

IMPACT OF ADDITIVE MANUFACTURING TECHNOLOGY ADOPTION ON SUPPLY CHAIN NETWORK STRUCTURES – AN EXPLORATORY CASE STUDY ANALYSIS

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Abstract

Purpose: This paper demonstrates that additive manufacturing (AM), as a technological driver, has the potential to change the structural composition of entire supply chains. The research comprises a first, systematic analysis about the impact of AM on the network structures in engineer-to-order supply chains.

Research Approach: The paper pursues an inductive research approach. Building on contingency theory as well as on general systems theory, and using extensive case studies from the medical industry, the implications of AM technology adoption on supply chain configurations are explored. The scope of the supply chains considered during the empirical analysis encompasses suppliers (i.e. material or machine suppliers), the focal firms (i.e. medical device manufacturers), and their customers (i.e. business customers and consumers). The qualitative investigations focus on the potential effects on the composition of the supply chain members, the structural dimensions of the network, as well as the different types of business process links across the supply chain. Contingency variables are identified, which constitute the context of supply chain configuration.

Findings and Originality: The findings underpin that AM can be regarded as a technological driver for SCM. It is shown how AM technology adoption in engineer-to-order production may impact the network structure of supply chains. Not only the composition of the supply chain members and the structural dimensions of the network are likely to be altered due to AM technology usage, but also the types of business process links among the different agents. The research suggests that the effects of AM on supply chain configuration are context-dependent, with endogenous and supply chain-related factors being relevant groups of contingency factors.

Research Impact: The study provides novel insights in the supply chain implications of AM, a still widely unexplored research field. It constructs a conceptual framework, which visualizes different context-dependent deployment alternatives for AM in engineer-to-order supply chains.

Practical Impact: The findings could influence managerial decision-making concerning new manufacturing processes. Companies should be aware that switching to AM may create a need to reconsider the design and the firm's positioning within the supply chain.

Keywords: additive manufacturing, 3D printing, direct digital manufacturing, supply chain configuration, supply chain network structures, engineer-to-order supply chains

Introduction

The demand for additively manufactured parts is constantly growing. According to a survey conducted by Gartner among 330 organizations, 50% of the firms in the consumer and heavy industry will use additive manufacturing (AM) technologies by 2018 (Bathia, 2014). Apart from prototyping, product development and product innovation (i.e. the creation of objects which can only be realized through AM), the development of customized parts is one of the most important application areas of AM technologies (Bathia, 2014). The relevance of AM in customized, engineer-to-order (ETO) production may be explained by the technologies' ability to manufacture parts without object-specific moulds or tools, which can make the production of small quantities – down to single objects – economically feasible (Holmström et al., 2010). This is due to the additive building process, whereby material is accumulated layer-by-layer (Bateman and Chen, 2006).

Several studies have already shown potential supply chain implications of AM technology usage. However, there is still a lack of research, which systematically examines the effects of AM technology adoption on supply chain configurations. Especially the impact of AM on network structures in engineer-to-order supply chains has rather been neglected by researchers. The present paper aims to fill these gaps in the literature by answering the following research question:

How does the adoption of AM technologies in customized production affect supply chain network structures, specifically with regard to (a) the members of the supply chain (b) the structural dimensions of the supply chain, and (c) the types of business process links among supply chain members?

Three exploratory case studies from the medical industry are used to address this question. The medical sector (e.g. hearing systems and dental industry) is well-suited for analyses on the effects of AM since AM technologies are already widely used here in engineer-to-order production. Contingency theory (Donaldson, 2001) and general systems theory (Bertalanffy, 1969) depict the theoretical foundation of the examinations.

Literature Review

In AM, products are built “layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM Standard, 2012). Specific advantages of AM compared to conventional manufacturing technologies include (Petrovic et al., 2011):

- Reduced time-to-market
- Possibility to customize products
- High flexibility in the design and construction of products
- Removal of the requirement for specific tools, punches or moulds
- High material saving potential

Due to the specific characteristics of AM, several studies claim that the adoption of AM technologies in industrial production may affect supply chain structures. Supply chain network structures can thereby be understood as the way how (1) the composition of the supply chain members, (2) the structural dimensions of the network as well as the different types of business process links across the supply chain are configured (Lambert, 2014). The structural dimensions of the network comprise the supply chain's horizontal structure (number of tiers), its vertical structure (number of customers or suppliers per tier) as well as a firm's horizontal position within the network (proximity to the initial source of supply or the final customer) (Lambert, 2014).

The large part of AM literature focuses on the spare parts sector (e.g. Holmström et al., 2010; Liu et al., 2014; Khajavi et al., 2014, Walter et al., 2004). For example, Holmström et al. (2010) and Khajavi

et al. (2014) note that AM technology deployment in spare parts supply chains may foster a decentralized, on-demand production of spare parts. In this way, the performance of such supply chains can be improved (Khajavi et al., 2014).

Oettmeier and Hofmann (2016a) analyze the influence of AM technology adoption in engineer-to-order production on SCM processes and SCM components. Their research, however, does not address AM technologies' impact on the configuration of supply chains. On a more general level, Mellor et al. (2014) develop a framework for AM implementation, which also includes a supply chain perspective. It suggests that AM system machine and material vendors, customers as well as the manufacturing location should also be considered during the AM implementation process (Mellor et al., 2014). However, the study does not provide any detailed insights in the way how supply chain structures are affected by AM technology usage.

Research by Oettmeier and Hofmann (2016b) indicates that adopters of AM technologies distinguish themselves from non-adopters by perceiving a greater potential in the decentralized production of customized parts. Moreover, AM users tend to be more convinced that a changeover to AM reduces the number of suppliers as well as the demand for transport services (Oettmeier and Hofmann, 2016b). This implies that a switchover to AM may provoke changes in the vertical and horizontal structure of a manufacturer's supply chain as well as in the firm's position within the supply chain. Nevertheless, the magnitude and exact specification of these possible effects remains largely unclear.

Overall, the analysis of the literature reveals the following research gaps: (1) in general, a systematic analysis of the effects of AM technology adoption on supply chain configurations is still missing, and (2) more specifically, the implications of AM technology usage on network structures in engineer-to-order supply chains have not yet been studied. By investigating the impact on supply chain configuration evoked by AM technology adoption in engineer-to-order production, this paper wants to address these research gaps.

Methodology

This paper pursues an inductive research approach. Since the analyzed phenomenon is relatively new, the case study method as described by Eisenhardt (1989) and Yin (2009) is employed.

Conceptual framework

Contingency theory (Donaldson, 2001) and general systems theory (Bertalanffy, 1969) serve as theoretical foundations for the investigations. The analyzed system thereby encompasses the supply chain with its different nodes (suppliers, focal firms, customers) and links. A contingency approach is employed as it is suspected that situational factors (e.g. exogenous, endogenous or supply chain-specific factors) moderate the relationship between AM technology usage and supply chain configuration. The primary structural aspects of supply chains outlined by Lambert (2014) are used to guide the investigations. The conceptual model of the present research is shown in Figure 1.

Case selection and data analysis

Three case studies from the medical industry (two from the hearing systems sector, one from the dental sector) are used to explore the effects of AM technology adoption on supply chain configurations in an engineer-to-order environment. The scope of the supply chains considered during the empirical analysis encompasses suppliers (i.e. material or machine suppliers), the focal firms (i.e. medical device manufacturers), and their customers (i.e. business customers as well as

consumers). Ten semi-structured interviews with informants from the case firms, their suppliers or customers were conducted. The interviews were transcribed and coded. All case firms use AM technologies in engineer-to-order production and previously engaged in manual manufacturing. To guarantee anonymity to the case firms, the company names are substituted by greek letters. Alpha and Beta both use AM for the production of customized hearing aid shells (AM technology: digital light processing), whereas Gamma produces removable partial dentures from metal powder (AM technology: selective laser melting).

First, a within-case analysis was conducted. Thereby, the supply chain configuration before and after the transition from manual production to AM were examined separately for each case company. Thereafter, a cross-case analysis followed, which detected common patterns and deviances between the different cases. It also served as a starting point for studying the role of contingency variables for explaining varying levels of impact on supply chain structures resulting from the switchover to AM.

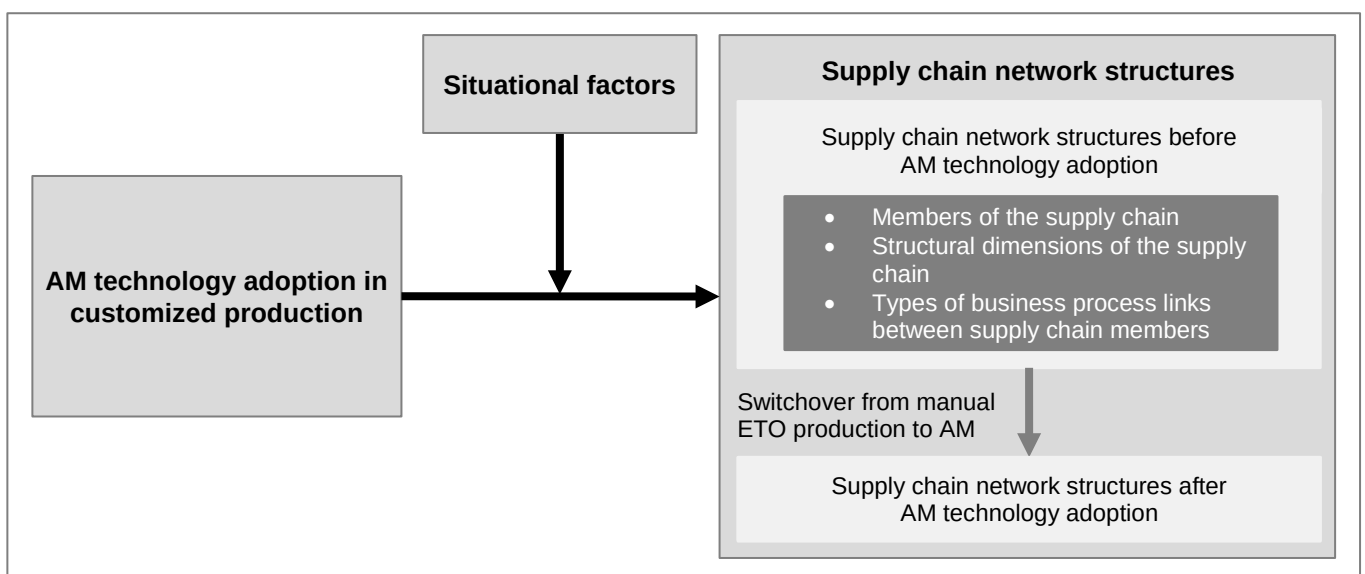


Figure 1: Conceptual framework
(based on Lambert (2014) as well as Oettmeier and Hofmann (2016a))

Results

In the following, the outcomes from the empirical analysis are presented. Thereby, it is distinguished between the different structural aspects of supply chains as outlined by Lambert (2014).

Members of the supply chain

When switching from manual production to AM, all three case firms had to integrate new suppliers into their network: the AM machine vendors. Moreover, Alpha's and Gamma's traditional material suppliers were substituted by specific AM material suppliers. Beta only had to change a part of its material supplier base since one of its existing material manufacturers also offered compatible materials for Beta's AM machine. With their switchover to AM, all case companies experienced a reduction in their material supplier base as only few material producers offer suitable materials for AM machines. This also provoked a geographic expansion of the networks structures on the supply-side: while materials were originally sourced from regional or supra-regional suppliers, the case firms now receive their materials from suppliers acting at an international or global scale.

Alpha and Beta did not experience any changes in their customer base (acousticians) when switching from manual production to AM. This may be due to the firms' strong presence on international markets. In contrast to that, Gamma quintupled its overall number of customers (especially dental laboratories) due to AM, but also lost some of its former clients. While previously producing removable partial dentures exclusively to local customers, Gamma now has customers nationwide (and also few international customers). The following proposition is suggested:

Proposition 1: A switchover from manual to additive manufacturing of engineer-to-order products is associated with a full or partial substitution of the material supplier base and the integration of new supply chain members, i.e. AM machine vendors. Producers whose existing suppliers offer AM materials are less likely to substitute the suppliers. Small firms serving local or regional markets tend to experience greater changes in their customer base due to a transition to AM than large firms with an international distribution network.

Structural dimensions of the supply chain

On the supplier side, the horizontal supply chain of all case firms increased in length. This was due to the inclusion of AM machine vendors into the network. Moreover, a 3D modeling process, which precedes production, had to be included in the supply chain. Originally, the customized products were manufactured through casting processes based on physical impressions (e.g. ear or dental impressions). With the switchover to AM, 3D model data of the product depicts the foundation for manufacturing. In the case of Alpha and Beta, the modeling process is conducted in-house whereas Gamma mostly receives ready-made 3D designs from its customers.

The vertical supply chain structures of the case firms changed with the adoption of AM technologies in several ways:

- at the stage of material producers, the supply chains narrowed,
- at the stage of the focal firms, the supply chain narrowed with regard to the number of production plants in the case of Alpha (which used to have many production plants) and remained unchanged for Beta and Gamma (which only have one or few production plants),
- at the stage of customers and consumers, the supply chain widened in the case of Gamma but it remained unchanged for Alpha and Beta.

The case studies also suggest that the horizontal position of the manufacturing firm tends to shift further downstream in the supply chain due to AM technology usage.

Proposition 2: A switchover from manual to additive manufacturing of engineer-to-order products is associated with longer and narrower upstream supply chains as well as shorter and wider downstream supply chains. Moreover, the horizontal position of the producer tends to shift further downstream upon adoption of AM technologies. Firms which receive 3D modeling data for AM from customers tend to have shorter and wider downstream supply chains than firms which conduct the modeling in-house.

Types of business process links between supply chain members

The switchover from manual engineer-to-order production to AM also had effects on the way how the members of the analyzed firms interact with each other. While in the past, the three producers predominantly maintained non-managed business process links with their material suppliers, they now seem to be more active in integrating and managing the business process linkages with the AM material suppliers. This especially applies to Alpha, which is the largest company in the sample. Moreover, the AM material and machine suppliers tend to work closely with

each other, e.g. when it comes to the development of new AM materials. Thus, they maintain managed business process linkages. With the adoption of AM technologies, the producers have developed relatively close relationships with the AM machine suppliers – even tighter than with the material suppliers. This may be attributed to the fact that most of the analyzed AM technology vendors pursue a closed-system approach with regard to AM raw materials (i.e. only certified materials can be used for running the AM machines). Therefore, the focal firms' communication with the AM material suppliers often occurs via the machine vendor.

On the demand-side, the switchover to AM seems to foster the development of managed business process links between the focal firms and their customers. For example, most of Gamma's customers design the 3D-models for AM themselves and upload the files on the firm's data server. Customers which do not conduct the modeling themselves typically upload 3D scanning data of the dental impressions on the server. Alpha has also taken steps towards a closer IT integration of its customers: a small share of the acousticians digitally transfers 3D impression data to the firm, thus omitting physical inbound deliveries. The business process linkages between the case companies' customers (here: acousticians, dental laboratories or dentists) and consumers do not seem to be affected by the transition to AM. An exemplary, graphical representation of the results is presented in Figure 2.

Proposition 3: A switchover from manual to additive manufacturing of engineer-to-order products is associated with a higher number of managed business process links on the supply- and demand-side of a manufacturing firm's supply chain. Large firms are more likely to have managed business process links with their AM machine and material suppliers than small firms. The ability of customers to conduct 3D modeling for AM is positively associated with the occurrence of managed business process links between AM producers and their customers.

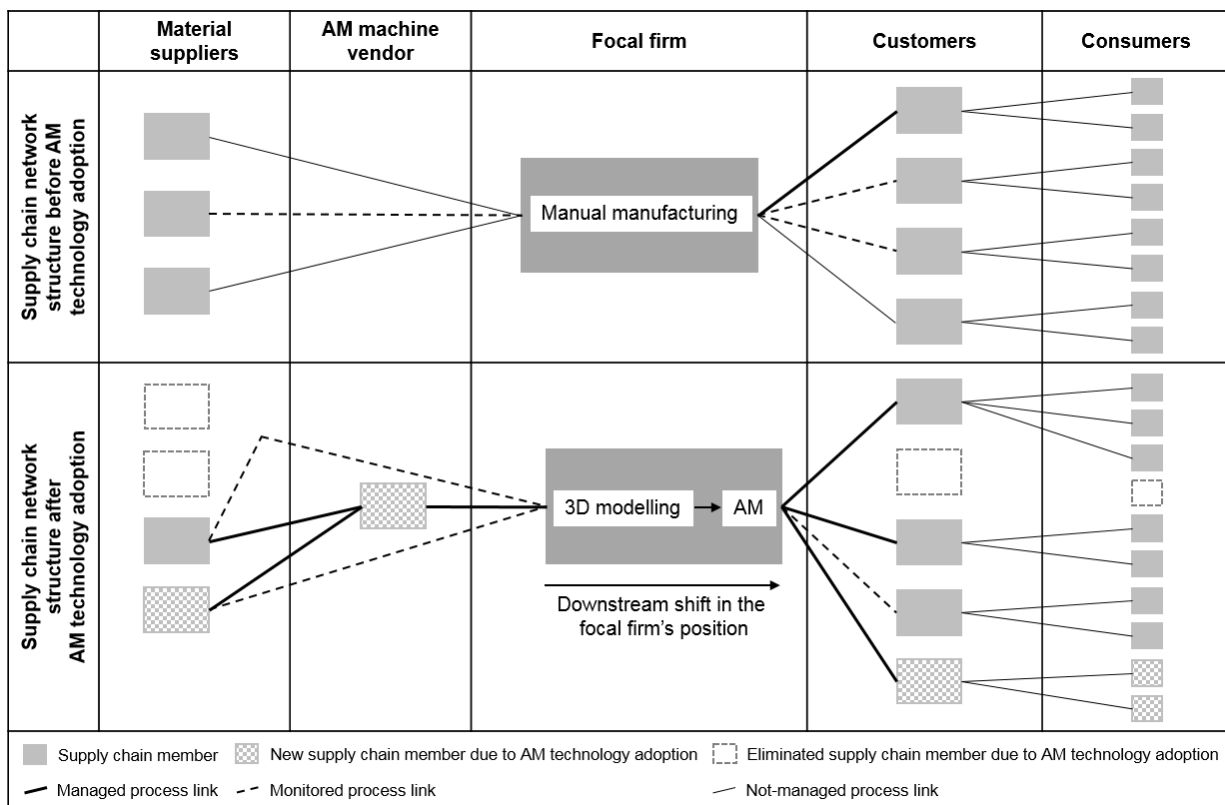


Figure 2: Results overview – impact of AM technology adoption on network structures in engineer-to-order supply chains (illustrative example)

Discussion

The outcomes of the exploratory empirical analysis suggest that AM technology adoption in engineer-to-order production affects the configuration of supply chains in various ways. New supply chain members are introduced (e.g. AM machine vendors or customers) and certain existing members are eliminated or replaced (e.g. material suppliers). The horizontal and vertical structure of the network also seems to be affected by a switchover to AM. Furthermore, AM technology adoption tends to be positively associated with the occurrence of managed business process links – both, between suppliers and manufacturers as well as between manufacturers and their customers.

The findings also indicate that the effects of AM technology adoption on supply chain network structures are context-dependent. The following two groups of contingency variables seem to be relevant for explaining differences between the analyzed cases: endogenous factors (firm size) and supply chain-related factors (geographic span of the supply chain, ability of customers to perform 3D modeling of AM parts, ability of material suppliers to provide AM materials). Figure 3 presents an explanatory framework, which demonstrates different ways of AM deployment in an engineer-to-order supply chain depending on context.

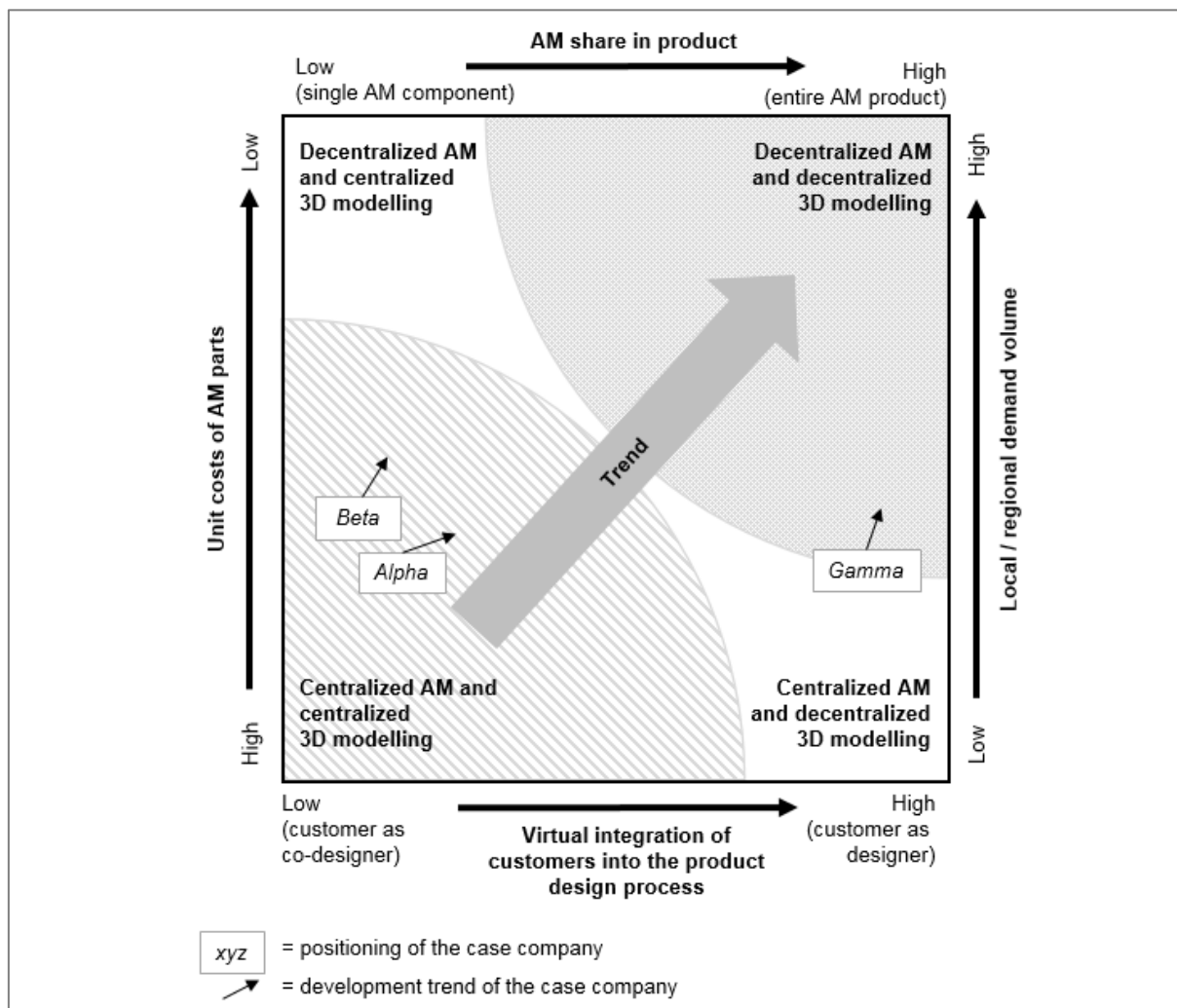


Figure 3: Proposed framework on the deployment of AM technologies in engineer-to-order supply chains

Interestingly, no managed business process links were found between consumers and the focal firm or the focal firm's customers. This seems to be contradictory to insights by other authors, who emphasize AM's potential to integrate customers as co-producers into the supply chain (e.g. Oettmeier and Hofmann, 2016b). However, the supposed contradiction can be refuted when considering the context in which AM is applied. The present study focuses on engineer-to-order production in markets, where consumers are only passively involved in the specification of the customized product since they lack the required knowledge. For example, for creating removable partial dentures, the consumer is only involved in the production process in that he provides a dental impression of his teeth. The actual modeling of the AM object is conducted by the dentist or the dental laboratory, who have the necessary expertise to communicate the product specifications to the AM firm. In such a case, the dentist or laboratory – as a direct customer of the AM firm – becomes the “designer” (or “co-producer”) of the AM part. In AM application areas, where customers have the capability to directly articulate their desired product properties (e.g. the jewelry sector), more managed business process links between manufacturers and consumers can be expected.

Conclusion

The analyses in this paper shed more light on the potential effects on supply chain network structures evoked by AM technology adoption in engineer-to-order production. Not only the composition of the supply chain members and the structural dimensions of the network are likely to be altered due to AM technology adoption, but also the types of business process links among the different agents. The research suggests that the implications of AM technology usage on supply chain configurations are context-dependent, with endogenous and supply chain-related factors being relevant groups of contingency factors.

The paper adds to theory building in operations management by proposing a framework, which visualizes different deployment alternatives for AM in engineer-to-order supply chains for varying contexts. It also emphasizes the relevance of using a contingency approach when studying the business impact of novel technologies as this may yield more differentiated insights.

From a managerial perspective, the findings could influence decision-making concerning the adoption of new manufacturing technologies. Firms should be aware that switching to AM may create a need to reconsider the design and the firm's positioning within the supply chain.

Limitations arise from the paper's focus on a single industry (i.e. medical products), which hampers generalizability. Moreover, the scope of the analyzed supply chains was wide, but not exhaustive. For example, supporting supply chain members such as banks and insurance companies as well as potential sub-suppliers of the AM machine or material manufacturers were not considered.

Future research could examine to what extent the proposed impact of AM in engineer-to-order supply chains also applies to other fields of AM technology usage, such as the production of lightweight or functional objects.

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