Received 17 December 2015
Revised 31 May 2016
Accepted 16 June 2016

Impact of additive manufacturing technology adoption on supply chain management processes and components

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Abstract

Purpose – The purpose of this paper is to provide a systematic analysis about the effects of additive manufacturing (AM) technology adoption on supply chain management (SCM) processes and SCM components in an engineer-to-order environment.

Design/methodology/approach – Based on two explorative case studies from the hearing systems industry, the impact of AM technology adoption on SCM processes and SCM components is investigated. General systems theory and the contingency approach serve as theoretical underpinning.

Findings – Not only the internal processes and management activities, e.g. in manufacturing and order fulfillment, of producers are affected by a changeover to AM, but also the SCM processes and components relating to the supply and demand side of a firm's supply chain. Endogenous and AM technology-related factors are contingency factors that help to explain differing effects of AM technology adoption on SCM processes and SCM components.

Research limitations/implications – It is proposed that AM's ability to economically build custom products provides the potential to alleviate the common dilemma between product variety and scale economies.

Practical implications – Manufacturing firms are encouraged to consider the potential effects of AM on SCM processes and SCM components when deciding whether to adopt AM technologies in the production of industrial parts.

Originality/value – The research adds to the widely unexplored effects that AM technology usage in customized parts production has on SCM processes and components. Moreover, the general lack of case studies analyzing the implications of AM technology adoption from a supply chain perspective is addressed. The resulting propositions may serve as a starting point for further research on the impact of AM in engineer-to-order supply chains.

Keywords Customization, Supply chain management, Additive manufacturing, 3D-printing

Paper type Research paper

1. Introduction

Due to tensioning competition and heightened customer requirements, there is an increased need for firms to differentiate themselves in order to secure a competitive edge. The production of customer individual parts may be an effective option to increase profit margins and customer satisfaction. One way to economically produce innovative, custom products with high added value is additive manufacturing (AM) (Mellor *et al.*, 2014). Whether products are customized based on a standard set of components (mass customization) or are completely engineered and built to order:

The authors would like to thank the anonymous reviewers for their invaluable and constructive feedback. Furthermore, the authors gratefully acknowledge the valuable comments on earlier versions of this paper from the participants of the NOFOMA 2016 Conference in Turku, Finland.

Journal of Manufacturing Technology Management
Vol. 27 No. 7, 2016
pp. 944-968
© Emerald Group Publishing Limited
1741-038X
DOI 10.1108/JMTM-12-2015-0113

offering customer individual products provides the opportunity to satisfy unmet customer needs (Hart, 1995). There is also evidence that consumers tend to have a greater willingness to pay and wait for customized products than for standard products (Chamberlin, 1962; Lee *et al.*, 2002). However, this all comes at a price: customized production calls for a tighter integration of customers into the value creation process (e.g. co-design), which requires appropriate information systems (Da Silveira *et al.*, 2001). Moreover, production costs may be higher than in mass manufacturing due to greater complexities in production planning and control, lower capacity utilization rates as well as a higher need for qualified labor (Piller *et al.*, 2004). Furthermore, it is usually harder to achieve scale economies in customized parts manufacturing as production costs (e.g. object-specific tooling costs) are allocated to a smaller number of units. Especially in an engineer-to-order environment, where the decoupling point is situated at the design stage (Olhager, 2003), the generation of scale economies tends to be challenging. This is due to the notion that customized products and processes require high levels of flexibility, which calls for an agile rather than a physically efficient ("lean") supply chain (Christopher, 2000; Gosling and Naim, 2009). AM, more commonly known as "3D-printing" or "direct digital manufacturing," has the potential to change the common dilemma between product variety and unit costs. AM stands for a number of different technologies, which all work according to the same principle: based on a digital blueprint, materials are joined to form 3D objects. The building process in AM typically happens "layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" (ASTM Standard, 2012). Examples of AM technologies include digital light processing, stereolithography, fused deposition modeling, laser melting, and selective laser sintering.

Since AM does not require object-specific tools, the production of small lot sizes – even of lot size one – may become economically feasible (Berman, 2012). Especially in industries, where individual products are built using a high amount of manual labor, adoption of AM technologies has the potential to cut costs since design changes can rapidly be conducted (Holmström *et al.*, 2010). This reduces the need for manual labor. Despite the immense potential in the production of customer individual parts, there is a lack of case studies, which examine how AM technology adoption affects the supply chain management (SCM) processes and management practices in engineer-to-order supply chains. There is, however, reason to believe that AM alters the way that such supply chains operate and are managed. Moreover, far less research exists on strategies for firms in engineer-to-order environments than in make-to-stock environments (Gosling and Naim, 2009).

The present paper aims to address these gaps in the literature by answering the following research questions:

RQ1. How does AM technology adoption in customized parts production impact SCM processes?

RQ2. How does AM technology adoption in customized parts production impact SCM components?

The terms "customized," "custom," and "customer individual" products are employed interchangeably to describe engineer-to-order products. Thereby, either the whole product or the core component can be tailored to individual customer needs. Two explorative case studies from the hearing aid sector shall help to address the research questions. The hearing aid industry is well suited for case studies on AM applications in customized production, because there is a high need for engineer-to-order products, which provide an optimal fit to the customer and ensure wearing comfort. Moreover, this is currently one of the fields (apart from the dental and the jewelry industry) where AM technologies are most heavily used in industrial parts manufacturing – as opposed to rapid prototyping and "household 3D-printing" by private consumers. To date, over ten million custom hearing aid shells have been produced worldwide using AM technologies (Crain's Chicago Business, 2014).

The use of case study research generally seems appropriate for answering the research questions, since the analyzed phenomenon is relatively new (Eisenhardt, 1989). General systems theory (Bertalanffy, 1969) serves as a theoretical basis for the examinations. In our study, the supply chain with its different actors (suppliers, focal firm, customers) as well as its inherent business processes and management components forms the "system" that is regarded. A contingency approach (Donaldson, 2001) is used to identify relevant situational factors which help to differentiate between contexts. More specifically, the contingency variables shall explain varying levels of impact on SCM processes and components resulting from the adoption of AM technologies. In order to yield a network perspective, the cases are not only constructed from interviews with representatives from the focal firms (i.e. the hearing aid manufacturers), but also include the perspectives of direct suppliers (i.e. material or AM machine suppliers) and customers (acousticians). The SCM framework presented by Lambert (2014) is used to guide the examinations.

The remaining part of this study is structured as follows: Section 2 provides a literature review on AM technologies in the context of SCM. Section 3 explains the methodological approach pursued in this paper. Section 4 presents the results from the explorative case studies and molds the findings into propositions. In Section 5, the outcomes from the empirical analysis are discussed in light of their theoretical and managerial implications. Finally, a conclusion is provided in Section 6, which also indicates the limitations of this paper and directions for future research.

2. Literature review

This section presents condensed findings of previous literature on AM and its implications on SCM. The literature review culminates in the identification of the research gaps, which lie at the heart of the present study.

2.1 AM

In AM, products are built layer-by-layer based on a digital representation of the object, stemming, e.g. from CAD-files or three-dimensional scans (Berman, 2012). Commonly used synonyms for AM are "rapid manufacturing," "digital manufacturing," "direct manufacturing," and "generative manufacturing" (Ebert *et al.*, 2009; Holmström *et al.*, 2010; Hopkinson and Dickens, 2001; Vinodh *et al.*, 2009). AM was invented in the 1980s and has since then predominantly been employed for the fast buildup of prototypes ("rapid prototyping"). However, over the past few years, there has been a rising interest in AM technology usage for producing industrial parts. According to Wohlers Associates (2014) (a consulting firm specialized in providing industry information about the AM market), 34.7 percent (US$1.065 billion) of the worldwide market for AM products and services in 2013 pertained to industrial manufacturing. In 2003, this share only amounted to a mere 3.9 percent of the global AM market (Wohlers Associates, 2014). Currently, the medical products sector is probably the most advanced industry in the usage of AM technologies for producing parts for final products. Between 2007 and

2013, approximately 50 million dental crowns, bridges and copings were produced using AM technologies (EOS, 2013). Moreover, in the past 15 years, notable hearing aid manufacturers such as Widex, Sonova, Beltone and audifon have switched from the manual production of customized hearing aid shells to AM. The aviation and automotive industry is also reaching out for AM, but is still at rather early stages of development. Liebherr Aerospace, a supplier to all major aircraft companies, is planning to build at least 64 different components using metal-based AM technologies in the near future. The firm expects that its first additively manufactured parts, relatively simple levers, will be integrated into airplanes in early 2016. These examples suggest that AM technologies may be relevant for various different industries and that there remains substantial room for growth.

Compared to other, more "traditional" manufacturing technologies such as milling and injection molding, AM technologies can offer distinct advantages: since no object-specific tools are needed in AM, the manufacturing costs may be reduced, especially when producing small batches (Mellor *et al.*, 2014). This can render AM economically feasible for the production of customized parts (Berman, 2012; Holmström *et al.*, 2010). Furthermore, design changes can be realized quickly in AM since the underlying CAD-files are easily adjusted (Berman, 2012). AM technologies also offer an increased freedom of design: even complex geometries can be realized, which would not be possible otherwise (Mellor *et al.*, 2014). Moreover, AM technologies are suitable for the creation of lightweight objects, because grids or even hollow structures can be produced (Petrovic *et al.*, 2011). Finally, AM allows for the functional optimization and integration of products, e.g. by building objects, which formerly consisted of several subcomponents, in a single piece (Holmström *et al.*, 2010; Glasschroeder *et al.*, 2015). According to Glasschroeder *et al.* (2015), three different types of function integration are relevant for AM: the integration of mechanical functions (e.g. movable parts), thermodynamic functions (e.g. tempering channels), and electrical functions (e.g. various conductive materials) into products.

Current limitations of AM technologies include the restricted choice of materials and surface finishes compared to traditional mass manufacturing technologies (Berman, 2012). Michael Schmidt, a professor for photonic technologies at the University of Erlangen-Nuremberg, said: "[…] in order to open up the whole potential of additive manufacturing, it is vital to broaden the so far limited choice of materials" (Gebhardt, 2014). According to Terry Wohlers, president and principal consultant at Wohlers Associates, "[t]here is significant demand for the ability to use more different types of materials in AM, but so far, the leading companies have not really pushed the envelope in terms of really going after a wide range of new materials yet" (Jenkins, 2015, pp. 21-22). Large-scale production of standardized products with AM also still involves higher costs and a lower speed than with other mass manufacturing technologies (Berman, 2012). However, AM machine vendors are actively addressing these issues (Campbell *et al.*, 2012). With ongoing technological advances, these limitations may therefore become less relevant in the future. For example, in 2016, Hewlett-Packard will launch a new AM machine running on HP Multi Jet Fusion technology, which operates ten times faster and delivers a higher product quality at considerably lower purchase prices than comparable AM machines (Hewlett-Packard, 2014).

2.2 SCM

Supply chains are networks formed by nodes (supply chain members) and links (connections between the members) (Carter *et al.*, 2015). According to Mentzer *et al.* (2001, p. 18), SCM refers to "[…] the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole". SCM is characterized by a strong customer focus (Chen and Paulraj, 2004). The ultimate aim of the inter-functional and inter-corporate coordination of business functions in SCM is customer satisfaction and the creation of value to the [final] customer (Mentzer *et al.*, 2001). Examples of such business functions are marketing, research and development, production as well as customer service.

SCM consists of three different elements (Lambert, 2014, p. 20; previously published in Cooper *et al.*, 1997; Lambert *et al.*, 1998; Lambert and Cooper, 2000):

(1) supply chain network structures ("the member firms and the links between these firms," e.g. customers and suppliers);

(2) SCM processes ("the activities that produce a specific output of value to the customer," e.g. order fulfillment and manufacturing flow management); and

(3) SCM components ("the managerial methods by which the business processes are integrated and managed across the supply chain," e.g. IT and work structures).

The SCM elements are closely linked to each other, which poses challenges for differentiated analyses of the single elements.

2.3 AM in the context of SCM

Although AM is *per se* not a new topic, it is still widely unexplored from a research perspective. Only in recent years has it sparked the interest of a greater number of scientists, who investigate AM from a technical or a business point-of-view. Current research on AM can broadly be classified into six different research streams: studies outlining the current state-of-the-art in AM, e.g. with regard to industry applications and technological maturity (e.g. Bak, 2003; Berman, 2012), engineering-focused studies, which aim to develop new or improve existing materials or technologies for AM (e.g. Murr *et al.*, 2012; Janaki Ram *et al.*, 2006), studies analyzing the adoption of AM technologies (e.g. Arvanitis and Hollenstein, 2001; Oettmeier and Hofmann, 2016), research examining the costs of AM (e.g. Hopkinson and Dickens, 2003; Ruffo *et al.*, 2006), studies on the implementation of AM and make-or-buy decisions (Mellor *et al.*, 2014; Ruffo *et al.*, 2007), and research addressing AM in the context of SCM (e.g. Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Nyman and Sarlin, 2014). The major part of the latter regards the opportunities and impact of AM in spare parts supply chains. There seems to be a consensus about AM's potential to enable a distributed production of (spare) parts, which may even occur on demand (Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Mellor *et al.*, 2014).

Several studies indicate that AM technology usage may have an impact on different actors in the supply chain, such as suppliers, manufacturing firms, and customers. For example, Holmström *et al.* (2010) note that AM has the potential to simplify supply chains by making them narrower and shorter. This is probably because AM technologies provide the opportunity to integrate additional functionality into products and to optimize products for function (Holmström *et al.*, 2010; Glasschroeder *et al.*, 2015), which can reduce the number of subcomponents needed and hence of suppliers. Berman (2012) suggests that small batch production could be transferred back from low- to high-wage countries since AM may lower the need for manual labor. This seems to be particularly relevant for firms offering handmade, customized products down to a lot size of one, as these are particularly labor-intensive. With AM, a firm's operations could also become more agile (Vinodh *et al.*, 2009), e.g. due to the technologies' ability to rapidly alter product designs. Customers of AM products could benefit from higher service levels as production may be decentralized and thus occur closer to the customer (e.g. Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Walter *et al.*, 2004).

The insights from the literature indicate that AM technology usage may not only have implications on the supply chain network structures, but also on SCM processes and SCM components employed by the different actors. For example, to seize the increased opportunities in product design enabled by AM technologies (e.g. lightweight construction and functional integration), new or adjusted processes and management practices in research and development seem to be inevitable. In their framework for AM implementation, Mellor *et al.* (2014) point out that – among other aspects – a transition to AM may evoke changes in process planning and product design as well as in quality control. Although the identified elements help to localize potential aspects in SCM affected by AM technology adoption, there still remains substantial room for further research in this area. To our knowledge, no study has systematically analyzed the effects of AM technology usage in customized parts production on SCM processes and SCM components. While the potential impact of AM on supply chain structures has already been examined to a certain extent (although not in a systematic fashion), the effects on SCM processes and components have been rather neglected. Additionally, we could not find any case study research, which examines the SCM implications of AM technology usage in an engineer-to-order environment.

2.4 Résumé of the literature review and research gaps

The review of the literature shows that in recent years, AM has increasingly been gaining attention from researchers. This is due to the fact that AM technology usage may have far-reaching business implications, which could go beyond a mere technological innovation. An analysis of the existing literature reveals two research gaps: first, although different studies mention potential supply chain-related benefits of AM (e.g. Berman, 2012; Holmström *et al.*, 2010), the impact of AM technology usage in customized parts production on SCM processes and SCM components has never been analyzed in a systematic way. Second, there seems to be a general lack of case studies, which explore the implications of AM technology adoption from a network perspective. By analyzing how AM technology adoption in customized parts production impacts SCM processes and components, this paper aims to fill these research gaps and contribute to theory building in the field of operations management.

3. Methodology

In order to close the identified research gaps, the case study method is used. This seems appropriate as our research is of explorative nature and aims to contribute to new theory building (Eisenhardt, 1989; Yin, 2009).

3.1 Conceptual framework

To explore the impact of AM technology usage on SCM processes and components, we analyze how these two SCM elements have changed due to AM technology adoption (see Figure 1). Following the understanding of Lambert (2014, p. 20), we define SCM processes as "the activities that produce a specific output of value to the customer." We distinguish between five different types of SCM processes: supplier relationship management, manufacturing flow management, product development and commercialization, order

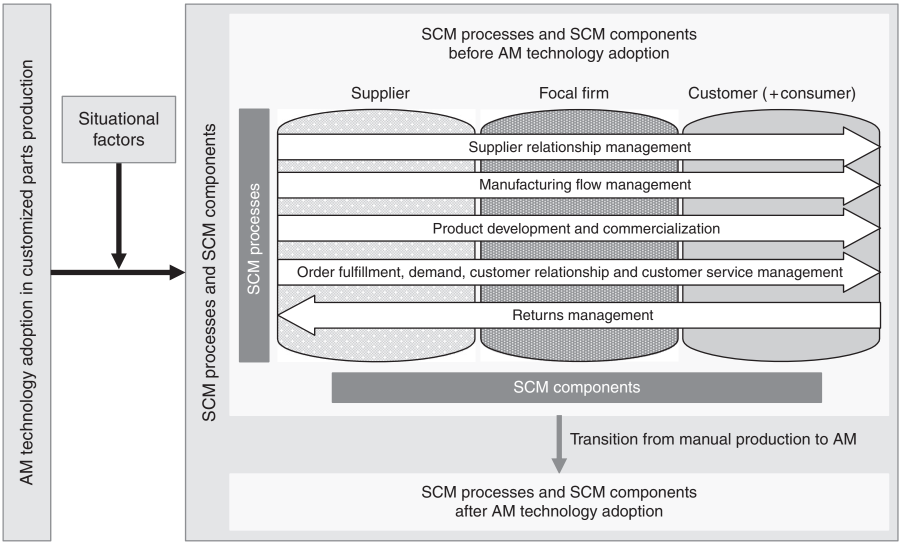

Figure 1.
Conceptual framework of this study

Sources: Adapted from the SCM framework by Lambert (2014) (originally published in Cooper *et al.*, 1997)

fulfillment, demand, customer relationship and customer service management, as well as returns management. The processes are defined as follows (cp. Lambert, 2014):

- supplier relationship management focuses on the development and maintenance of the relationships to the suppliers;
- manufacturing flow management comprises of the activities needed for obtaining, implementing and managing the manufacturing flexibility and the flow of goods in the supply chain;
- product development and commercialization refers to the activities involved in the joint development and launch of products with suppliers and customers;
- order fulfillment, demand, customer relationship and customer service management deal with the development and maintenance of the relationships with customers, the administration of product and service agreements, the balancing of customer demand with supply chain capabilities as well as the activities needed to fulfill customer requests; and
- returns management comprises all activities in the supply chain concerned with reverse logistics and returns, including the avoidance of unwanted returns as well as the management of reusable assets (e.g. reusable packaging or materials).

The SCM components are defined as “the managerial methods by which the business processes are integrated and managed across the supply chain” (Lambert, 2014, p. 20). In our study, we specifically focus on how planning and control structures, organizational, IT and work structures, as well as management methods are altered due to the adoption of AM technologies in customized production.

Our research takes a contingency perspective (Donaldson, 2001). This shall help to obtain a more differentiated view on the effects of AM technology adoption on SCM processes and SCM components. It is suspected that the degree to which AM technology adoption impacts the SCM elements (the "context") is influenced by contingency variables (such as a firm's experience with AM). Consequently, it is assumed that situational factors moderate the relationship between AM technology adoption and SCM processes as well as SCM components. Following Kajüter and Kulmala (2005) as well as Oettmeier and Hofmann (2016), we consider exogenous (environmental), endogenous (firm specific), AM technology- and supply chain-related factors as potentially relevant groups of contingency variables.

3.2 Study design

As our research questions focus on the impact of AM technology adoption on SCM processes and SCM components, we take a network perspective as our level of analysis. The scope of the analyzed supply chain is thereby limited to the triadic network formed by the focal firm (hearing aid manufacturer), its direct suppliers (material or AM machine suppliers) and direct customers (acousticians). Interviews were not only conducted with key informants of the hearing aid manufacturers' production, logistics or research and development (R&D) departments, but also with liaison persons from sales or R&D of their suppliers (material or machine suppliers) and customers (acousticians). In order to increase construct validity, we employed multiple sources and types of data collection. Semi-structured interviews are the main source of information for this study. They lasted between 30 minutes and five hours and were all carried out by the same research team. The interviews with representatives from the focal firms and two of their customers were conducted on-site, whereas those with the informants from the suppliers and one customer were carried out on the phone. Overall, we conducted eight in-depth interviews: two with representatives from the suppliers, three with informants from the focal firms and three with informants from the customer-side. The interviews covered the topics laid down in a research guide, which was based on the elements of SCM processes and components outlined by Lambert (2014). Appendix 1 shows an extract of the interview guide, which was employed during the data collection at the hearing aid firms. All interviews were recorded and transcribed. The transcripts were sent to the interviewees for inspection. Eventual ambiguities concerning the data were clarified ad hoc with the informants.

3.3 Case selection and sampling

Our study focuses on the effects of AM technology adoption in customized parts production on SCM processes and SCM components. To analyze these aspects, we chose firms, which currently use AM technologies to build customized parts and had engaged in traditional manufacturing of customized parts before changing to AM. The case companies both stem from the same industry (hearing systems), but differ with regard to their experience with AM as well as the way and extent to which the technology is deployed within the supply chain. By collecting such diverse cases, we aim to increase external validity and thus make the results more generalizable (Eisenhardt, 1989; Yin, 2009). The hearing aid industry appears to be an appropriate focus for this study because there is a high need for engineer-to-order products to guarantee the best possible accuracy of fit to the customer. Moreover, this depicts one of the few fields – apart from the dental sector – where AM technologies have already been extensively used in industrial parts production for more than ten years. It is assumed that the full scale of changes in SCM processes and components due to AM technology adoption are better visible in industries, where AM is an established technology, as opposed to sectors currently undergoing the transition toward AM. Before their switchover to AM, both case firms engaged in "manual manufacturing," meaning that the hearing aid shells were handcrafted. It is suspected that in industries with a high share of manual labor, the potential impact of AM technology adoption will become particularly apparent. An overview of the cases is provided in Table I. Greek letters replace the company names as we promised anonymity to the interviewees. Short case descriptions can be found in Appendix 2.

In line with Eisenhardt (1989) as well as Seawright and Gerring (2008), we pursued a two-step analytical sampling approach. In a first step, we aimed to identify a relatively homogenous sample with regard to origin (Europe, to ensure that all firms operate in a similar legal and market environment), firm size (only large- or medium-sized companies), and area of AM technology usage (production of customer individual in-the-ear hearing aid shells). Large firms were selected because we suspected the impact of AM technology adoption to be more visible here than in small companies, as more efforts need to be taken to integrate the technology into the existing systems. In a second step, we identified firms that had different levels of experience with AM technology usage in customized production. Therefore, apart from a firm with a long-term history in large-scale AM, we also included a company in the sample, which had only recently started to use AM technologies for medium-scale production. In this way, we aimed to obtain a better understanding of SCM processes and SCM instruments or practices, which are immediately impacted by a transition to AM, as well as those, which may be altered or implemented in later stages of AM technology deployment.

3.4 Data analysis

We followed the qualitative data analysis approach by Strauss and Corbin (1990), as our collected data were rich in information but unstructured. First, we conducted a within-case analysis to understand the SCM processes and components used by the firms and the way in which AM technology adoption impacted these. We thereby triangulated data, using not only insights from the transcribed interviews, but also from our observations during the site visits as well as official company documents (e.g. information from the company website). Thereafter, we performed a cross-case analysis in order to spot common patterns among the cases. Finally, we chose those SCM processes and components, which were particularly affected from AM technology adoption and promised to be most interesting for future research. To make the coding process more transparent, Table II presents extracts from the interviews as well as the categories and codes they were assigned to.

4. Results

In this section, the observations from our explorative empirical analysis on the effects of AM technology adoption on SCM processes and SCM components are presented.

4.1 Supplier relationship management

In general, there are two different options with regard to procurement in the field of AM: a firm sources ready-made AM parts (contract manufacturing), or a company purchases the required materials and capital goods in order to engage in AM itself. The two case companies both chose the latter option. With the adoption of AM technologies in the production of hearing aid shells, Alpha (fictitious company name) increased

Table I. Cases overview

Study perspective		Case characteristics			Number of interviews			
Case	Selection criterion	Size	Origin	Industry	Suppliers	Focal firm	Customers	Total
Alpha	Large-scale worldwide customized production of AM technologies, long-term experience with AM technologies in industrial parts manufacturing	Large	Switzerland	Hearing solutions	1 (machine and material supplier) = Supplier A	1 (strategy and operations manager)	2 (acousticians) = customers A1 and A2	4
Beta	Medium-scale customized production with AM technologies, short-term experience with AM technologies in industrial parts manufacturing	Medium	Germany	Hearing solutions	1 (machine supplier) = supplier B	2 (plant and operations manager, R&D manager)	1 (acoustician) = customer B (+customer A1, who is a customer of both, Alpha and Beta)	4 (+1)

Categories	Codes	Original statements
Supplier relationship management	Procurement process	"We work with minimum stock levels. When these are undershot, a purchase order is triggered. The order quantities are predefined and are regularly reviewed" (Beta)
	Quality management in procurement by the focal firms	"We test all the machines. Everything that goes to Europe, Asia, South America, Australia or New Zealand, is first tested. The machine is brought here [company headquarters] and tested for two weeks with batches like in production. Only once the machine has passed these tests, works well and has no defects, it is shipped" (Alpha)
	Quality management by suppliers	"Together with the material supplier, we have validated the production facility. That means we have validated the machine and the material together. Different tests and pilot series are run. When these are completed, we can be sure that the materials and machines are compatible with each other." (Supplier A) "The challenge [for machine manufacturers with an 'open' AM system] is of course that different materials from different producers need to be processed. That means we have to agree upon a certain standard" (Supplier B)
Manufacturing flow management	Industrialization of manufacturing	"[In the past,] everything was often done by one person: from the beginning until the end, including the testing. Today one person only carries out one step, e.g. the modeling. This kind of industrialization certainly makes people become more experienced and gets them to fulfill their tasks at a hundred percent. Those who build something in build in and do not also carry out the varnishing and testing" (Alpha)
	Quality management and employee training in manufacturing	"Nowadays we can better control and train these things [how hearing aids are to be built]. There is a relative consensus, e.g. about how an impression is cut electronically and in which angle it is build best, so that in the end, the finger can reach the device, e.g. in order to adjust the potentiometer." (Alpha) "You have to make sure that the materials are correctly stored, stirred and used in order to achieve a constancy [in product quality]. And you have to set up the machine in a proper place and not place it next to the polishing machine, where dusts emerge that can cover the optical system, i.e. the production unit" (Supplier A)
Product development and commercialization	AM implications on product development	"There are less barriers to what can physically be done. […] Moreover, I get better support from the software – in case I want to be supported by it" (Alpha)

Table II. Original statements, codes, and categories derived from the interviews (extract)

(*continued*)

Categories	Codes	Original statements
	Rapid prototyping implications on product development and commercialization	"Today there is a completely different way of communication, which is of course also new to the elderly colleagues. They sometimes have trouble coming over with their drafts at an early stage and putting them up for discussion." (Beta) "In the past, user studies whereby the devices are presented [to customers], were conducted relatively late [in the development process]. The device was already elaborated to a degree to which it was almost finished" (Beta)
Order fulfillment, demand, customer relationship and customer service management	Order fulfillment	"The majority [of the acousticians] works with ear impressions, i.e. with impression material, and oftentimes also with paper-based order forms, which are sent in via regular mail together with the impression. The system variant, where the scanning is done in the specialist shop, whether with an impression or directly in the ear, is not yet established with the large part of customers. I think this will come, especially the direct ear scanning." (Beta) "The acoustician, who has taken the impression, can scan it and send the 3D data to us. In this way, we can directly start the modeling, avoid the shipping through the post and save a day of [processing] time." (Alpha)
	Demand forecasting	"We still have a make-to-order production. The demand on the market has not really changed due to additive manufacturing" (Beta)
Returns management	Waste material and material reuse	"When the casting process was executed seriously [in the past – with manual production], the material, which had not been cured, was poured away. It was not reused." (Beta) "The support structure and the base plate […], which is generated with every building job, is waste. Moreover, there is always a little bit of liquid plastics hanging on the hearing aid shell. This is of course also waste. But in sum, I would say this is little." (Beta) "On the weekend, you can pour the liquid [material] back into the bottle and fill the machine again with it on Monday" (Alpha)
	Replacement processing	"[With AM], you have the shaping more under control. […] When a modification is needed, a component needs to be rebuilt or a shell is crushed, you can build it again based on the data you have. You can also react faster and reduce staff deployment." (Beta) "[In case a rebuild is needed], we would call [Alpha] and tell them which device we had – we save the serial number from the very beginning. Based on this, [Alpha] can manufacture the new device." (Customer A1) "[The returns process] has accelerated because I already have the customer's data. […] When I have a device from [Alpha] that has been manufactured three months ago and has a broken shell, I give them a call and based on the existing data they build a new one" (Customer A2)

Table II.

standardization in procurement: "We have the same processes, the same materials, the same equipment and the same processing time [in all our plants where AM technologies are employed for hearing aid shell production]." This is due to a greater need to gain control over product quality as AM machines are not only very sensitive to different parameter configurations, but also to material properties. "We test all the machines. Everything that goes to Europe, Asia, South America, Australia or New Zealand, is first tested. The machine is brought here [company headquarters] and tested for two weeks with batches like in production. Only when the machine has passed these tests, works well and has no defects, it is shipped." Thus, a centralized incoming goods inspection for AM machines and materials was implemented. Furthermore, Alpha's purchasing department now pursues a more long-term vision when spotting and evaluating new AM technologies because "[t]he machines that are in place today will also be in place in the next five years."

With its transition to AM, Beta (fictitious company name) had to develop new selection criteria specific to the procurement of AM machines: "One topic during machine selection was the integration into our strategic production planning, i.e. the reduction of lot sizes and the shortening of lead times." Such considerations were not relevant for procurement in times of the manual hearing aid shell production because production lot sizes were always one back then. While Alpha conducts daily tests to assess the AM material quality and machine calibration, Beta leaves most inbound quality management responsibilities to its AM suppliers. As the informant at Beta notes: "In our company, we do not have the possibility to check the material quality – apart from the expiration date." This can be attributed to Beta's shorter experience with AM and hence its lower level of know-how in this area. Moreover, Alpha's AM technology was less technologically mature upon adoption than Beta's. This is due to the fact that Alpha is one of the pioneers in its industry with its AM technology usage, whereas Beta is a late adopter. Alpha thus needed to collaborate closer with its AM machine and material suppliers and incurred greater investments in internal quality control measures to bring the AM products to an adequate quality. Experience with AM and the maturity of the AM technology therefore both seem to be contingency factors for the degree to which AM-related quality control tasks are distributed among manufacturers and AM suppliers.

Considering all our findings in the field of supplier relationship management, it is proposed that:

P1a. (SCM processes): the transition from manual to AM of custom products increases the relevance of including considerations about strategic production planning in the procurement activities.

P1b. (SCM components): the transition from manual to AM of custom products requires the buildup of specific know-how in procurement about the characteristics of AM machines and compatible raw materials. A firm's experience with AM is negatively and the maturity of the adopted AM technology is positively associated with the level of AM-related quality control tasks that are transferred to suppliers.

4.2 Manufacturing flow management

Before switching to AM, Alpha and Beta both engaged in manual hearing aid shell production. The production processes before and after this transition are similar for both firms and are summarized in Figure 2. It becomes apparent that Alpha and Beta now produce the customized shells in batches of 12 to 40 parts per building job (depending on the part size and the size of the AM machine's building platform). In the past, shell manufacturing was a single part production, where the formation of batches was not possible at any point in the process. Furthermore, the division of labor in manufacturing has increased since AM technology adoption. While the production of a hearing aid was originally oftentimes carried out by a single person, there are now various employees involved in this process, e.g. 3D modelers, AM machine controllers (who also carry out post-processing of the shells) and specialists, who build in the electronics and conduct the testing. This specialization of manufacturing staff is enabled by the outcomes of the 3D modeling process: a printout of the customer individual hearing aid model visualizes the shape of the finished product and illustrates where the electronics is to be placed inside the shell. The information is transmitted to every employee who is involved in the production of the specific hearing aid. The higher separation of labor has had positive effects on process and product quality. A strategy and operations manager at Alpha said concerning this aspect: "[In the past,] everything was often done by one person: from the beginning until the end, including the testing. Today one person only carries out one step, e.g. the modeling. This kind of industrialization certainly makes people become more experienced and gets them to fulfill their tasks at a hundred percent." From a management perspective, the transition to AM helped both producers to improve the training and evaluation of manufacturing staff. For example, the informant from Alpha expressed: "Nowadays we can better control and train these things [how hearing aids are to be built]. There is a relative consensus, e.g. about how an impression is cut electronically and in which angle it is build best. […] In the past, this was harder or actually not possible. Previously, you did not really know what was done there – it was just done."

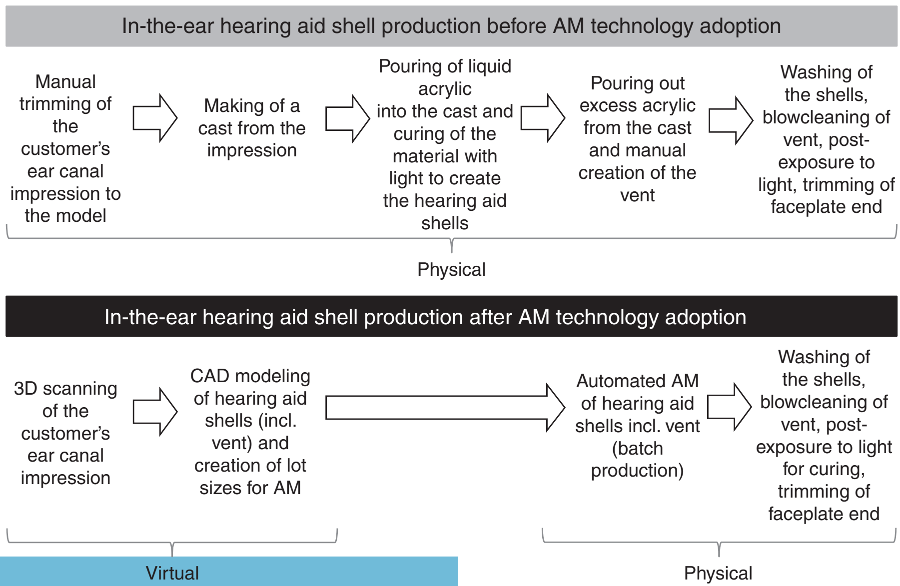

Figure 2. In-the-ear hearing aid shell production before and after AM technology adoption

According to the plant and operations manager at Beta, building up the know-how for modeling the hearing aids was a challenging task as very specific expertise is needed. The required visualization skills could not always be found among the existing manufacturing staff. Therefore, the company also had to recruit employees who had the required skills and could bring in new know-how. Due to the transition to AM, Alpha and Beta not only needed to include a 3D modeling process in their supply chain, but also had the opportunity to bundle their modeling competences and differentiate between product design (i.e. modeling) and manufacturing. For example, the digital blueprints for hearing aids for the North American market are created by Beta's plant in Germany, since the company's US plant lacks the required modeling know-how. Thus, the plant in the USA sends the 3D scans of the ear impressions to the German plant, where the customer individual products are designed. Thereafter, the digital construction data are transferred back to the USA, where the manufacturing occurs. According to the plant and operations manager at Beta, this process has another benefit: "[…] you can take advantage of the time difference. In this way, we are even faster than if we would do everything there [in the USA]." In the future, Beta plans to further bundle its 3D scanning and modeling tasks.

No major differences concerning the effects of AM technology adoption on manufacturing flow management could be found between Alpha and Beta. Therefore, the following propositions are suggested to apply to firms switching from manual engineer-to-order production to AM, regardless of their specific context:

P2a. (SCM processes): the transition from manual to AM of custom products increases the industrialization of manufacturing. Additionally, a switchover from manual production to AM fosters the generation of scale economies in product modeling (e.g. due to a bundling of design authority) and production (e.g. through batch manufacturing).

P2b. (SCM components): the transition from manual to AM of custom products increases quality management and employee training possibilities. It requires new skill profiles and work structures since technical experts are needed for operating the 3D scanning and modeling programs as well as the AM machines.

4.3 Product development and commercialization

Alpha and Beta both use AM technologies for building prototypes ("rapid prototyping"). According to the R&D manager at Beta, whenever possible the AM machines employed in serial production are used in order to quickly visualize new product ideas. Otherwise, external service providers build the prototypes based on 3D model data. Due to rapid prototyping, Beta has been able to increase the market acceptance of new products since customers (acousticians) can earlier be integrated into the product development process, e.g. for usability studies. Beta's R&D manager notes that with rapid prototyping, the tasks in product development have become modularized and interaction between developers has increased: "Nowadays there is a completely different way of communication, which is of course also new to the elderly colleagues. They sometimes have trouble coming over with their drafts at an early stage and putting them up for discussion."

The analysis indicates how the usage of AM technologies in prototyping may impact SCM processes and management activities in product development. However, a clear distinction should be made between the effects of rapid prototyping and the changes that AM technology adoption in industrial parts manufacturing evokes in the field of R&D. Numerous manufacturing firms have already employed rapid prototyping to speed up development processes. However, a transition to AM in industrial production does not necessarily imply that firms will also engage in rapid prototyping, although in practice this often seems to be the case.

The informant at Alpha notes that due to their transition to AM in hearing aid shell production, there are less barriers to what can physically be realized. For example, thanks to AM, the shells have a smaller and better controllable thickness, which allows engineers to integrate more functionality in there. Compared to that, the design opportunities during the original casting process were rather limited. Additionally, Alpha's developers are supported in their modeling tasks by CAD software, which limits the risk of conceptual flaws. However, the increased design opportunities due to AM technologies also require the buildup of specific know-how in R&D in order to seize this potential. In the future, the company is hoping to develop better materials and modeling strategies thanks to a more accurate input database fed with automatically generated data captured during the AM process. The strategy and operations manager of Alpha highlights the importance of a close collaboration internally and with suppliers during AM implementation and product development: "You have to seek contact with production employees early in the process and you especially need to develop a good, cooperative approach with the [AM machine] manufacturer or the [material] supplier – in contrast to a protective approach. This is something we have learned and will certainly do differently when qualifying a second source." Overall, the analysis shows that despite an increased freedom of design and corresponding employee training needs, a switchover from manual production to AM of customized parts only has a limited impact on product development and commercialization. Greater effects in this area can be found when AM technologies are also used for rapid prototyping.

No notable differences between the case of Alpha and Beta could be detected, suggesting that the implications of AM technology adoption on product development and commercialization tend to be similar for varying contexts. It is proposed that:

P3a. (SCM processes): the transition from manual to AM of custom products fosters the development of new or improved products by providing more detailed input data about the manufacturing process.

P3b. (SCM components): the transition from manual to AM of custom products requires the buildup of specific know-how in R&D to utilize the greater freedom of design enabled by AM technology adoption.

4.4 Order fulfillment, demand, customer relationship, and customer service management

Due to the switchover to AM, Alpha is striving for a stronger digitization in its relationship to the customers (acousticians), particularly in order fulfillment. The company already has a process with around two percent of its customers in place, where the acoustician scans the ear impression and digitally transmits the 3D data to Alpha along with the order form. In this way, a physical delivery is omitted and the production process can begin quickly. This positively affects order lead time. For the remaining customers, the firm still receives the impressions by regular mail and conducts the scanning process itself.

Since AM of hearing aid shells is rather new for Beta, the firm has not started to use 3D scanning with its customers yet. The hearing systems manufacturer currently receives all order information (order forms and ear impressions) from acousticians via regular mail.

The representatives from Alpha and Beta both expect that in the future, ear impressions from final consumers may be substituted by 3D ear scanning. Such a higher degree of process integration could further strengthen the relationship with customers. Moreover, the informant from Alpha notes that thanks to AM technology usage, consumers could benefit from a constant order lead time, a greater fitting accuracy as well as a smaller product size.

The case studies do not show any impact of AM technology adoption on-demand forecasting. As the plant and operations manager from Beta explains: "We still have a make-to-order production. The demand on the market has not really changed due to additive manufacturing." The findings culminate in the following propositions:

P4a. (SCM processes): the transition from manual to AM of custom products tends to reduce order lead time (e.g. by eliminating certain physical deliveries), but does not affect demand forecasting.

P4b. (SCM components): the transition from manual to AM of custom products fosters the integration of customers into the value creation process (especially virtually by using electronic means). A firm's experience with AM is positively associated with the level of customer integration into the value creation process resulting from AM technology adoption in customized production.

4.5 Returns management

According to Beta, the material utilization rate of the hearing aid shell material (acrylic) has increased to around 98 percent since AM technology adoption whereas material usage has declined. The material, which is not cured throughout the additive building process, can be reused and filled up with additional liquid acrylic. In contrast, excess material from the traditional casting method was typically disposed of. The plant and operations manager from Beta mentions concerning that aspect: "When the casting process was executed seriously, the material, which had not been cured, was poured away. It was not reused." Due to the switchover to AM, Alpha's material utilization rate has also increased to almost 100 percent because of the possibility to reuse uncured AM material. The firm has introduced a new process whereby the liquid acrylic for AM is filtered from time to time to remove any potential remains of cured material.

Furthermore, the informants from Alpha and Beta note that due to their transition to AM, replacement processing is accelerated and object replicability has greatly improved. This can be traced back to the automated production process and the fact that the firms have established a database for storing the 3D model data. "[…] [w]hen a new shell has to be built, you have the possibility to quickly react to it with additive manufacturing. You do not need another impression for that. […] If you still have the 3D data of the impression, you can instantly newly produce [the shell]" (plant and operations manager from Beta). However, in the hearing systems industry, storing the 3D data for more than six months only makes little sense for replacement purposes. As the strategy and operations manager from Alpha said: "The ear is one of the few organs, which keeps on growing throughout its life." Hence, new hearing canal data are needed when shells are to be replaced more than six month after taking the ear impression. In such cases, Beta's customers send physical order forms and impression data to the manufacturer, as the acousticians do not employ 3D scanners. In contrast, Alpha, which already has long-term experience with AM, has established a digital process with some of its customers. Thereby, the acousticians transfer the replacement form and impression data virtually by electronic means.

Based on our findings in the field of returns management, we propose the following:

P5a. (SCM processes): the transition from manual to AM of custom products increases material utilization due to the possibility to reutilize unprocessed AM material. Specific reprocessing activities (e.g. filtering) may be required to ensure an adequate quality of the AM materials that are to be reused.

P5b. (SCM components): the transition from manual to AM of custom products accelerates replacement processes, provided that IT systems for storing the 3D model data are in place. A firm's experience with AM is positively associated with the existence of a virtually integrated replacement process with customers with regard to AM parts.

5. Discussion

Based on our empirical analysis, we developed five propositions that touch upon the impact of AM technology adoption in customized parts production on SCM processes and SCM components. It becomes apparent that AM may not only have far-reaching implications on manufacturing flow management, but also on supplier relationship management, product development, order fulfillment, demand, customer relationship and customer service management, as well as on returns management. Thus, besides the manufacturing firm, suppliers and customers are also to some degree affected by a switchover to AM.

On the supply side, AM technology adoption seems to increase the need for a close collaboration between material and machine suppliers, because the materials and machines for AM need to be compatible with each other in order to achieve optimal outcomes. This may not only hold true for AM technology usage in customized production, but also in other potential fields of AM application, such as spare parts or lightweight construction. Due to a switchover from manual production to AM, producers have to develop new selection criteria specific to the procurement of AM machines. Longer-term considerations such as strategic production plans thereby need to be included, since a potential transition from single unit to batch production needs to fit in well with the overall production system. Experience in AM seems to be an endogenous contingency factor for the distribution of quality control tasks between manufacturers and AM suppliers. Firms with short-term experience in AM tend to leave more quality control tasks to their suppliers than long-term users of AM technologies. This may be due to new adopters' stronger focus on other AM-affected activities, which cannot easily be transferred, such as tasks in manufacturing flow management. Once the corresponding processes run smoothly, firms have the capacity to redirect their resources to the internalization of previously outsourced tasks. The maturity of the adopted AM technology seems to be another relevant situational factor for explaining the degree to which AM-related quality control measures are transferred to suppliers.

It is possible that the impact of AM technology adoption on SCM processes and components in supplier relationship management will be different for firms, which do not engage in AM themselves, but source customized AM parts from contract manufacturers.

For example, it can be expected that a close interaction between the focal firm's engineers, who develop the 3D models, and the contract manufacturer's production department will be needed in order to quickly realize design changes. However, this topic is not addressed in the present paper as both case companies conduct AM in-house.

The findings with regard to production suggest that a change from manual engineer-to-order production to AM has the potential to increase the division of labor in manufacturing. Scale economies may be generated by bundling 3D modeling competences and by simultaneously producing several customer individual parts in the same production job. AM's ability to economically build custom products provides the potential to alleviate the common dilemma between product variety and scale economies. Thus, unit production could shift to customer individual mass production (see Figure 3). We propose that the smaller the products are and the greater the ability to build entire custom products with AM technologies is, the greater the decline in unit costs and the increase in batch sizes will be when switching from manual production to AM. This linkage is suggested to apply to any producer changing from manual to AM of customized parts, regardless of its experience with AM, the AM technology's maturity or other potential contingency variables. Our research also shows that AM technology adoption may help to improve quality management, including employee training and evaluation. This seems to be particularly relevant in an engineer-to-order environment such as in the production of customized hearing aid shells, jewelry, dental crowns, and implants. A greater product variety and the higher need for manual labor

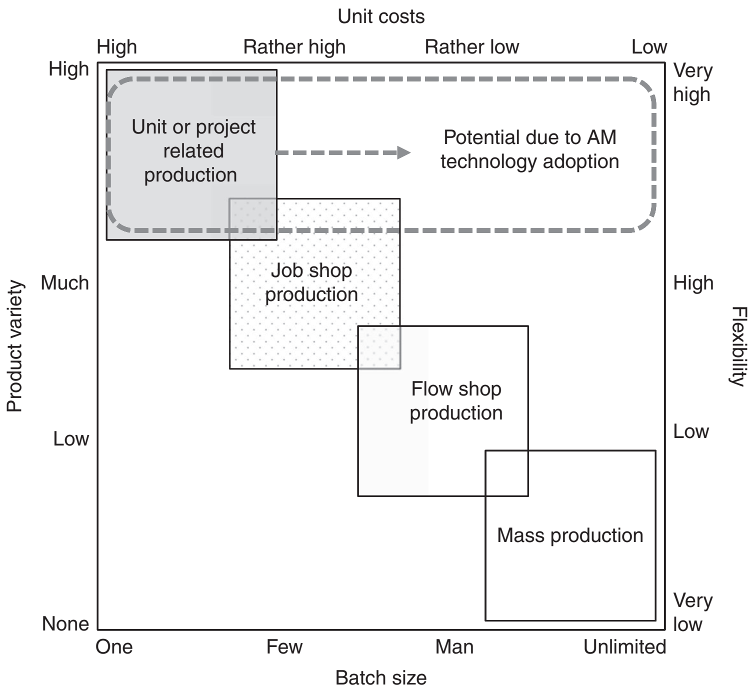

Figure 3.
Potential of AM technology adoption in customized parts production

Sources: Proposed by the authors; adapted from Meredith (1987) and Miltenburg (2005) compared to mass manufacturing make it harder to ensure object replicability and a consistent product quality in such areas.

On the demand-side, AM of custom products may increase the level to which customers are virtually integrated in a manufacturer's supply chain. This can eliminate certain inbound or outbound deliveries and reduce order lead time. Demand forecasting does not seem to be affected by a changeover from manual to AM since the demand in innovative supply chains with a high product variety is typically unpredictable (Fisher *et al.*, 1997). With regard to returns management, AM may not only increase material utilization, but can also speed up replacement processing by replicating custom products based on stored digital representations of the object. The level of virtual integration with customers in ordering and replacement processes seems to be contingent upon a firm's experience with AM. New adopters tend to be less connected with customers via electronic means than long-term users of AM technologies. This phenomenon can be explained by old adopters' higher maturity level with regard to AM-affected processes: firms that have already adjusted their internal processes to the requirements of AM seem to have more available resources for improvement activities with customers.

Overall, our research suggests that AM technology-related factors (e.g. technological maturity) and endogenous factors (e.g. a firm's experience with AM) are relevant groups of contingency variables. They may explain different levels of impact on SCM processes and components resulting from the adoption of AM technologies. In contrast, exogenous factors (e.g. the intensity of competition) and supply chain-related factors (e.g. the geographic span of the supply chain) do not seem to be discriminators. Maybe these factors will become relevant when comparing more diverse cases, e.g. with firms from various industries.

6. Conclusion

Based on two in-depth case studies from the hearing aid industry, this paper analyzed how AM technology adoption in customized parts production impacts SCM processes and SCM components. The findings reveal that not only primarily manufacturing firms' internal affairs (e.g. material flow management) are affected by a changeover to AM, but also SCM processes and SCM components that touch upon the supply and demand side of a firm's supply chain (e.g. supplier and customer relationship management). It is suggested that AM's ability to economically build custom products provides the potential to alleviate the common dilemma between product variety and scale economies. Therefore, thanks to AM, firms that manually produce customized objects may realize a transition from single unit to batch production while at the same time maintaining their flexibility to offer customer individual products. The findings also suggest that AM technology-related factors and endogenous (firm specific) factors are relevant groups of contingency variables. They may help to explain differing effects of AM technology adoption on SCM processes and SCM components.

The contribution of this paper is manifold. From a theoretical perspective, it adds to the widely unexplored field in the literature that studies the effects of AM technology adoption in engineer-to-order supply chains. Moreover, we hope to foster theory-building research in operations management in general, and on the business implications of AM in particular, through the proposed matrix about AM's potential in customized parts production. Practitioners can benefit from a better understanding of the opportunities and challenges resulting from AM technology adoption in engineer-to-order production. Thus, manufacturing firms are encouraged to consider the potential effects of AM on SCM processes and SCM components when deciding about whether to produce industrial AM parts.

The explanatory power of this study is somewhat limited due to the relatively small sample size and the focus on the hearing aid industry. Consequently, the findings cannot easily be generalized. Although the questions posed to the interviewees always emphasized the changes that can directly be attributed to AM technology adoption, it cannot fully be ruled out that other influencing factors (e.g. general improvements in operations) may also have had an impact on the firms' SCM processes and SCM components.

Future research should provide more detailed insights in the SCM implications of AM technology usage in an engineer-to-order environment. The areas of impact identified in the mark of the present paper could provide a starting point for such investigations. Research which further explores the proposed potential of AM to alleviate the common dilemma between scale economies and product variety in customized production would be particularly interesting. Another potential research area could be the procurement of ready-made customized AM parts. From a SCM perspective, especially the interaction between the purchasing firm and the contract manufacturer seems to be worth studying, as it can be suspected that different processes and information flows are needed when sourcing custom AM parts as opposed to manually (or mass) manufactured parts. Furthermore, case studies from other industries that apply AM technologies in engineer-to-order supply chains (e.g. the dental and jewelry sector) would be of value in order to improve generalizability.

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.

Bak, D. (2003), "Rapid prototyping or rapid production? 3D printing processes move industry towards the latter", *Assembly Automation*, Vol. 23 No. 4, pp. 340-345.

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

Bertalanffy, L. (1969), *General System Theory – Foundations, Development, Applications*, Braziller, New York, NY.

Campbell, I., Bourell, D. and Gibson, I. (2012), "Additive manufacturing: rapid prototyping comes of age", *Rapid Prototyping Journal*, Vol. 18 No. 4, pp. 255-258.

Carter, C.R., Rogers, D.S. and Thomas, Y.C. (2015), "Toward the theory of the supply chain", *Journal of Supply Chain Management*, Vol. 51 No. 2, pp. 89-97.

Chamberlin, E.H. (1962), *The Theory of Monopolistic Competition*, Harvard University Press, Cambridge, MA.

Chen, I.J. and Paulraj, A. (2004), "Towards a theory of supply chain management: the constructs and measurements", *Journal of Operations Management*, Vol. 22 No. 2, pp. 119-150.

Christopher, M. (2000), "The agile supply chain: competing in volatile markets", *Industrial Marketing Management*, Vol. 29 No. 1, pp. 37-44.

Cooper, M.C., Lambert, D.M. and Pagh, J.D. (1997), "Supply chain management: more than a new name for logistics", *The International Journal of Logistics Management*, Vol. 8 No. 1, pp. 1-14.

Crain's Chicago Business (2014), "Printers let hearing aid manufacturer automate, yet customize", available at: www.chicagobusiness.com/article/20140322/ISSUE01/303229986/printers-let-hearing-aid-manufacturer-automate-yet-customize (accessed November 8, 2015).

Da Silveira, G., Borenstein, D. and Fogliatto, F.S. (2001), "Mass customization: literature review and research directions", *International Journal of Production Economics*, Vol. 72 No. 1, pp. 1-13.

Donaldson, L. (2001), *The Contingency Theory of Organizations*, Sage Publications, Thousand Oaks, CA.

Ebert, J., Özkol, E., Zeichner, A., Uibel, K., Weiss, Ö., Koops, U., Telle, R. and Fischer, H. (2009), "Direct inkjet printing of dental prostheses made of zirconia", *Journal of Dental Research*, Vol. 88 No. 7, pp. 673-676.

Eisenhardt, K.M. (1989), "Building theory from case study research", *Academy of Management Review*, Vol. 14 No. 4, pp. 532-550.

EOS (2013), "Laser Sintering is replacing traditional processes in dental industry", available at: www.eos.info/press/press_releases/2013_260213 (accessed November 11, 2015).

Fisher, M.L., Day, G.S. and Ryan, W. (1997), "What is the right supply chain for your product?", *Harvard Business Review*, Vol. 75 No. 2, pp. 105-116.

Gebhardt, R. (2014), "Additive manufacturing at the Mechanical Engineering Summit", available at: www.vdma.org/en/article/-/articleview/3836114 (accessed May 27, 2015).

Glasschroeder, J., Prager, E. and Zaeh, M.F. (2015), "Powder-bed-based 3D-printing of function integrated parts", *Rapid Prototyping Journal*, Vol. 21 No. 2, pp. 207-215.

Gosling, J. and Naim, M.M. (2009), "Engineer-to-order supply chain management: a literature review and research agenda", *International Journal of Production Economics*, Vol. 122 No. 2, pp. 741-754.

Hart, C.W.L. (1995), "Mass customization: conceptual underpinnings, opportunities and limits", *International Journal of Service Industry Management*, Vol. 6 No. 2, pp. 36-45.

Hewlett-Packard (2014), "HP multi jet fusion technology – disruptive 3D printing technology for a new era of manufacturing", available at: www8.hp.com/h20195/v2/GetPDF.aspx/4AA4-5472ENW.pdf (accessed December 17, 2015).

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. and Dickens, P. (2001), "Rapid prototyping for direct manufacture", *Rapid Prototyping Journal*, Vol. 7 No. 4, pp. 197-202.

Hopkinson, N. and Dickens, P.M. (2003), "Analysis of rapid manufacturing – using layer manufacturing processes for production", *Proceedings of the Institute of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 217 No. 1, pp. 31-39.

Janaki Ram, G.D., Yang, Y. and Stucker, B.E. (2006), "Effect of process parameters on bond formation during ultrasonic consolidation of aluminum alloy 3003", *Journal of Manufacturing Systems*, Vol. 25 No. 3, pp. 221-238.

Jenkins, S. (2015), "3-D printing accelerates, creating CPI opportunities", Chemical Engineering, February, pp. 20-23.

Kajüter, P. and Kulmala, H.I. (2005), "Open-book accounting in networks – potential achievements and reasons for failures", *Management Accounting Research*, Vol. 16 No. 2, pp. 179-204.

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.

Lambert, D.M. (2014), *Supply Chain Management: Processes, Partnerships, Performance*, 4th ed., Supply Chain Management Institute, Sarasota, FL.

Lambert, D.M. and Cooper, M.C. (2000), "Issues in supply chain management", *Industrial Marketing Management*, Vol. 29 No. 1, pp. 65-83.

Lambert, D.M., Cooper, M.C. and Pagh, J.D. (1998), "Supply chain management: implementation issues and research opportunities", *The International Journal of Logistics Management*, Vol. 9 No. 2, pp. 1-20.

Lee, S.-E., Kunz, G., Fiore, A.M. and Campbell, J.R. (2002), "Acceptance of mass customization of apparel: merchandising issues associated with preference for product, process, and place", *Clothing and Textiles Research Journal*, Vol. 20 No. 3, pp. 138-146.

Mellor, S., Hao, L. and Zhang, D. (2014), "Additive manufacturing: a framework for implementation", *International Journal of Production Economics*, Vol. 149 No. C, pp. 194-201.

Mentzer, J.T., DeWitt, W., Keebler, J.S., Min, S., Nix, N.W., Smith, C.D. and Zacharia, Z.G. (2001), "Defining supply chain management", *Journal of Business Logistics*, Vol. 22 No. 2, pp. 1-25.

Meredith, J. (1987), "The strategic advantages of new manufacturing technologies for small firms", *Strategic Management Journal*, Vol. 8 No. 3, pp. 249-258.

Miltenburg, J. (2005), *Manufacturing Strategy: How to Formulate and Implement a Winning Plan*, Productivity Press, New York, NY.

Murr, L.E., Gaytan, S.M., Ramirez, D.A., Martinez, E., Hernandez, J., Amato, K.N., Shindo, P.W., Medina, F.R. and Wicker, R.B. (2012), "Metal fabrication by additive manufacturing using laser and electron beam melting technologies", *Journal of Materials Science and Technology*, Vol. 28 No. 1, pp. 1-14.

Nyman, H.J. and Sarlin, P. (2014), "From bits to atoms: 3D printing in the context of supply chain strategies", *Proceedings of the Annual Hawaii International Conference on System Sciences, Waikoloa, HI, January 6-9*, pp. 4190-4199.

Oettmeier, K. and Hofmann, E. (2016), "Additive manufacturing technology adoption: an empirical analysis of general and supply chain-related determinants", *Journal of Business Economics*, pp. 1-28, doi: 10.1007/s11573-016-0806-8, available at: http://link.springer.com/article/10.1007/s11573-016-0806-8

Olhager, J. (2003), "Strategic positioning of the order penetration point", *International Journal of Production Economics*, Vol. 85 No. 3, pp. 319-329.

Petrovic, V., Gonzalez, J.V.H., Ferrando, O.J., Gordillo, J.D., Puchades, J.R.B. and Griñan, L.P. (2011), "Additive layered manufacturing: sectors of industrial application shown through case studies", *International Journal of Production Research*, Vol. 49 No. 4, pp. 1061-1079.

Piller, F.T., Moeslein, K. and Stotko, C.M. (2004), "Does mass customization pay? An economic approach to evaluate customer integration", *Production Planning & Control*, Vol. 15 No. 4, pp. 435-444.

Ruffo, M., Tuck, C. and Hague, R. (2006), "Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 220 No. 9*, pp. 1417-1427.

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.

Seawright, J. and Gerring, J. (2008), "Case selection techniques in case study research – a menu of qualitative and quantitative options", *Political Research Quarterly*, Vol. 61 No. 2, pp. 294-308.

Strauss, A.L. and Corbin, J. (1990), *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*, Sage Publications, Newbury Park, CA.

Vinodh, S., Sundararaj, G., Devadasan, S.R., Kuttalingam, D. and Rajanayagam, D. (2009), "Agility through rapid prototyping technology in a manufacturing environment using a 3D printer", *Journal of Manufacturing Technology Management*, Vol. 20 No. 7, pp. 1023-1041.

Walter, M., Holmström, J., Tuomi, J. and Yrjölä, H. (2004), "Rapid manufacturing and its impact on supply chain management", *Proceedings of the Logistics Research Network Annual Conference, Dublin, September 9-10*.

Wohlers Associates (2014), "Production of parts for final products is now 34.7% of the market for additive manufacturing", available at: www.wohlersassociates.com/press68.html (accessed November 11, 2015).

Yin, R.K. (2009), *Case Study Research: Design and Methods*, 4th ed., Sage Publications, Thousand Oaks, CA.

Appendix 1. Extract from the semi-structured interview guide employed during data collection at the focal firms

1. General situation of the firm with regard to AM technologies

- When did your company start to use AM technologies for the production of customized parts?
- How many AM machines does your company currently have in use (for customized parts production)?
- How many different parts does your firm manufacture using AM technologies?

2. Impact of AM technology adoption on supplier relationship management

SCM processes:

- How does your procurement process for in-the-ear hearing aids currently work?
- What did you have to change in your original procurement process (before AM technology adoption) due to the adoption of AM technologies in hearing aid shell production?

SCM components:

- According to which criteria does your company select its suppliers? Have there been any changes to this, which can be traced back to your company's adoption of AM technologies in hearing aid shell production?
- Which measures does your company take to ensure the quality of the procured AM material?

3. Impact of AM technology adoption on manufacturing flow management

SCM processes:

- How does the production of in-the-ear hearing aids currently work?
- What did you have to change in your original production process (before AM technology adoption) due to the adoption of AM technologies in hearing aid shell manufacturing?

SCM components:

- To what extent have your storage and production costs (per piece) changed due to the adoption of AM in hearing aid shell production?
- Which management methods does your company use to ensure quality and process stability in AM?
- To what extent did your company have to buildup new know-how in manufacturing due to the adoption of AM technologies? How did your company tackle this?

Note: The interview questions for the remaining SCM processes (product development and commercialization, order fulfillment, demand, customer relationship and customer service management, as well as returns management) follow the same structure as the questions in parts 2 and 3 of the semi-structured interview guide.

Appendix 2. Case descriptions

Alpha

Alpha is a large Swiss-based multinational hearing systems manufacturer. Alpha started to use AM technologies for the production of customer individual in-the-ear hearing aid shells and ear pieces in 2004. Initially, the company employed the selective laser sintering (SLS) technology before changing to digital light processing (DLP) in 2007. Currently, Alpha's annual production volume of additively manufactured parts exceeds one million units.

Supplier A is a medium-sized US American producer of AM machines, which serves various industries, including the aerospace, architecture, hearing aid, and automotive sector. The AM machines for hearing aid shell manufacturing are produced in Germany. Supplier A pursues a "closed" approach to AM materials. Thus, its AM machines only run on material exclusively supplied by the company. Supplier A closely collaborates with a sub-contractor, who develops and produces the specific material for the AM machines.

Customer A1 is a Swiss-based specialized store for hearing systems and optical products. It belongs to a large multinational company, which operates in the same field and owns over 600 specialized stores across Europe. Customer A1 distributes in-the-ear hearing aids from Alpha as well as from Beta. There are no major differences in the way in which Customer A1 works together with the two manufacturers.

Customer A2 is a small, independent Swiss specialized store, which has been distributing in-the-ear hearing aids from Alpha and other hearing systems manufacturers for over 20 years. Unlike Customer A1, the firm owns a 3D scanner, which was provided by one of its partnering in-the-ear hearing aid producers. Thus, Customer A2 has the ability to digitally transfer its order information (including 3D impression data) to the manufacturer.

Beta

Beta is a German hearing systems manufacturer with manufacturing sites in other European countries and North America. It is part of a medium-sized company from Germany that focuses on hearing aid acoustics and owns several hundred specialized stores worldwide. Beta adopted AM technologies for the production of customer individual in-the-ear hearing aid shells and ear pieces in 2014 using DLP. Beta's annual production volume of additively manufactured hearing aid shells currently exceeds 20,000 units.

Supplier B is a small producer of AM machines for the dental, hearing aid, and jewelry sector. It belongs to a Germany-based medium-sized company focusing on manufacturing systems engineering. The firm pursues an "open" approach to AM materials, which means that its machines can run on materials from different producers. The AM material supplier employed by Beta is still the same acrylic producer who served the company in the past (when the shells were manufactured by hand). However, the material supplier had to adjust its original acrylic to make it compatible with Supplier B's AM machines. Today, there exists a close collaboration between Supplier B and Beta's AM material supplier.

Customer B is an independent firm that specializes in the distribution of hearing systems. The company operates three stores in Austria. It has a long-term business relationship with Beta. Just like Customer A1, Customer B does not own a 3D scanner and has no specific IT-connection with Beta.

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