

3D-PRINTING: HOW ADDITIVE MANUFACTURING IMPACTS SUPPLY CHAIN BUSINESS PROCESSES AND MANAGEMENT COMPONENTS

Katrin Oettmeier*

Erik Hofmann**

*) University of St.Gallen, Chair of Logistics Management, 9000, St. Gallen, Switzerland,
E-mail: katrin.oettmeier@unisg.ch, Tel: +41 71 224 71 34

**) University of St.Gallen, Chair of Logistics Management, 9000, St. Gallen, Switzerland,
E-mail: erik.hofmann@unisg.ch, Tel: +41 71 224 72 95

ABSTRACT

Purpose

The business implications of additive manufacturing (AM) are explored; specific focus thereby lies on the impact of AM technology adoption in customized parts production.

Design/methodology/approach

Based on two explorative case studies from the hearing aid industry, the impact of AM technology adoption on supply chain business processes and management components is analyzed. General systems theory and a supply chain management framework serve as theoretical underpinning.

Findings

Not only primarily manufacturing firms' internal processes and management activities, e.g. in material flow management, are affected by a changeover to AM, but also business processes and management components relating to the supply- and demand-side of a company's supply chain.

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 supply chain processes and management components when deciding about the adoption of AM technologies in the manufacturing of industrial parts.

Original/value

The research adds to the widely unexplored effects that AM technology usage in customized parts production has on supply chain business processes and management components. Moreover, the general lack of case studies analyzing 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: additive manufacturing, 3D-printing, supply chain management, customization, engineer-to-order, business processes, management components

1. INTRODUCTION

Due to increasing competition and heightened customer requirements, there is an increased need for firms to differentiate themselves in order to secure a competitive advantage. The customization of products 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: 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 (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, additional costs compared to mass manufacturing can arise from a loss of scale economies (e.g. due to the need for object-specific tooling), greater complexities in production planning and control, lower capacity utilization rates and a higher need for qualified labor (Piller et al., 2004). AM, commonly known as “3D-printing”, has the potential to change the common dilemma between unit costs and technological flexibility. The building process in AM typically happens “layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM Standard, 2012). Since it does not require object specific tools, the production of small lot sizes – even of lot size 1 – 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 quickly 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 may affect the business processes and management practices in engineer-to-order supply chains. There is however reason to believe that AM may alter the way that such supply chains operate and are managed.

The present paper aims at filling this research gap by exploring the changes in supply chain business processes and management components, which result from two medical product manufacturers’ transition from manual to additive manufacturing of in-the-ear hearing aid shells. The hearing systems industry is well suited for case studies on AM applications in customized production, because there is a high need for individual products, which provide an optimal fit to the customer and ensure wearing comfort. Moreover, this is currently one of the fields (besides 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 10 million custom hearing aid shells have been produced worldwide using AM technologies (Crain’s Chicago Business, 2014).

This paper aims to answer the following research questions:

- RQ1: How does AM technology adoption in customized parts production impact supply chain business processes?
- RQ2: How does AM technology adoption in customized parts production impact supply chain management components?

Two explorative case studies from the hearing aid sector shall help to address these questions. General systems theory (Bertalanffy, 1969) serves as the 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. In order to yield a supply chain 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 paper builds upon the supply chain management (SCM) understanding outlined by the Global Supply Chain Forum, according to which SCM is defined as “[...] *the integration of key business processes from end user through original suppliers that provides products, services, and information that add value for customers and other stakeholders*” (Cooper et al., 1997, p. 2). Moreover, the SCM framework presented by Lambert et al. (1998) is used to structure the examinations on the effects of AM technology adoption on supply chain business processes and management components. The terms “customized”, “custom”, and “customer individual” products are used interchangeably to describe products which are tailored to individual customer needs.

2. LITERATURE REVIEW

This section presents condensed findings of previous literature on additive manufacturing (AM) and its implications on supply chain management (SCM). The literature review culminates in the identification of research gaps, which lie at the heart of our study.

2.1. Additive manufacturing

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). Compared to other, more “traditional” manufacturing technologies such as milling and injection molding, AM technologies may offer distinct advantages (Berman, 2012; Holmström et al., 2010; Khajavi et al., 2014; Walter et al., 2004): since no object-specific tools are needed in AM, the manufacturing costs may be reduced, especially when producing small batches. This can render AM economically feasible for the production of customer individual parts. Furthermore, design changes can quickly be realized in AM since the tooling requirement is eliminated and the underlying CAD-files are easily adjusted. Material usage during parts manufacturing might also be reduced because – apart from potential support structures – material is only applied where it is needed to build the desired object. AM technologies also offer an increased freedom of design: even complex geometries can be realized, which would not be possible otherwise. Moreover, AM technologies are suitable for the creation of lightweight objects, because grids or even hollow structures may be produced. 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.

Current limitations of AM technologies include the restricted choice of materials and finishes, the lower level of precision compared to other manufacturing technologies as well as higher costs and a lower speed in the large-scale production of standardized products (Berman, 2012). However, AM machine vendors are actively addressing these issues. Thus, with ongoing technological advances, these limitations may become less relevant in the future.

2.2. Additive manufacturing in the context of SCM

Although AM is per se not a new topic, it is still widely unexplored from a research perspective. Current research on AM can broadly be classified into six different research streams: (1) 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), (2) engineering-focused studies, which aim to develop new or improve existing materials or technologies for AM (e.g. Murr et al., 2012), (3) studies analyzing the adoption of AM technologies (e.g. Oettmeier and Hofmann, 2016), (4) research examining the costs of AM (e.g. Hopkinson and Dickens, 2003; Ruffo et al., 2006), (5) studies on the implementation of AM and make-or-buy decisions (Mellor et al., 2014; Ruffo et al., 2007), and (6) research addressing AM in the context of SCM (e.g. Holmström et al., 2010; Khajavi et al., 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 take place 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 for simpler (shorter and narrower) supply chains. This is probably because AM technologies provide the opportunity to integrate more functionality into products and to optimize products for function (Holmström et al. 2010), 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 additively manufactured 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 configuration of supply chains, but also on business processes and management components employed by 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 also evoke changes in process planning and product design as well as in quality control and the required workforce skills. Although the identified elements help to localize potential areas of impact of AM technology adoption on processes and management practices, there is still 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 supply chain business processes and management 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 business processes and management components have been rather neglected. Moreover, the implications of AM technology adoption on SCM have only been pointed out generically, but have not been discussed in a differentiated way.

2.3. Résumé of the literature review and research gaps

The review of the literature has shown 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: (1) Although different studies

mention potential benefits of AM (e.g. Berman, 2012; Holmström et al., 2010), which may have an effect on SCM, the impact of AM technology usage in customized parts production on supply chain business processes and management components has never analyzed in a systematic way. Moreover, (2) there seems to be a general lack of case studies, which explore the implications of AM technology adoption from a supply chain perspective. By analyzing how AM technology adoption in customized parts production impacts supply chain business processes and management components, this paper aims to fill these gaps in research.

3. METHODOLOGY

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

3.1. Study design and conceptual framework

As our research questions focus on the impact of AM technology adoption on supply chain business processes and management components, we take a network perspective as our level of analysis. The scope of the analyzed supply chain encompasses the triadic network formed by the focal firm (hearing aid manufacturer), its direct suppliers (material or AM machine suppliers) and customers (acousticians). Interviews were not only collected from key informants of the hearing-aid manufacturers' production, logistics or R&D departments, but also from 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 5 hours and were all carried out by the same research team. The interviews covered the topics laid down in a semi-structured interview guide, which was based on the elements of supply chain business processes and management components outlined by Cooper et al. (1997).

To explore the impact of AM technology usage on supply chain business processes and management components, we analyze how these two SCM elements have changed due to AM technology adoption (see Figure 3.1). Following the understanding of Cooper et al. (1997, p. 5), we define supply chain business processes as "activities that produce a specific output of value to the customer." We distinguish between 5 types of such processes: (1) order fulfillment, demand, customer relationship and service management, (2) manufacturing flow management, (3) procurement, (4) product development and commercialization, and (5) returns. The SCM components are specified as "the components by which the business processes are structured and managed" (Cooper et al., 1997, p. 5). 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.

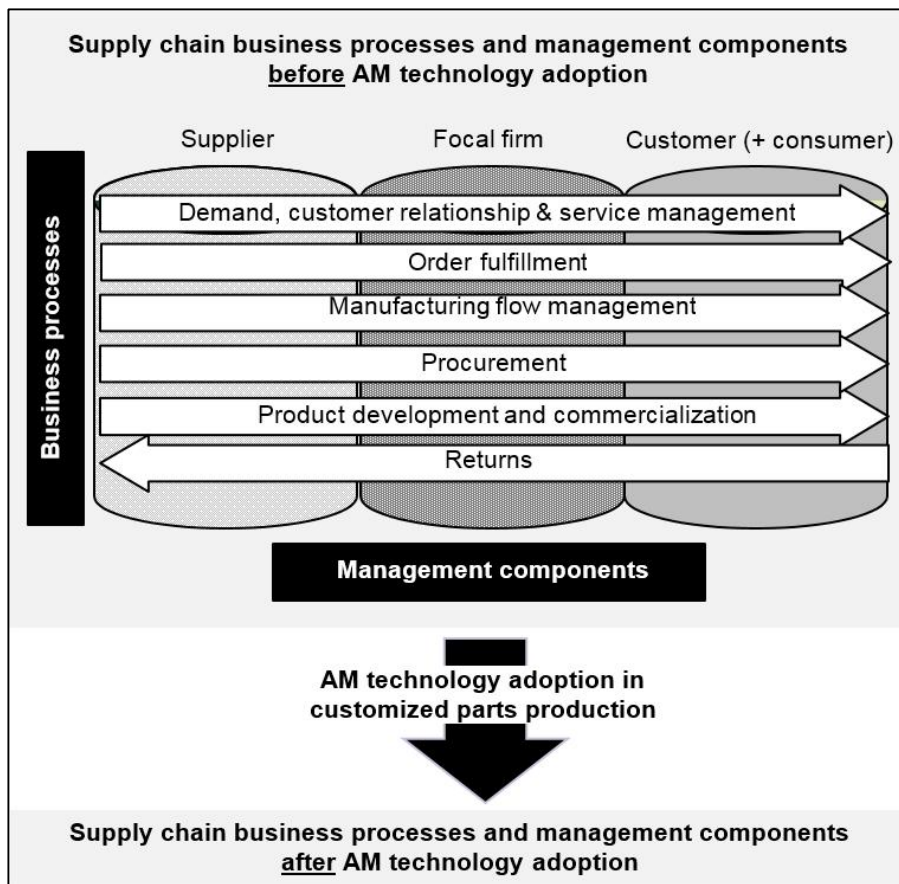


Figure 3.1 Conceptual framework of this study (based on the SCM framework by Cooper et al. (1997))

3.2. Case selection and sampling

Our study examines the impact of AM technology adoption in customized parts production on supply chain business processes and management components. To analyze these aspects, we chose firms, which (1) currently use AM technologies to build customized parts and (2) 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 customized products in order to guarantee the best possible accuracy of fit to the customer. In-the-ear hearing aids consist of shells, which are shaped according to the individual consumer's ear canal. Typically, acousticians take silicone ear impressions from consumers, which then depict the basis for (manual or additive) shell manufacturing. Apart from the shell, in-the-ear hearing aids contain a kit with electronics (e.g. battery, volume control, microphone, and buttons for selecting between different programs). It is a standard part that can be adapted to specific customer needs if necessary. The electronics are usually mass produced using traditional manufacturing technologies, whereas the integration of the kit into the shell is mostly a manual process. The hearing systems industry 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 10 years. It is assumed that the full scale of changes in supply chain business processes and management components due to AM technology adoption can best be studied in such an industry, where AM is an established technology, as opposed to sectors, which are currently undergoing the transition towards AM. Before their switchover to AM, both case firms engaged in “manual manufacturing”, meaning that hearing aid shells were handcrafted. The high share of manual labor is typical for the hearing systems industry, because the small size of the final products with dozens of tiny components and complex geometries requires a great level of precision in manufacturing, which cannot be easily automated. We suspect 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 3.1. Greek letters replace the company names as we promised anonymity to the interviewees.

Table 3.1 Case 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 A1 (is a customer of both, Alpha and Beta)]	3

In line with Eisenhardt (1989) and 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 customized in-the-ear hearing aid shells). Large firms were selected because we suspected that the impact of AM technology adoption on supply chain business processes and management components will be more visible here than in small

companies, as more efforts need to be taken to integrate the technology into 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 business processes and management 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.

3.3. Data analysis

We followed the qualitative data analysis approach by Strauss and Corbin (1990), as our collected data was rich in information but unstructured. First we conducted a within-case analysis to understand the supply chain business processes and management components used by the firms and the way in which AM technology adoption impacted these. We 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 to spot common patterns among the cases. Finally, we chose those business processes and management components, which were particularly affected from AM technology adoption and promised to be most interesting for future research.

4. RESULTS

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

4.1. Procurement

With the adoption of AM technologies in the production of hearing aid shells, Alpha (fictitious company name) had to change its supplier base and purchasing process. While in the past, the liquid acrylic for shell manufacturing was sourced from local suppliers in a decentralized way, the firm now centrally procures the acrylic via the machine manufacturer. The material is specifically tuned to the AM machines to ensure optimal product quality. Therefore, the machine manufacturer works closely together with a material supplier, who exclusively produces the acrylic for the AM machines. This “closed system” creates a lock-in effect for Alpha as the company cannot easily qualify another material supplier. Apart from setting up a centralized system for the procurement of AM materials and processes, the firm also increased standardization: *“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 in-the-ear hearing aid shell production].”* This was due to a greater need to gain control over product quality as the AM machines are not only very sensitive to different parameter configurations, but also to material properties. Consequently, the acrylic procured for AM is the same for all plants worldwide and a centralized incoming goods inspection for machines and materials was implemented. Moreover, Alpha’s purchasing department now has to pursue 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 5 years.”*

With its transition to AM, Beta (fictitious company name) also had to include a machine supplier into its supply chain. However, the company did not need to change its material supplier as the acrylic producer offers material that is compatible with Beta's AM machine. The hearing systems firm chose an "open system", according to which the machine supplier does not oblige manufacturers to obtain their AM materials from a single source. Beta also had to develop new criteria for supplier selection: *"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 production of customized hearing aid shells, because lot sizes were always one, regardless of which material was used. Beta's remaining criteria for supplier selection remained unchanged: The firm has always placed great emphasis on service quality and the technological reliability or availability of procured machines. However, in the past, the latter criteria did not apply to the purchasing activities for shell manufacturing as no machines were used in hearing aid shell production. Overall, it is proposed that:

Proposition 1a (business processes): Considerations concerning strategic production planning and potential lock-in effects are more relevant in the selection of suppliers for AM than for manual manufacturing.

Proposition 1b (management components): The transition from manual to additive manufacturing of custom products requires the buildup of specific know-how in procurement about the characteristics of AM machines and compatible raw materials.

4.2. Manufacturing flow management

Before changing to the usage of additive technologies in hearing aid shell manufacturing, Alpha and Beta engaged in manual shell production. The production processes before and after this transition are similar for both firms and are summarized in Figure 4.1.

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. Moreover, the division of labor in manufacturing has increased since AM technology usage. 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 much more experienced and gets them to fulfill their tasks at a hundred percent."* From a management perspective, the transition to AM helped the firms 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, so that in the end, the finger can reach the device [...] In the past, this was harder or actually not possible. Previously, you did not really know what was*

done there – it was just done.” Alpha’s order lead time of 5 days (inbound delivery of the impression: 1 day, hearing aid production: 3 days, outbound delivery of the final product: 1 day) has not decreased substantially due to the transition from manual production to AM. However, changing from single unit to batch production of shells greatly improved process reliability. Thus, the firm’s aim of manufacturing its products within 3 days was increased from only 50% (with manual production) to 80% (with AM).

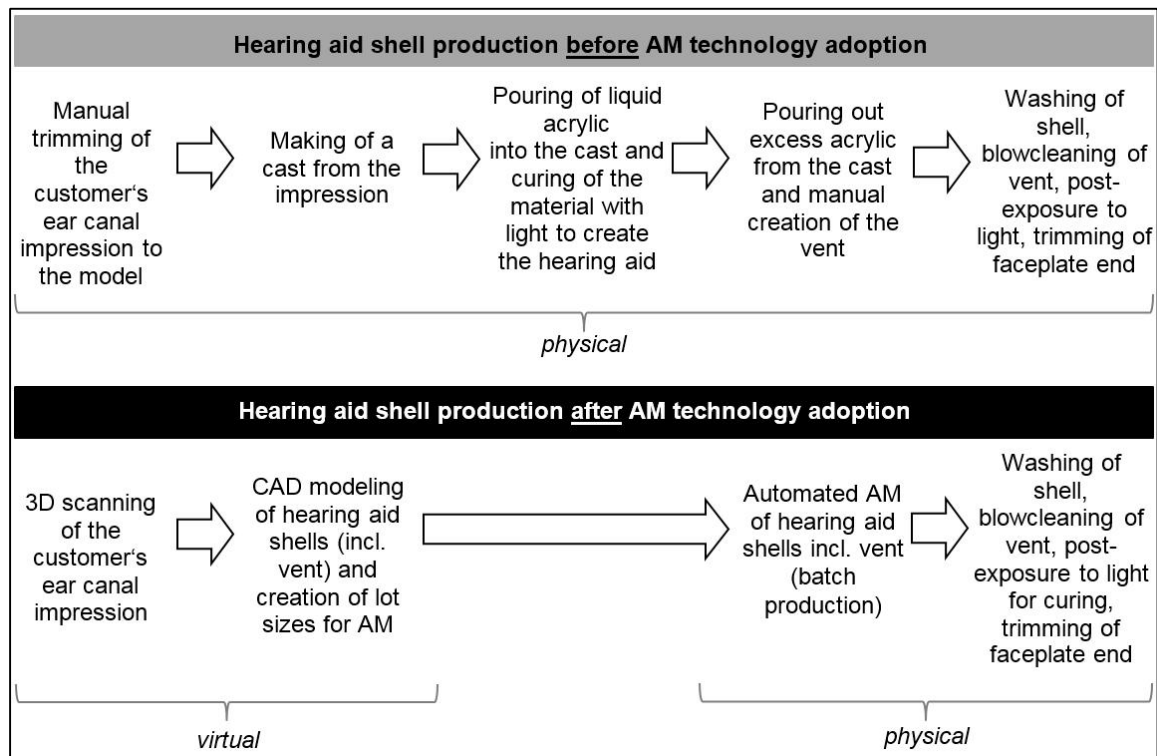


Figure 4.1 Hearing aid shell production before and after AM technology adoption

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, the firm not only needed to include a 3D modeling process in their supply chain, but also had the opportunity to bundle its modeling competences and differentiate between product design (i.e. modeling) and manufacturing. For example, the digital blueprints for the 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.

Proposition 2a (business processes): The adoption of AM technologies in customized production increases industrialization of manufacturing. Scale economies can be generated in product modeling (e.g. due to a bundling of design authority) and through batch production.

Proposition 2b (management components): AM offers greater quality management and employee training possibilities than manual manufacturing. 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

The adoption of AM technologies also has implications on product development and commercialization. The informant at Alpha notes that due to their switchover to AM, there are less barriers to what can physically be realized. For example, thanks to AM technologies, the hearing aid shells have a smaller and better controllable thickness, which allows engineers to integrate more functionality into the shell. 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. Alpha's switchover to AM did not evoke any substantial improvements in the overall time-to-market. 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 AM.

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. The firm also managed to decrease its time-to-market due to AM technology adoption, although only to a small extent. New product developments at Beta typically take 2 years – a duration, which seems to be hard to shorten. According to Beta's R&D manager, the most important advantage of using AM technologies in prototyping is the higher level of product security, which could be achieved. Instead of developing products that do not function as desired, errors can be detected early in the process. Thus, although product development has hardly accelerated in terms of duration, it has become more cost efficient. The informant also notes that due to 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 above analysis indicates how the usage of AM technologies in prototyping may impact processes and management activities in product development. However, a clear distinction should be made between the effects in 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 seized the opportunities of rapid prototyping to speed up development processes. However, a transition to AM in industrial parts manufacturing does not necessarily imply that firms will also engage in rapid prototyping, although in practice this often seems to be the case. Overall, the analysis shows that despite an increased freedom of design and corresponding employee training needs, the impact that AM technology adoption in customized production has on product development and commercialization, is rather small. Greater effects in this area can be found when AM technologies are also used for rapid prototyping. Overall, it is proposed that:

Proposition 3a (business processes): AM technology adoption fosters the development of new or improved products by providing detailed input data about the manufacturing process.

Proposition 3b (management components): The buildup of new know-how in R&D is required to seize the greater freedom of design enabled by AM technology adoption.

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

Due to the transition to AM of hearing aid shells, Alpha is driving for a stronger digitization in its relationship to the customers (acousticians), particularly in order fulfillment. The company already has a process with around 2 % 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 of the impression is omitted and the production process can begin quickly. For the remaining customers, the firm still receives the impression and conducts the scanning process itself. The interviewee from Alpha notes that thanks to AM technology usage, the firm's customers could benefit from a constant order lead time, a greater fitting accuracy as well as a smaller size of the in-the-ear hearing aids.

Since AM of hearing aid shells is still rather new for Beta, the firm has not started to use 3D scanning with its customers yet. However, the firm has already introduced a process where the physical impressions received from affiliate stores are all scanned, even if they are destined for other hearing systems manufacturers. The third party manufacturers thus do not receive any physical shipment with impressions but only the 3D data along with the order information.

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 strengthen the relationship with customers. The case studies do not show any impact of AM technology adoption on demand forecasting. 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." These findings culminate in the following propositions:

Proposition 4a (business processes): Demand forecasting remains unchanged when switching from manual to additive manufacturing of custom products, whereas order lead time is reduced.

Proposition 4b (management components): AM technology adoption in customized parts production leads to a tighter integration of customers into the value creation process (especially virtually by using electronic means).

4.5. Returns

Since AM allows for a greater precision than the traditional shell manufacturing process, the thickness of the shells can be decreased and the amount of unnecessarily cured acrylic during the building process is minimized. According to Beta, the material utilization rate has increased to around 98% while overall 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.

Furthermore, the informants from Alpha and Beta note that due to their transition to AM, complaint processing is accelerated and object replicability greatly improved. This can be traced back to the automated production process and the fact that the firms have established a database where they keep 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). Based on our findings in the field of returns, we propose the following:

Proposition 5a (business processes): The adoption of AM technologies in customized parts production speeds up complaint processing and increases material utilization compared to manual engineer-to-order production.

Proposition 5b (management components): Firms can only benefit from accelerated complaint processing due to AM technology adoption, when IT systems are in place for storing the 3d model data.

5. DISCUSSION

Based on our empirical analysis, we developed five propositions which touch upon the impact of AM technology adoption in customized parts production on supply chain business processes and management components. It becomes apparent that AM may not only have far-reaching implications on manufacturing flow management, but also on procurement, product development, order fulfillment, demand, customer relationship and service management, as well as on returns.

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 customized 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 5.1). 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 when switching from manual production to AM.

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 customer individual hearing aid shells, jewelry, dental crowns and implants. Differing customer requirements per product and the higher need for manual labor compared to mass manufacturing make it harder to ensure object replicability and a consistent product quality.

On the supply-side, AM technology adoption seems to increase the need for collaboration between material and machine suppliers, because AM materials and machines have to be compatible with each other to yield quality products. This may not only hold true for customized parts manufacturing, but also for other potential fields of AM application, such as spare parts or lightweight construction. Furthermore, manufacturing firms may have to extend their supplier selection criteria by longer-term considerations such as strategic production plans, since a potential transition from single unit to batch production needs to fit the overall production system. It can be argued that the need to acquire new know-how in procurement concerning AM machines and materials generally depicts the “price” of switching from manual to automated production. However, this does not seem to be completely accurate for AM: while materials for traditional manufacturing processes (e.g. metal blocks for milling or drilling) can typically be used in both, manual and automated production, the materials for AM are often specifically developed for AM machines. Thus, the materials here are usually different from those employed in manual manufacturing.

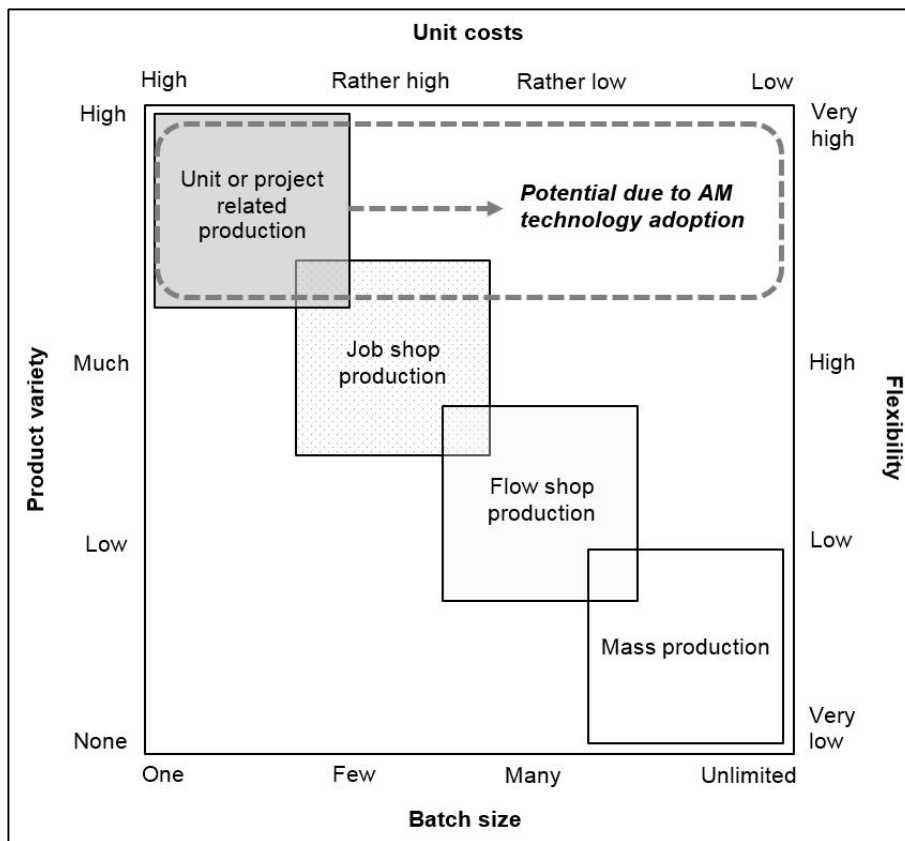


Figure 5.1 Potential of AM technology adoption in customized parts production (proposed by the authors) (based on Fisher (1997), Meredith (1987) and Miltenburg (2005))

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 additive manufacturing because the demand in innovative supply chains with a high product variety is typically unpredictable (Fisher, 1997). With regard to returns, AM may not only increase material utilization, but can also speed up claims processing by replicating parts based on digital representations of the object.

6. CONCLUSION

Based on two in-depth case studies from the hearing systems industry, this paper analyzed how AM technology adoption in customized parts production impacts supply chain business processes and management components. The findings reveal that not only primarily manufacturing firm-internal affairs (e.g. material flow management) are affected by a changeover to AM, but also business processes and management components that touch upon the supply- and demand-side of a firm's supply chain (e.g. procurement 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 engage in the traditional production of customized objects may realize a transition from single unit to batch production while at the same time maintaining their flexibility to offer customized products.

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 that AM technology usage may bring in customized parts production. Manufacturing firms are encouraged to consider the potential effects of AM on supply chain processes and management components when deciding about the adoption of AM technologies in the manufacturing of industrial parts.

The explanatory power of this study is somewhat limited due to the relatively small sample size and the focus on the hearing systems industry. Consequently, the findings cannot easily be generalized. Although the questions posed to the interviewees always emphasized on 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' supply chain business processes and management components.

Future research should provide more detailed insights in the supply chain 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. Especially research which further investigates the proposed potential of AM to alleviate the common dilemma between scale economies and product variety would be interesting. Moreover, 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.

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