosted productivity of metal AM products.	Further research should also study companies that have not adopted AM.

Source	Method and context	Findings	Gap justifying this study
Oettmeier and Hofmann, 2017	Questionnaire survey (n=195). Large, medium, and small companies; adopters and non-adopters; various industries. AM application: wide range of materials and applications.	Supply chain-related factors have a strong influence on AM adoption.	Future research should provide insight into the drivers of AM adoption; different supply chain positions considering AM should be investigated.

A majority of the studies include both large firms and SMEs (Oettmeier and Hofmann, 2016, 2017; Flores Ituarte et al., 2016b; Niaki and Nonino, 2017; Deradjat and Minshall, 2017) and emphasize the possibilities and adoption requirements of AM technologies. Only a few studies have focused on SMEs specifically and tend to be small-scale case studies (Mellor et al., 2014; Rylands et al., 2016), offering a very limited perspective on the specific nature of adopting AM. Previous research has studied AM adoption only from the viewpoint of a single supply chain position and use case companies from the aerospace, automotive, dental, medical, marine, defense, and pharmaceutical industries (e.g., Oettmeier and Hofmann, 2016, 2017; Mellor et al., 2014), where leveraging of AM provides strategic benefits, or only concern plastics (Flores Ituarte et al., 2016b). The study of Rylands et al. (2016) is an exception where case companies are adopting AM to enhance their production system in a very different industry set-up. Further research is needed to cover multiple supply chain positions in AM networks and outside of the advanced AM-adopter industries.

2.3 Challenges in adopting AM and overcoming them

AM technology is not a response or solution to every manufacturing concern, and it may suffer from trade-offs compared to traditional manufacturing, e.g., in terms of available materials, costs, processing speed, energy consumption, and industry-level standards (Mellor et al., 2014). The main barriers for SMEs are suggested to be the cost of AM machines and lack of highly-skilled personnel (Mellor et al., 2014; Niaki and Nonino, 2017). These can generate barriers for firms adopting AM if they do not simultaneously find clear strategic advantages. Various barriers have been mapped in some conceptual studies (e.g., Berman, 2012; Ruffo et al., 2007). Challenges in and barriers to AM adoption discovered in previous empirical studies are quite varied, and Table 2 summarizes them, using Mellor et al.'s (2014) thematic categorization into technology-related, strategic, supply chain-related, operational, organizational, and external AM implementation factors.

Table 2. Previously identified challenges to AM adoption.

Type of challenge:	**Technology-related**		**Strategic**		**Supply chain-related**		**Operational**		**Organi-zational**		**External**
Empirical studies	Technology	Material	Strategic	Investment/ Operational costs	Supply chain	Customer	Design	Operation /Process	Skills /Learning	Management	Market
Gausemeier et al., 2013	x	x					x				
Mellor et al., 2014	x			x	x	x	x		x		x
Flores Ituarte et al., 2016b			x		x					x	
Oettmeier and Hofmann, 2016			x		x				x		
Deradjat and Minshall, 2017	x	x	x	x	x			x	x		
Niaki and Nonino, 2017	x	x		x							
Murmura and Bravi, 2017	x			x					x		

The review of previous empirical research shows that the majority of the research concerning challenges to AM adoption have been carried out either solely in large firms (Flores Ituarte et al., 2016b), or in a mixed setting of different–sized firms without explicitly uncovering the viewpoint of SMEs (Gausemeier and Echterhoff, 2013; Niaki and Nonino, 2017; Deradjat and Minshall, 2017). Evidence on SMEs shows that in contrast to large firms that can utilize their expertise internally and have the capital to invest in several AM machines in-house to solve operational challenges, SMEs suffer from a lack of capital and expertise, meaning they have to rely on collaboration with external partners (Deradjat and Minshall, 2017). This tight dependence on external supply network partners creates an entirely new dimension for AM adoption among SMEs, and calls for new knowledge and research.

Overcoming the challenges of AM adoption may take many forms, including investments into technological advances (Weller et al., 2015), innovations in design (Mellor et al., 2014), strategic value chain changes, manufacturing relocation (Flores Ituarte et al., 2016b), and developing specialized know-how (Oettmeier and Hofmann, 2016). Where certain studies offer partial solutions to overcoming specific barriers, there is a need to holistically develop further knowledge on AM adoption challenges and their solutions among different types of SMEs.

3. Research methods

3.1 Research design and selection of companies

This research focuses on the adoption of metallic AM within SMEs in prospective new AM application industries, namely the machine manufacturing and process industries. As a contrast to previous studies that mostly examined technology-centric larger firms, combined large firms and SMEs, or only took a single-company perspective, this research is exploratory, and attempts to address a larger variety of SMEs in different kinds of supply chain positions in machine manufacturing and process industries where the use of subcontractors is common.

SMEs were sought from a delimited geographical region, and they were expected to be somewhat related to the manufacturing industry in the region. We focused on SMEs in different positions in AM supply chains, including design, subcontracting, original equipment manufacturing, and service provision, with the expectation of gathering about 20 interviewees to enable comparison across supply chain positions. Altogether, 17 companies participated. Table 3 summarizes the target companies and provides some context. We use letter codes to denote the companies, to maintain their anonymity and confidentiality. With this sampling approach, a good variety of different types and sizes of SMEs was achieved. All of the firms stated their willingness to be active innovators in order to maintain their competitiveness in their supply chain. The firms can be into divided into four clusters: medium-sized original equipment manufacturers (OEMs), small or medium subcontractors, small subcontractors providing AM services and an AM machine supplier, and firms providing engineering and industrial design.

Table 3. Background information on companies and interviewees included in the study.

Type of company	Company code	Nr. of emp-loyees (appr.)	Inter-viewees (nr)	Respondents' positions	Experience in AM	Inter-view dura-tion (mins)
Medium-sized OEMs (Cluster 1)	Company A	200	1	Production development manager	Rapid prototyping	65
	Company H	50	1	VP of Technology	Rapid prototyping	83
	Company I	200	2	CEO; CFO	Rapid prototyping & manufacturing	63
	Company K	150	1	R&D manager	Rapid prototyping & information	58
	Company M	60	2	VP of R&D; R&D engineer	Rapid prototyping & information	69
Small or medium subcontractor (Cluster 2)	Company B	50	1	Managing director	No experience	71
	Company E	15	2	CEO; Chief design engineer	Post-process	72
	Company F	160	1	Production R&D engineer	Rapid prototyping & tooling	77
	Company J	20	1	Managing director	No experience	51
Small subcontractor / AM service provider using AM	Company N	5	1	CEO	AM machine	75
	Company Q	5	1	Sales & marketing manager	AM machine	43
AM machine supplier (Cluster 3)	Company O	20	1	Business development director	AM machine supplier	98
Engineering and industrial design (Cluster 4)	Company C	1	1	Entrepreneur	Rapid prototyping & manufacturing	40
	Company D	5	1	CFO	Rapid prototyping & information	69
	Company G	280	2	VP; Chief design engineer	Testing rapid manufacturing	81
	Company L	70	1	VP	Rapid prototyping	80
	Company P	1	1	Entrepreneur	Rapid prototyping, manufacturing & tooling	70

3.2 Data collection

Interviews with SME managers are used as the primary data source, along with two researcher workshops and four workshops with SME managers as the secondary data to validate the findings from the interviews. A total of 21 people were interviewed using a thematic outline to identify the challenges associated with AM adoption and their possible solutions. Table 3 shows that the interviewees are top managers in SMEs, as they were considered key decision makers regarding the adoption of new technology.

The interview outline was developed jointly in the research team based on key issues identified in the literature, and ideas were proposed during two company workshops. The interview outline was initially tested with the first interviewees and subsequently modified for further use. The interviews covered the following themes: the background and position of the respondent; the company's experience and plans for adopting AM; identified challenges in implementing AM; possible industry-specific needs for AM; opportunities to add value for the business and its customers by using AM; and production and supply chain changes required by AM. For Cluster 3 (firms operating AM machines and an AM machine provider), an additional question regarding their customers' challenges in adopting AM was added. All the interviews were recorded and transcribed, and brief notes were taken.

Secondary data were collected in the workshops with industry participants. Two researcher workshops were used to validate the interview frame, discuss the findings, and identify potential analytical frames. Two of the company workshops were used to establish an initial understanding of the AM field, and two were used to report and test some of the interview findings. Workshops were documented through handwritten notes.

3.3 Data analysis

In the first phase of reading the interview transcripts, the data were explored to note locations where possible challenges and requirements regarding AM adoption were discussed, and examples of their potential solutions were mentioned. In the second phase, the focus was on the challenges. Common themes and patterns were identified, particularly concerning the challenges of AM adoption, using Mellor et al.'s (2014) thematic framework as a starting point for coding the interviewees' experiences. Such frameworks point out various technology-related, strategic, supply chain-related, operational, organizational, and external factors in AM adoption, and these rough themes were used as the starting point for coding. All the different challenges to adopting AM in SMEs were identified and grouped into these themes. To identify potential differences across company types, we checked how frequently each topic appeared in the interviews per company cluster, and built a cross-tabulation covering all the challenges and their comparison across company clusters.

In the third phase, the requirements and actions for promoting AM adoption were coded. The initial reading of the data suggested that most of the requirements intersected with multiple challenge-related themes. Therefore, an inductive approach was chosen to let the solution categories arise from the data. The five main requirements in promoting AM adoption deal with AM technology, knowledge, strategic decisions, digitalization, and cooperation. Finally, the challenges and requirements of AM adoption were processed in two workshops to identify actions to help the SMEs overcome the challenges. Six actions (three strategic and three operational) are proposed, structured according to the AM implementation factors (Mellor et al., 2014). In reporting the findings, we use quotations from the interviews, and calculated frequencies and cross-tabulations of key issues.

4. Results

4.1 SMEs' experiences of challenges in AM adoption

A total of 33 different challenges were identified among SMEs in AM adoption, and we summarize the technology-related, strategic, supply chain-related, operational, organizational, and external challenges here. *Technology-related challenges* appeared as the third most often mentioned among the companies in this study. Technological challenges were particularly experienced in OEMs and subcontractor firms that have a manufacturing position in the value chain. They included material and quality challenges, long production time, size limitations, technological immaturity, and missing cost calculation models. For example: "*When thinking whether it is possible to make a certain type of component by AM in a demanding operating environment, then firstly, the dimensions are critical, the piece is too big to fit on the AM platform and then the material requirements are hard, compared to what is available for AM, and then the price is of course going to be the limiting factor*". (Cluster 4, Company D) The technological challenges appeared rather inconsistent among the different types of firms; even if service providers and industrial designers also experienced some technical challenges, they were somewhat different from each other and those of the manufacturing firms.

Strategic challenges were discussed among the interviewees the least often, and they were particularly apparent among the manufacturing firms. Interviewees from OEMs and subcontractor firms stated that they lack a company-wide strategy for AM, and an interviewee in a service provider firm said that it seems to be the challenge amongst their customers. Adopting AM is, therefore, not yet strategic or systematic and it may rely only on one person's interest in the technology. Interviewees in SME subcontractor firms in particular expressed that they are afraid to invest in AM machines since it is so expensive, and payback is not guaranteed.

Supply chain-related challenges were experienced among the interviewees not only in terms of the supply chain itself, but the digital solutions through which data are transmitted between supply chain actors. Uncertainty of the emerging supply chain structure was considered a challenge to AM adoption by three-quarters of the subcontractors. Their uncertainty regarding their own position in the emerging supply chain lessens their enthusiasm for adopting AM, at least in terms of investing in machinery. Interviewees in subcontractor and industrial design firms emphasized digitalization-related challenges in the supply chain. Subcontractor firm interviewees said that paper blueprints remain the industry standard, and if a customer sends a 3D model it is done with a poor transfer standard, as the 3D models are not yet supported. If a better standard, for example STEP 242, were more widely used, subcontractors themselves would decide which manufacturing method was the most suitable. An interviewee explained this challenge as follows:

> *"Not a single well-supported 3D model has come out, yet. I would say that it is the inexperience of designers that it only comes as a STEP-203 model and with information that does something like this. Then we need to go through a lot of trouble to find out what the designer really wants this component to do. For example, there is a free hole – should we make threads there? The 3D model does not explain such details if there is no data entered into the 3D model. Consequently, it is necessary to always have a 2D drawing that explains the details and tolerances."* (Cluster 2, Company E).

Interviewees, especially in the industrial design firms, also pointed out that design software is expensive and simulation programs for AM are underdeveloped, which creates challenges to even start to design components to be manufactured using AM.

Operational challenges were expressed concerning design and development as the second most typical challenge, and the challenges stated appeared fairly evenly across the company clusters. Designing for AM and its challenges was discussed in many firms. The legacy of existing product designs and their unsuitability for AM were also discussed. In the relatively early stages of AM, products have to be specifically designed for AM and most likely to a specific machine. Interviewees in the OEMs emphasized the need to identify the right components for AM manufacturing, which is not easy. These challenges can be partly explained by the habit of sticking to old practices and the mindset of "if it ain't broke, don't fix it." The cost of AM components, together with the lack of good cost calculation models, creates another challenge, when the benefits may be realized only during the lifecycle of the component. An interviewee from a service provider firm described the challenging link between design and production as follows:

> *"Parts that come to be printed are still clearly designed for other manufacturing methods, even though the parts are topologically optimized, and for some reason, the customer may not necessarily even want to change it. Then, the challenge is that when you may not understand the manufacturing method properly, it is very difficult to start discussing optimization and such if the customer has no idea of this manufacturing method. There are still a lot of different weird preconceptions about the AM, or it is compared directly to machining, for example. It may be that*

company bureaucracy prevents or makes redesigning a particular product for this manufacturing method too slow." (Cluster 3, Company Q).

Organizational challenges were expressed in terms of lack of knowledge and readiness, and satisfaction with the status quo. Organizational challenges appeared as the most frequently expressed challenge. Interviewees in OEMs, subcontractor, and industrial design firms stated that the lack of knowledge about the technology is a clear barrier to adopting AM technology, even if some experiments have been carried out. AM components (costs, manufacturing time, surface quality, etc.) are directly compared to traditional components even if it was recognized that different indicators are needed for their evaluation:

"So many people still doubt the technology, cannot see the benefits. Everything has to start from the design. It would not be so hard to understand if AM were another standard production machine, only a bit more effective, so it would be easy to see that the part was done a lot faster and then the costs are these. But we have to understand that we get a better design, which affects the customer value, or a component can deliver better performance and because of that we can put a bigger price tag on it." (Cluster 3, Company O).

Satisfaction with the status quo can hinder experimentation when adopting AM technologies. The interviewees, particularly in OEMs, subcontractor firms, and industrial design firms, expressed that they do not have time to learn the new technology; they use traditional advanced manufacturing equipment that delivers great performance. The companies' competitiveness relies on that efficiency, as well as traditional materials, and the quality of their end products are well known and satisfy customer needs. AM production would require new competences on new materials, new design paradigms, new AM processes, and new testing methods, and this learning curve is considered too expensive and time consuming for SMEs.

The *external challenges* were not as easy to code in terms of the interviewees' experiences, and some of the challenges now classified as external could also belong to the strategic and supply chain categories. Lack of inspiration from other examples was recognized in all firm types, and this may be more a company-specific challenge than reflecting a particular supply chain position. Subcontractors experienced the most external challenges to adopt AM by investing in AM machinery, for two reasons: 1) they do not have secure orders for AM and they cannot invest unless there are orders for AM, and 2) they are afraid of competition, i.e., larger companies or OEMs investing in their own AM machines. An interviewee in a subcontractor firm stated: "*Not a single customer has ever asked us anything about AM capabilities, and then, if they ask, we have to think about it.*" (Cluster 2, Company B). Interviewees in OEMs, in turn, said that they are not willing to invest in their own AM machines if they can use a subcontractor, but their subcontractors have not offered them any ideas about leveraging AM. This indeed may be a strategic challenge, as explained by one of the interviewees: "*We do not have enough knowledge to ask about AM from subcontractors and discuss it. AM is such a new technology, even if we have carried out a few experiments. But in a way, if the subcontractor would comprehensively begin to go through what potential 3D printing would offer to this particular product, we could definitely consider AM as an option.*" (Cluster 1, Company K).

Table 4 summarizes the key challenges identified and the comparison across the four clusters of SMEs, based on the mapping of interviewees' experiences of AM adoption. The data indicates that all kinds of challenges are experienced by the SMEs, but to somewhat varying extents. There are evident differences across the SMEs' supply chain positions in which kinds of challenges dominate and how.

Table 4. Identified challenges in adopting AM and comparison of different company clusters.

	Type of company			
Challenges in adopting AM	**OEMs n=5**	**Subcon-tractors n=4**	**AM service providers n=3**	**Designers n=5**
Technology-related: AM technology and material uncertainties				
Distrust of materials, AM parts' quality, durability, and process standardization	**3**	**2**		**3**
Long production time and limitations regarding the size of a component	**2**	**1**		
Immaturity of AM technology/rapid development of AM technology	**2**		**1**	
No standards amongst different AM machines/different brands of machinery require special skills	**1**		**2**	
Costs/lack of cost calculation models	**2**			
Need for post-processing and resulting costs		**1**		
Missing certifications/standards	**1**			
Strategy-related: Strategy and economic situation				
Lack of enterprise-wide strategy for AM/willingness to adopt	**1**	**2**	**1**	
AM technology is an expensive investment	**1**	**3**		
Competitors are hesitant to adopt AM	**1**	**1**		
Recession in orders, no willingness to invest in a bad financial situation		**1**		
Supply chain-related: Digital data transfer, software				
Uncertainty of the emerging supply chain structure	**1**	**3**		
Reliable data transfer, quality, and accuracy of the design file are insufficient		**2**		**2**
Full digital design chain from the designer to machine operator does not yet exist or is incomplete		**2**		**2**
Undeveloped and expensive calculation and simulation software, no material models of AM		**1**		**2**
Paper designs/blueprints are still the industry standard		**2**		
Operational: Design, R&D, innovation				
Right parts/applications for AM productions have not yet been identified	**5**	**1**	**2**	**2**
Current production parts are not suitable for AM production	**1**	**2**	**2**	**1**
Designers' weak knowledge of production and post-processing		**2**	**1**	**1**
Overall optimization using the potential of AM is challenging	**1**		**1**	
Lack of availability of product development data from the customer				**2**
Organizational: Current skills and practices; lack of knowledge				
Limited/lack of knowledge about AM technology and design	**4**	**2**		**3**
Current production machines deliver great performance	**4**	**2**		**1**
The difficulty of perceiving the benefits and applications	**2**	**3**		**1**
Learning all the new skills required is too time consuming with current workload	**1**	**3**		**1**
Production indicators/metrics lean strongly towards traditional manufacturing		**2**	**1**	**1**
External: Customer and subcontractor relationships and marketing				
Lack of inspiring examples and applications	**2**	**1**	**1**	**1**
No existing or assured orders for new machines		**3**	**1**	
Customers have not made any requests about AM capabilities		**2**		**1**
Customer R&D does not take AM method into account when designing parts		**2**	**1**	

Product protection is challenging, and appropriate agreements are missing				**2**
Customer’s management does not have a full picture about AM technology and its possibilities			**1**	
Subcontractors do not see the potential of AM or have not taken the initiative	**1**			

Note: Numbers indicate how many companies experienced the challenge in the cluster.

Among the studied companies, only the service providers have AM machines in-house. Interviewees in the service provider firms stated that they need to do a lot of marketing, customer convincing, and education since they lack industry contacts (in line with Mellor et al., 2014), because their customers’ management does not fully understand AM technology and its possibilities. There were some general key differences between the companies in different supply chain positions, regarding interest in investing in or sourcing AM capacity. OEM companies considered both perspectives, and they were most uncertain about AM technology. Subcontractors mostly considered investing in machinery, or alternatively being one part of the supply chain, conducting post-processing for AM service providers. They experienced various challenges rather similarly across the categories, and supply chain-related challenges were emphasized. AM service providers relied upon their customers’ acceptance to adopt sourced AM components and depended on their partner network as an important driver in AM-related decisions. They experienced the most challenges in cooperation (operational and external), such as educating, marketing, and designing with their customers to deliver enough value. Industrial designers also relied on their customers’ acceptance of AM, and expressed facing the most challenges in the design process. They had very clearly experienced the customers’ habit of sticking to old practices, and the lost opportunities to redevelop products for economic or customer relationship reasons.

4.2 Requirements for promoting the adoption of AM in SMEs

Interviewees pointed out different requirements for promoting AM in their firm and supply chain, and these requirements often dealt with multiple challenges. The requirements were divided into five categories through an inductive analysis: AM technology, knowledge, strategic decision, digitalization, and cooperation.

Table 5. Requirements for adopting AM and comparison of different company clusters.

Requirements \ Type of company	OEMs n=5	Subcontractors n=4	AM service providers n=3	Industrial designers n=5
AM technology AM technology and processes need to advance; the right application needs to be found for AM manufacturing	**4**	**1**	**1**	**3**
Knowledge Specific type of knowledge is needed to adopt AM	**5**	**4**	**3**	**4**
Strategic decision Strategic decision-making is needed to initiate AM adoption			**2**	**2**
Digitalization Some specific digitalization advances are needed to promote AM adoption		**3**		**2**
Cooperation Some kind of cooperation is needed, as most of the SMEs cannot compete on the AM market with their own resources alone	**1**	**3**	**2**	**3**

Note: Numbers indicate how many companies mentioned the requirement in the cluster.

Prior research has already collected most of the *technological and AM process*-related requirements for improving the expansion of AM manufacturing, which can be seen in Gausemeier and Echterhoff's (2013) study. Despite the technical limitations and iterative progress of AM technology, nine of the interviewees said that AM is already applicable, standards are being created for AM, and technology as such can no longer be seen as an implementation barrier. Investments and innovation are needed to overcome the challenges, and it may mean research and/or development. For example, one interviewee pointed out the need for research funding: "*Somebody needs to finance material research in order to develop calculation models for designs and simulations. After that, industrial designers can really start leveraging AM in challenging applications.*" (Cluster 4, Company L).

In order to find the right applications, companies need more *knowledge* about AM. Most of the interviewees expressed that their company management is aware of AM manufacturing, but more information is needed about the principles, and more know-how, education, and training are required, especially concerning AM technology and manufacturing. The knowledge requirement was strongly evident in companies in all supply chain positions. The interviews mostly concerned product-level AM, only superficially mentioning process and production levels. According to the interviewees, more information is needed about the production and supply chain benefits and trade-offs of adopting AM. One interviewee emphasized the strategic aspects of this knowledge: "*At this point, the most important thing is to educate decision-makers in OEM companies—they need to realize all of the benefits of AM, not just concerning the product but also production. After that, designers may get enough resources to start making use of AM.*" (Cluster 4, Company P).

SME management has to realize the potential strategic benefits of supporting the designers and production in adopting AM by creating a company-wide strategy to properly use AM in their business, and the requirement of *strategic decisions* appeared particularly central among service providers and industrial designers. Even if OEMs and subcontractors did not express strategic decisions as a requirement, they found the lack of a strategy as a challenge, which implies that it is also important. Service providers and industrial designers recognized that their customers (i.e., manufacturing firms) need a strategic decision to start using AM comprehensively. As AM differs so much from traditional manufacturing technology, the adoption should start with strategic management. Designers have the capability to learn this new manufacturing method, its benefits, and limits, if they get the resources and encouragement they need from management.

Regarding strategy, the interviewees particularly discussed the products to be manufactured using AM, and that the customers are ready for new kinds of products. As one interviewee explained: "*Customers need to learn and become accustomed to the price level, and therefore find the products where value can be added to justify a higher price.*" (Cluster 1, Company I). Interviewees pointed out that AM can either replace traditional production, or enable the creation of completely new kinds of offerings, and decisions concerning this are highly strategic in SMEs. Where AM replaces traditional production, the products have more or less the same design. The replacement approach would require that machine and material prices drop, the speed of the AM machines increases, customers order, and cooperation with customers increases. Creating new offerings for AM implies identifying a completely new way to create customer value, and designing and producing completely novel components or products. This novelty approach would require that a company takes the risk of investing heavily in R&D, finds a sufficient customer base with unique needs, and has a strategy for designing innovative products that can create bigger customer value. Although the AM components may cost more than ordinary components, their novelty and added value justify the cost. According to one interviewee: "*Certain applications will certainly bring a great deal of added value, especially for products that could not otherwise be manufactured. The role of designers has to be emphasized.*" (Cluster 2, Company J). The company could also try to find assemblies where AM could be used for integrating multiple components (i.e., offering a more complete solution to customers), resulting in significant supply chain and cost benefits. Both in the replacement approach and novelty approach, it is crucial to find the right applications and components for AM manufacturing.

Some of the supply chain and data transfer challenges can be overcome by introducing *digitalization*, which may mean implementing a high-quality data transfer standard as well as toleranced 3D CAD models throughout the supply chain. With increased supply chain digitalization, subcontractors could decide the most suitable manufacturing method for a given product, which could then enable reliable quality control in the process. This is done by measuring or scanning a finished product and comparing that to a toleranced CAD model, revealing the dimensional accuracy. Quality control of microstructures has to be embedded into the building process, which will probably be solved as technology advances.

> *"Industry standard currently is STEP-203, but it is a poor standard. The whole industry network should start using STEP-242 as soon as possible, from where we can get all that knowledge that we really need about the features of geometric elements, including all the tolerances and surface roughness, to essentially determine how it is to be manufactured. So more complete data transfer is required."* (Cluster of subcontractors, Company B).

Currently, there is no established *cooperation* model for AM manufacturing between companies, which was said to be an important factor to facilitate finding the right people and capacity. Therefore, cooperation models should be created through the supply chain. With little direct demand for AM products in the domain of machine manufacturing and process industries (i.e., outside major AM application industries), SMEs in this sector have to bravely conduct experiments, understand how customers' needs could be met with AM, and take a proactive role in creating demand. Investing in cooperation with AM service providers was experienced as an advantage. "*Customer relationships should be more transparent and based on trust or good contracts, because information restrictions hinder the design process.*" (Cluster 4, Company D).

5. Discussion

5.1 Holistic view of the adoption challenge: AM as a systemic innovation

In the first research question, we inquired: "How do SMEs in different supply chain positions differ in their challenges in adopting AM?" The findings of this exploratory study offer evidence that all AM implementation factors in Mellor et al.'s (2014) framework present challenges concerning AM adoption. Compared to studies of large firms (Flores Ituarte et al., 2016b) and mixing large firms and SMEs (Gausemeier and Echterhoff, 2013; Niaki and Nonino, 2017; Deradjat and Minshall, 2017), we have unveiled the specific nature of SMEs' AM adoption, and specifically offered initial empirical support for the centrality of partner orientation in SMEs (Deradjat and Minshall, 2017).

Exploring different types of companies reveals all kinds of challenges (Table 4), shows a different combination of challenges for SMEs in different supply chain positions, and therefore adds to previous studies that are often restricted to a certain supply chain position (Table 2). Recently, only Muir and Haddud (2018) have compared supplier and customer challenges in AM adoption, and none of the previous research has covered the AM adoption challenges across different supply chain positions. The findings show that SMEs in different supply chain positions experience similar operational and external challenges, while experiencing different technology, strategy, supply chain, and organizational challenges. One possible explanation for the differences may stem from whether the SMEs plan to invest in AM machinery or source AM from service providers. Also the broad range of different SMEs, each with their unique technology, strategy and innovativeness features, will likely have an effect on the firms' AM adoption even within the same supply chain position, which has been suggested in previous research concerning the adoption of traditional advanced manufacturing technologies (Thomas et al. 2008). Especially within subcontractor firms and OEMs, it was noted that different companies had quite a different approach to technology utilization, ranging from static and low-technology to more dynamic and development oriented. Among the companies in this study, only the service providers could be considered as high-tech companies in the context of AM.

The importance of digitalization was highlighted in the interviews as an element of supply chain-related challenges, especially amongst subcontractors and industrial designers. The findings provide empirical evidence concerning a recent prediction (Oettmeier and Hofmann, 2017) that using AM for industrial components production requires a higher level of integration in information technology systems and process flows. The finding on the uncertainty of supply chain structure as an AM adoption challenge also lends support to an earlier proposition that a special focus should be given to supply chain-related issues (Oettmeier and Hofmann, 2017).

The findings have offered evidence of the generally challenging nature of adopting AM in a new sector, namely the machine manufacturing and process industries. While previous research has centered on early adopters and straightforward supplier–customer relationships (e.g., Rylands et al., 2016), our findings portray AM adoption as a supply chain issue since the machine building sector is accustomed to collaborating with a variety of subcontractors and service providers. We have shown that the successful adoption of AM would require time and effort across the supply chain, and finding solutions to each supply chain actor’s specific AM adoption challenges. Based on these findings, we propose the following:

> **Proposition 1.** The benefits of AM on a large scale will likely be reaped in the context of machine manufacturing and process industries if the entire supply chain adopts AM technology and its consequences.

In the scope of this exploratory research, AM seems to display some features of a systemic innovation, i.e. innovation “whose benefits can be realized only in conjunction with related, complementary innovations” (Chesbrough and Teece, 2002, p. 128). Our study focused on machine manufacturing and process industries that have a tradition of using subcontractors and external services in their value chain. In this context, it was not self-evident which firm should own the AM machines, and as the technology influences the value chain from customer needs analysis and design to manufacturing, AM innovation has to spread throughout the network to start working properly, and in line with Steenhuis and Pretorius (2017) the levels of innovation may vary. Muir and Haddud (2018) have also recognized the importance of system-wide AM adoption.

5.2 Solutions and actions to overcome the adoption challenges in the supply chain

The second research question asked: “How can SMEs overcome the challenges?” Our analysis yielded five themes of requirements for AM adoption, and some differences were identified among the various supply chain positions. The requirements to solve technology challenges, add knowledge, and activate cooperation were experienced fairly consistently across companies in different supply chain positions, whereas digitalization was requested by subcontractors and industrial designers, and strategic decision making was expected from manufacturing firms. We divided the actions to overcome the adoption challenges into strategic actions and operative actions.

The interviews revealed a need for AM strategy, particularly among the customers of the service-centric and industrial design firms, to promote AM adoption. This finding lends support to Steenhuis and Pretorius (2017) who link the use of selected process technologies with certain (strategic) performance objectives. The interviewees also recognized inter-company cooperation as a requirement for AM adoption in SMEs, which offers empirical evidence in support of previous research. Oettmeier and Hofmann (2016) proposed that a focal firm’s engineers and the contract manufacturer’s production department would need to closely interact to create successful components and make fast product design changes. Deradjat and Minshall (2017) found that a firm’s smaller size forces it to collaborate. In order for SMEs in any of the supply chain positions to be able to create demand for AM components, they would need to cooperate with some lead customers and develop innovative prototypes to demonstrate the benefits of AM to other customers. If the firm sources AM components, it can start activating potentially interested partners in the supply chain. Partnering may involve other kinds of organizations, too. Our findings indicated that some SMEs initially adopted AM through involvement in government-funded research projects, in line with earlier research (Deradjat and Minshall, 2017; Rylands et al., 2016). Based on these findings, we propose the following:

> **Proposition 2.** To advance the progress of AM, SMEs should take strategic actions to overcome the challenges in AM adoption, including:
>
> - developing strategies by identifying the benefits of AM, selecting the focal application areas, and deciding on "make or buy";
> - scouting and collaborating to accumulate AM information, and advancing digitalization;
> - starting with lead customers, creating demand through prototypes, and activating supply chain partners.

The findings concerning operative actions showed that SMEs need new knowledge and technological advances to solve various technological and material uncertainties, including quality problems. Requirements of knowledge and skills have been pointed out in recent research as well (Murmura and Bravi, 2018), and our findings suggest a need for learning through research and active experimentation as operational actions towards the adoption of AM. Deradjat and Minshall (2017) discovered that the poor quality of metal AM parts in the beginning of AM diffusion created a negative image that still exists as a prejudgment that AM does not meet the necessary requirements. Therefore, technological advancement needs to be complemented by active efforts to improve AM's image, for instance by educating customers and other companies in the supply chain on working with AM. Besides separate education efforts, sufficient resources should be given to designers to learn and experiment, so that they can incrementally move from small-scale AM pilots towards the ramping up of full-scale AM deliveries in selected niche products and markets. This of course requires that the SME's management sees the benefits of AM. Furthermore, our findings showed that SMEs need to overcome the hurdle concerning the performance strengths of traditional manufacturing, and tolerate AM's learning curve. This potentially means that the SMEs should create new assessment criteria and metrics that take AM into consideration when monitoring business performance. Based on the findings, we propose the following:

> **Proposition 3.** To advance the progress of AM, SMEs should take operational actions to overcome the challenges in AM adoption, including:
>
> - reducing technical and material uncertainties through learning, small-scale experiments, and research;
> - giving resources to designers to learn and experiment, scaling up AM deliveries in selected niche products and markets; and
> - creating new assessment criteria and metrics for AM manufacturing.

6. Conclusion

The analysis of managers' experiences in four different types of SMEs revealed a variety of challenges and some clear differences, according to the firms' supply chain positions. Where OEMs and subcontractors struggle with technology, strategic decision making, and organizational issues, service providers and industrial designers face various operational, organizational, and supply chain issues that possibly relate to their customers' choices and knowledge. Overall, a supply chain setting may in fact pose a major barrier to diffusing AM in the industry. By mapping the challenges and pointing out the importance of supply chain position across different firms, this study contributes to the literature on AM adoption through evidence specific to SMEs and metallic AM in the machine manufacturing and process industry context.

Besides understanding the variety of challenges, the goal was to identify the requirements in adopting AM across the supply chain, and develop new knowledge on the practices that are needed to promote AM adoption. As technology-related requirements and actions have already been covered, we focused on the socio-economic factors that need to be resolved to overcome the challenges in AM adoption. The identified requirements set out a development agenda for SMEs if they want to benefit from AM in their business. Our results showed somewhat different development priorities between the supply chain positions in that service firms (AM service providers and industrial designers) set certain expectations for manufacturing firms as their customers, and manufacturing firms in turn need to decide whether to "make or buy" regarding

AM capacity. Although we proposed certain general actions to drive the advancement of AM adoption, the industrial field is still open to a first-mover advantage—at least in the context of the companies in this study.

The findings in this study offer practical possibilities for SMEs to position themselves in the versatile supply chain alternatives, and map their AM adoption challenges in comparison to others. As we also pointed out specific requirements experienced by SMEs as prerequisites for AM advancement, other SMEs could also find these requirements useful when defining their learning tasks and roadmaps for AM adoption, and in action planning. Large companies may also use the framework of AM adoption challenges and themes when involving their subcontractors in AM-related transformation. Furthermore, the findings may act as a starting point for education providers to identify and prioritize AM-related learning content to educate manufacturing firm personnel.

This study has revealed the systemic nature of AM technology innovations, implying that SMEs and large firms cannot develop their AM capabilities in isolation. Thereby, the findings of this study are relevant to national innovation systems across countries. As digitalization of manufacturing industries is underway in different countries, SMEs will need broader networks and support, to adopt AM and promote related changes in their business networks. Novel R&D programs and networking instruments may be needed, to promote AM adoption in different domains, including machine and process industries. Alternatively, neglecting the systemic nature of AM technologies may slow down or fully hinder the technology adoption.

The exploratory research design has offered a broader perspective on SMEs' experiences than single or comparative case studies, but it also has limitations. The SMEs in this study are from machine manufacturing and process industries, thereby limiting the findings to this context and to the early phases of the AM adoption process. We purposefully excluded large firms, which creates another limitation. At the same time, we drew attention to multiple different positions in the AM supply chain. In the future, full supply chains and their different actors should be studied in relation to each other, and different firms' expectations in the specific supply chains should be explored.

Qualitative interview data and the selection of informants may cause validity limitations, of which we are aware. We chose the interviewees among SME managers who know their firms' strategic priorities, so that they would be knowledgeable informants regarding the prospects of AM adoption. We also had multiple firms and informants concerning each specific supply chain position, and this approach was expected to alleviate the concern for potential respondent bias. We also explicated the interview protocol and analytical procedures to offer transparency. It is possible that some validity concerns may persist despite these practices, and we propose developing the AM adoption challenges and requirements into a questionnaire survey and testing the findings in broader questionnaire studies, covering different companies in supply chain positions, industries, and phases of AM adoption. To achieve a complete picture of supply chain-level challenges, we propose carrying out in-depth case studies at the level of AM supply chains, to complement the previous studies concerning only certain manufacturing firms.

References

Arvanitis, S. and Hollenstein, H. (2001), “The determinants of the adoption of advanced manufacturing technology”, *Economics of Innovation and New Technology*, Vol. 10 No. 5, pp. 377–414.

ASTM Standard (2012), *Standard Terminology for Additive Manufacturing Technologies*, Vol. 10.04, ASTM International, West Conshohocken, PA.

Archer, N., Wang, S. and Kang, C. (2008), "Barriers to the adoption of online supply chain solutions in small and medium enterprises", *Supply Chain Management: An International Journal*, Vol. 13 No. 1, pp.73-82

Berman, B. (2012), “3-D printing: The new industrial revolution”, *Business Horizons*, Vol. 55 No. 2, pp. 155–162.

Chesbrough, H. and Teece, D. (2002), “Organizing for innovation: When is virtual virtuous?” *Harvard Business Review*, Vol. 80 No. 2, pp. 127–136.

Davis, F.D., Bagozzi, R.P. and Warshaw, P.R. (1989), “User acceptance of computer technology: a comparison of two theoretical models”, *Management Science*, Vol. 35 No. 8, pp. 982–1003.

Deradjat, D. and Minshall, T. (2017), “Implementation of rapid manufacturing for mass customisation”, *Journal of Manufacturing Technology Management*, Vol. 28 No. 1, pp. 95–121.

Diegel, O., Singamneni, S., Reay, S. and Withell, A. (2010), “Tools for sustainable product design: Additive manufacturing”, *Journal of Sustainable Development*, Vol. 3 No. 3, pp. 68–75.

Farooq, S. and O’Brien, C. (2012), “A technology selection framework for integrating manufacturing within a supply chain”, *International Journal of Production Research*, Vol. 50 No. 11, pp. 2987–3010.

Federici, T. (2009), “Factors influencing ERP outcomes in SMEs: A post-introduction assessment”, *Journal of Enterprise Information Management*, Vol. 22 No. 1-2, pp. 81–98.

Flores Ituarte, I., Huotilainen, E., Mohite, A., Chekurov, S., Salmi, M., Helle, J., Wang, M., Kukko, K., Björkstrand, R., Tuomi, J. and Partanen, J. (2016a), “3D printing and applications: Academic research through case studies in Finland”, *Proceedings of NordDesign 2016*, Vol. 2, 10–12 August, 2016, Trondheim, Norway.

Flores Ituarte, I., Khajavi, S. and Partanen, J. (2016b), “Challenges to implementing additive manufacturing in globalised production environments”, *International Journal of Collaborative Enterprise*, Vol. 5 No. 3/4, pp. 232–247.

Ford, S., Mortara, L. and Minshall, T. (2016), “The emergence of additive manufacturing: Introduction to the special issue”, *Technological Forecasting and Social Change*, Vol. 102, pp. 156–159.

Fulton, M. and Hon, B. (2010), "Managing advanced manufacturing technology (AMT) implementation in manufacturing SMEs", *International Journal of Productivity and Performance Management*, Vol. 59 No. 4, pp. 351-371.

Gausemeier, J. and Echterhoff, N.W. (2013), *Thinking ahead the Future of Additive Manufacturing – Innovation Roadmapping of Required Advancements*, University of Paderborn, Paderborn, Germany.

Holmström, J., Partanen, J., Tuomi, J. and Walter, M. (2010), “Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment”, *Journal of Manufacturing Technology Management*, Vol. 21 No. 6, pp. 687–697.

Hopkinson, N., Hague, R. and Dickens, P. (2006), *Rapid Manufacturing – An Industrial Revolution for the Digital Age*, Wiley, Hoboken, NJ.

Khajavi, S.H., Partanen, J. and Holmström, J. (2014), “Additive manufacturing in the spare parts supply chain”, *Computers in Industry*, Vol. 65 No. 1, pp. 50–63.

Knofius, N., van der Heijden, M.C. and Zijm, W.H.M. (2016), “Selecting parts for additive manufacturing in service logistics”, *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 915–931.

Lasagni, A. (2012), “How can external relationships enhance innovation in SMEs? New evidence for Europe”, *Journal of Small Business Management*, Vol. 50 No. 2, pp. 310–339.

Mellor, S., Hao, L. and Zhang, D. (2014), “Additive manufacturing: A framework for implementation”, *International Journal of Production Economics*, Vol. 149, pp. 194–201.

Mishra, R. (2016), "A comparative evaluation of manufacturing flexibility adoption in SMEs and large firms in India", *Journal of Manufacturing Technology Management*, Vol. 27 No. 5, pp. 730-762.

Muir, M. and Haddud, A. (2018), “Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain”, *Journal of Manufacturing Technology Management*, Vol. 29 No. 2, pp. 372-397.

Murmura, F. and Bravi, L. (2018), “Additive manufacturing in the wood-furniture sector: Sustainability of the technology, benefits and limitations of adoption”, *Journal of Manufacturing Technology Management*, Vol. 29 No. 2, pp. 350-371.

Niaki, M.K. and Nonino, F. (2017), “Impact of additive manufacturing on business competitiveness: A multiple case study”, *Journal of Manufacturing Technology Management*, Vol. 28 No. 1, pp. 56–74.

Oettmeier, K. and Hofmann, E. (2016), “Impact of additive manufacturing technology adoption on supply chain management processes and components”, *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 944–968.

Oettmeier, K. and Hofmann, E. (2017), “Additive manufacturing technology adoption: An empirical analysis of general and supply chain-related determinants”, *Journal of Business Economics*, Vol. 87, pp. 97–124.

Ortt, R. (2016), “Guest editorial”, *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 890–897.

Peltola, J., Sierla, S., Vepsalainen, T. and Koskinen, K. (2011), “Challenges in industrial adoption of model-driven technologies in process control application design,” *in Proceedings of 9th IEEE International Conference on Industrial Informatics*, Lisbon, Portugal, 2011, pp. 565–572.

Rogers, E.M. (1962), *Diffusion of Innovations*, Free Press, New York, NY.

Rogers, E.M. (2003), *Diffusion of innovations*, 5th ed., Free Press, New York, NY.

Rogers, H., Baricz, N., Kulwant, S. and Pawar, K.S. (2016), “3D printing services: Classification, supply chain implications and research agenda”, *International Journal of Physical Distribution & Logistics Management*, Vol. 46 No. 10, pp. 886–907.

Rothwell, R. (1989), “Small firms, innovation and industrial change”, *Small Business Economics*, Vol. 1, pp. 51–64.

Ruffo, M., Tuck, C. and Hague, R. (2007), “Make or buy analysis for rapid manufacturing”, *Rapid Prototyping Journal*, Vol. 13 No. 1, pp. 23–29.

Rylands, B., Böhme, T., Gorkin, R. III, Fan, J. and Birtchnell, T. (2016), “The adoption process and impact of additive manufacturing on manufacturing systems”, *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 969–989.

Sasson, A. and Johnson, J.C. (2016), “The 3D printing order: Variability, supercenters and supply chain reconfigurations ", *International Journal of Physical Distribution & Logistics Management*, Vol. 46 No. 1, pp. 82–94.

Steenhuis, H-M. and Pretorius, L. (2017), “The additive manufacturing innovation: A range of implications”, *Journal of Manufacturing Technology Management*, Vol. 28 No. 1, pp. 122–143.

Thomas, A.J., Barton, R., John, E.G. (2008) "Advanced manufacturing technology implementation: A review of benefits and a model for change", *International Journal of Productivity and Performance Management*, Vol. 57 No. 2, pp.156-176.

Thong, J.Y.L., Yap, C.-S. and Raman, K.S. (1996), “Top management support, external expertise and information systems implementation in small businesses”, *Information Systems Research*, Vol. 7 No. 2, pp. 248–267.

Tovstiga, G. and Birchall, D.W. (2008), “Henley SME innovation study 2007”, *PICMET 2008 Proceedings, pp. 479-485, Portland International Conference on Management of Engineering & Technology, 27–31 July, 2008, Cape Town, South Africa.*

Weller, C., Kleer, R. and Piller, F.T. (2015), “Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited”, *International Journal of Production Economics*, Vol. 164, pp. 43–56.

Vossen, R.W. (1998), “Relative strengths and weaknesses of small firms in innovation”, *International Small Business Journal*, Vol. 16 No. 3, pp. 88–94.