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ORIGINAL PAPER

Additive manufacturing technology adoption: an empirical analysis of general and supply chain-related determinants

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Abstract Despite experiencing immense growth in the past decade, additive manufacturing (AM) technologies—colloquially known as 3D-printing—are still rarely used in industrial fabrication. Being at the interface between technology, innovation, behavioral science and operations management research, this paper identifies multifaceted factors that determine the decision to adopt AM technologies for the production of industrial parts. A review of the relevant literature revealed eight potential factors. These can be classified into four interdisciplinary categories: technology-related factors, firm-related-factors, market structure-related factors, and supply chain-related factors. Special focus is placed on the impact of supply chain-related issues, because there are indicatives that these aspects have an influence on the decision to adopt AM technologies since AM may offer distinct opportunities for both, the supply- and demand-side of a firm's operations. No work in the field of manufacturing technology adoption has examined the role of such inter-organizational factors before. The results of an empirical study among 195 firms indicate that demand-side benefits and compatibility are the main determinants of AM technology adoption. This suggests that not only intra- but also inter-organizational factors should be considered when investigating the adoption of technological innovations. Furthermore, it is carved out that the adoption of AM technologies has an interdisciplinary nature.

This paper is an extension of Oettmeier and Hofmann (2015).

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1 Introduction

In times of increasing competition, innovation in manufacturing technology can be used strategically to differentiate firms from competitors (Skinner 1984). According to Olesen (1990), successful organizations distinguish themselves by their willingness and ability to acquire technology and to take technology risks. Additive manufacturing (AM) technologies represent such innovative solutions in the field of fabrication, which may foster a company's competitiveness. AM refers to "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" (ASTM Standard 2012). Frequently used synonyms for AM include "rapid manufacturing", "direct manufacturing" and "digital manufacturing" (Holmström et al. 2010; Hopkinson and Dickens 2001; Vinodh et al. 2009). Examples of popular AM technologies are 3D-printing, fused deposition modeling, selective laser sintering, stereolithography, electron beam melting and laminated object modeling.

AM technologies were originally employed for the fast creation of prototypes, so-called "rapid prototyping" (RP). However, in recent years, there has been a tremendous growth in the use of AM technologies for the production of parts for final products. According to "Wohlers Report (2014)", a study on the global AM market conducted by Wohlers Associates (an independent consultancy that has monitored and quantified the worldwide AM market for more than 17 years), revenues from industrial parts production accounted for almost 35 % of the global market for AM products and services (US $1.065 billion) in 2013 (Wohlers Associates 2014). Ten years earlier, revenues from AM only represented a 3.9 % share of that market (Wohlers Associates 2014). More than 10 million individualized hearing aid shells have already been made using AM technologies (Crain's Chicago Business 2014). 90 % of the hearing aids from US-based manufacturer Beltone are currently produced with AM technologies (Crain's Chicago Business 2014)—similar steps towards AM have been taken by other major players in that market, such as Swiss-based hearing aid manufacturer Sonova. In the dental industry, around 50 million bridges, copings and crowns were additively manufactured between 2007 and 2013 (EOS 2013). The aerospace sector is also heavily investing in AM technologies. To date, general electric (GE) has more than 300 AM machines in use worldwide. The aviation branch of the company plans to build 100,000 additively manufactured parts (such as fuel nozzles for jet engines) by 2020 (GE 2015). These examples from practice illustrate the increasing relevance of AM technologies in industrial parts manufacturing.

Advantages of AM compared to other manufacturing technologies include their ability to build complex geometries and lightweight products, reduced costs in the production of small quantities of individualized products, lower material usage during product manufacturing, a high freedom of design, the elimination of object-specific tooling and the ability to quickly conduct design changes (Berman 2012; Holmström et al. 2010; Khajavi et al. 2014; Walter et al. 2004).

Despite their benefits and immense market growth, the use of additive processes is still rather uncommon (Vinodh et al. 2009), especially in direct parts manufacturing. Reasons for firms' hesitant adoption of AM technologies include high costs of machines and materials, the limited choice of colors, materials and surface finishes, as well as difficulties in management and implementation (Berman 2012; Hopkinson and Dickens 2001; Ruffo et al. 2007). Additionally, companies' reluctance to use AM may also be attributed to their insecurity about the how, where and why to employ additive technologies. This implies that more efforts need to be taken to foster understanding about the factors, which affect the decision to pursue AM.

In this paper, we explore the determinants of AM technology adoption for the production of industrial parts (as opposed to 3D-printing conducted by private households). Since the 1960s, a lot of researchers—especially from marketing, but also from other academic domains (e.g. information systems and operations management)—have examined innovation adoption and diffusion processes (e.g. Davis et al. 1989; Ray et al. 1969; Rogers 1962). In a B2B context, studies about the adoption and diffusion of innovations are conducted at two different levels: the *inter-firm* or the *intra-firm* level (Van Everdingen and Wierenga 2002). *Inter-firm* adoption occurs when an organization (i.e. at least one individual within the firm) adopts the innovation. That is: a firm or one or several individuals within the firm (e.g. top managers) makes a resource commitment to an innovation. *Intra-firm* adoption and diffusion refers to the spread of an innovation within an organization (i.e. across individuals, departments, and subsidiaries) (Van Everdingen and Wierenga 2002). Intra-firm adoption and diffusion of an innovation starts as soon as inter-firm adoption has taken place. As we aim to identify the factors affecting the decision to adopt AM technologies, our study focuses on the level of inter-firm adoption.

Although innovation adoption literature provides cues about potentially relevant factors for AM technology adoption, no research has specifically addressed this topic yet. Moreover, there are indicatives that supply chain-related factors may have an influence on the decision to adopt AM technologies, because usage of these technologies offers distinct opportunities for both, the supply- and demand-side of a firm's operations (e.g. Berman 2012; Holmström et al. 2010; Walter et al. 2004). For example, on the supply-side, pre-assembly activities may be eliminated and the need for transport services be reduced due to AM technologies' ability to integrate more functionality into products. On the demand-side, customers can get involved in the product design process because in AM, design and manufacturing can easily be separated (Berman 2012). To our knowledge, no study has examined the role of such inter-organizational aspects in the field of manufacturing technology adoption. Therefore, special emphasis in this paper will be placed on the impact of supply chain-related factors (i.e. supply- and demand-side benefits) on AM technology adoption. The interdisciplinary focus of our research is supplemented through inclusion of technology-, firm- as well as market-related determinants. Based on these circumstances, we suggest the following research questions:

– RQ 1. Which factors determine the adoption of AM technologies for industrial parts production?
– RQ 2. Do supply chain-related factors have an impact on the adoption of AM technologies for industrial parts production?

In order to answer the questions, we start with a literature review to identify potentially relevant adoption determinants. Building on the condensed findings from previous research, we develop a conceptual model with underlying hypotheses to explain AM technology adoption. As we bridge insights from technology, innovation, behavioral science and operations management research in order to determine the factors affecting AM technology adoption, we take an interdisciplinary perspective. The hypotheses are empirically tested in a survey research among 195 companies. Thereby, information reported from adopters of AM technologies is contrasted with non-adopters in order to determine discriminating factors. In an eclectic approach, we use contingency theory (CT) (Donaldson 2001), innovation diffusion theory (IDT) (Rogers 1962) and the technology acceptance model (TAM) (Davis et al. 1989) as theoretical foundation for our investigations. CT is employed because various studies indicate that contextual factors have an impact on the adoption decision (e.g. Ungan 2004). IDT and the TAM are seminal works in the field of innovation adoption and diffusion. They have been applied to study adoption behavior for a wide range of different innovations, ranging from consumer adoption of mobile payments to user utilization of software and RFID adoption by firms (e.g. Dishaw and Strong 1999; Mallat 2007; Wang et al. 2010). Other theoretical works, which may also be relevant, include the theory of reasoned action (TRA) (Ajzen and Fishbein 1980; Fishbein and Ajzen 1975) and the theory of planned behavior (TBA) (Ajzen 1991). However, we found IDT (for providing cues about adoption determinants in general) and the TAM (for identifying behavioral motivations for technology adoption in particular) better suited for our research.

The remaining part of this paper is organized as follows: Sect. 2 provides a review of the literature on innovation adoption in general and AM technology adoption in particular. In Sect. 3, the conceptual model of this paper is presented and hypotheses regarding the determinants of AM technology adoption for industrial parts production are developed. Section 4 points out the methods that were employed in data collection as well as in measure refinement and validation. Section 5 presents the results from the empirical analysis. The paper ends with a discussion of theoretical and managerial implications, limitations and directions for future research.

2 Literature review

2.1 General determinants

Innovation diffusion theory (IDT) (Rogers 1962) is an influential work, which helps to explain the adoption of innovations. According to the theory, an innovation's adoption rate depends, besides some other factors, on five specific innovation attributes (Rogers 2003): (1) relative advantage (i.e. perceived superiority of an innovation to existing practices), (2), compatibility (i.e. perceived consistency of an innovation with existing values, past experiences and needs of potential adopters), (3) complexity (i.e. perceived difficulty to understand and use the innovation), (4) trialability (i.e. perceived degree to which the innovation can be experimented with), and (5) observability (i.e. perceived degree to which results of an innovation are visible to others). IDT suggests that a high degree of relative advantage, compatibility, trialability and observability of an innovation is positively associated with its adoption rate, whereas complexity is negatively related to an innovation's rate of adoption. The theory is used in both, studies examining adoption at an individual and an organizational level. However, applications in the latter case are more frequent.

The technology acceptance model (TAM) (Davis et al. 1989) is extensively employed by information systems and marketing researchers to investigate technology adoption behavior, especially at an individual level. The model was originally developed to explain user acceptance of computer technologies (hardware and software). However, it is also frequently applied to study the adoption of other types of technological innovations, e.g. internet banking and mobile data services (e.g. Gounaris and Koritos 2008; Qi et al. 2009). According to the TAM, users' decision to adopt a technological innovation is primarily influenced by two beliefs (Davis et al. 1989, p. 320): (1) perceived usefulness (i.e. "degree to which a person believes that using a particular system would enhance his or her job performance"), and (2) perceived ease-of-use (i.e. "degree to which a person believes that using a particularly stem would be free of effort").

Based on the condensed findings from IDT (Rogers 1962), TAM (Davis et al. 1989) and other influential studies in the field of innovation adoption (e.g. Cohen and Levinthal 1990; Moore and Benbasat 1991), three groups of variables can be emphasized, which seem to be relevant for AM technology adoption: (1) technology-related factors [relative advantage and ease of use (complexity)], (2) firm-related factors (absorptive capacity and compatibility), and (3) market structure-related factors (external pressure and perceived outside support). In the following, the potential determinants are described in greater detail.

2.1.1 Relative advantage

Relative advantage is based on Rogers' (1962) IDT. It indicates the ratio between the costs and expected benefits of an innovation's adoption (Rogers 1962). Various studies in the innovation management realm suggest that relative advantage is an important predictor for the adoption rate of an innovation (e.g. Gounaris and Koritos 2008). The TAM (Davis et al. 1989) includes the variable "perceived usefulness" to explain user acceptance of information technology. Perceived usefulness thereby means "the degree to which a person believes that using a particular system would enhance his or her job performance" (Davis et al. 1989, p. 320). As such, it is similar to relative advantage because it implies that the costs and benefits of adopting an innovation are weighted against each other. However, the TAM is mainly applied for examining innovation adoption at an individual level whereas

IDT is used for studying both, adoption by individuals and organizations. In our context, the relative advantage of AM technologies is closely linked to the technologies' benefits compared to other manufacturing technologies. Relative advantages of AM technologies include (Berman 2012; Holmström et al. 2010; Khajavi et al. 2014; Walter et al. 2004):

- Cost reduction, particularly when building small quantities of custom products (due to the elimination of object-specific tooling),
- Lower material usage during product manufacturing (since material is only accumulated where it is needed to build up the object),
- Freedom of design (due to the capability to build complex geometries),
- Ability to build lightweight products (e.g. by producing hollow spaces or grid structures in an object's interior),
- Ability to optimize products for function and integrate more functionality into an object (e.g. by reducing the number of components to a few subcomponents).

2.1.2 Ease of use (complexity)

In IDT, complexity means "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers 2003, p. 257). Several studies found a negative relationship between complexity and innovation adoption (e.g. Rogers 2003; Tornatzky and Klein 1982; Verhoef and Langerak 2001), although results are not always conclusive (e.g. Beatty et al. 2001). The TAM (Davis et al. 1989) employs the variable "perceived ease of use" to predict user acceptance of information technology. Perceived ease of use can thereby be regarded as antonym to complexity. The close relation between the two constructs becomes obvious in the perceived characteristics of an innovation (PCI) framework (Moore and Benbasat 1991), where the parameter "ease of use (complexity)" is theorized as a driver for innovation adoption. We assume that ease of use (complexity) is also a relevant determinant for AM technology adoption, because firms may be reluctant to pursue AM if they find the technology hard to understand and use.

2.1.3 Absorptive capacity

The absorptive capacity of an organization refers to its "ability to exploit external knowledge" (Cohen and Levinthal 1990, p. 128). Previous research implies that firms, which can easily assimilate new information and commercially seize that knowledge, tend to be faster at adopting novel technologies (Cohen and Levinthal 1989, 1990). The relevance of "absorptive" or "learning capacity" as a determinant of (early and intensive) technology usage has already been shown for advanced manufacturing technologies (AMT) (Arvanitis and Hollenstein 2001). AMT stand for various modern—usually computer-based—systems that aim at improving manufacturing operations (Small and Yasin 1997). Examples of AMT are computer-aided design (CAD), computer-aided manufacturing (CAM), computer numerically controlled machines (CNC), flexible manufacturing systems (FMS) and material resource planning (MRP) systems (Hofmann and Orr 2005; Small and Yasin 1997). AM technologies are also considered as AMT (Arvanitis and Hollenstein 2001). Therefore, we claim that absorptive capacity is also a relevant determinant for the adoption of AM technologies for industrial parts production. Building on Arvanitis and Hollenstein (2001) and Cohen and Levinthal (1990), we consider three aspects with regard to absorptive capacity: (1) the firm's ability to utilize external information and build up internal competences, which mainly depends on its involvement in own R&D, (2) the firm's embedding in knowledge networks, which can be operationalized as the degree of involvement in R&D co-operations with other companies or institutions, and (3) the firm's ability to evaluate technological opportunities, which can primarily be attributed to its endowment with human capital.

2.1.4 Compatibility

Compatibility, which constitutes an element of both, IDT (Rogers 1962) and the perceived characteristics of an innovation (PCI) framework (Moore and Benbasat 1991), refers to "the degree to which an innovation is perceived as consistent with the existing values, past experiences and needs of potential adopters" (Rogers 2003, p. 240). Innovations can thereby be "compatible or incompatible with (1) sociocultural values and beliefs, (2) previously introduced ideas, and/or (3) client needs for the innovation" (Rogers 2003, p. 240). Various studies point out that an innovation's compatibility is positively related with its adoption (e.g. Tornatzky and Klein 1982). The same could hold true for AM technology adoption, because firms may be more likely to pursue AM if the technology provides a good fit with their existing systems (e.g. process flows and information technology).

2.1.5 External pressure

Not only internal or technology-related aspects like the ability to make lightweight products may evoke companies to employ AM technologies. Use of such advanced technologies can also be the result of external pressures. The forces that shape an organization's environment include competition, volatile customer needs, government regulations as well as changing business fields and technologies (Carr et al. 1996; Porter 1979). Several studies find positive links between different types of external pressures, such as competitive and legal pressures, and organizational adoption (e.g. Iacovou et al. 1995; Jeyaraj et al. 2006; Premkumar and Ramamurthy 1995; Ungan 2004). Therefore, we assume that this also seems to be true for AM.

2.1.6 Perceived outside support

Previous research indicates that innovation adoption is facilitated by (the perceived availability of) outside support, e.g. from vendors or consultants (Cragg and King 1993; Yap et al. 1992). This phenomenon can be explained by IDT, which views innovation diffusion as an uncertainty reduction process: throughout the innovation decision process, individuals or organizations collect information in order to decrease uncertainty about the innovation's relative advantage (Rogers 2003). The contribution of external experts to uncertainty reduction about AM technologies may be twofold: (1) by providing information about AM technologies, e.g. through cost-benefit analyses and employee training, and (2) by offering support during implementation and operation.

2.2 Supply chain-related determinants

Currently, the body of literature specifically addressing the adoption of AM technologies is rather limited. Vinodh et al. (2009) investigated AM technology adoption concerning its ability to infuse agility in traditional manufacturing firms. They found that sensitization of industry leaders and employees are crucial in order to fully exploit the potential of 3D printers and to achieve mass customization (Vinodh et al. 2009). However, this work does not provide clues about the determinants, which evoke companies to pursue AM in first instance.

More research has been dedicated to the adoption of AMT (e.g. Arvanitis and Hollenstein 2001; Hofmann and Orr 2005; Small and Yasin 1997). To our knowledge, the study of Arvanitis and Hollenstein (2001) is the only one in the field of inter-firm AMT adoption, which, among others, also addresses AM technologies. Classified as a design AMT, the authors examine motives and impediments to RP technology adoption. They find that higher flexibility and improvements in product development are motivators for the adoption of design AMT, whereas high investment costs and uncertainties concerning capacity utilization depict hindrances (Arvanitis and Hollenstein 2001).

Although providing cues about the determinants of AM technology usage, we argue that the results from existing studies on AMT adoption (e.g. Arvanitis and Hollenstein 2001) cannot directly be transferred to the adoption of AM technologies for industrial parts production for three reasons: (1) Unlike in RP, AM technologies used in AM serve the purpose of building industrial parts rather than visualizing newly developed products. Thus, in an industrial setting, assigning AM technologies to the functional group of fabrication technologies (e.g. flexible manufacturing systems, computer numerically controlled machines, pick-and-place robots) instead of design technologies (e.g. CAD, CAE) seems more appropriate. (2) Using AM technologies for industrial parts production requires a higher level of integration (e.g. information systems and process flows) than only for building prototypes. Thus, adoption determinants for RP can be different from those relevant for AM. For example, compatibility with a firm's existing IT landscape may be more important for AM than for RP. (3) Several scholars have already indicated that AM can create specific opportunities on both, the supply- and demand-side of a firm's operations (e.g. Berman 2012; Holmström et al. 2010; Mellor et al. 2014; Nyman and Sarlin 2014). Upstream, for instance, firms may reach a higher level of vertical integration, whereas downstream, a closer proximity to customers can be achieved. Since supply- and demand-side benefits of AM are likely to have an impact on the management of supply chains (e.g. supply chain configuration), it seems reasonable to assume that supply chain-related factors also have an influence on the decision to adopt AM technologies. Therefore, in the following, an extract of the existing knowledge about potential supply- and demand-side benefits of AM technology usage is provided.

2.2.1 Supply-side benefits

Several studies indicate that the adoption of AM technologies may impact the supply side of value-generating networks (e.g. Berman 2012; Holmström et al. 2010; Nyman and Sarlin 2014). Berman (2012) points out that production of small lot sizes may shift back to high-wage countries (upstream vertical integration) since AM lowers the need for manual labor. He also notes that AM technology usage facilitates outsourcing because product design and production can easily be separated (Berman 2012). This seems contradictory to Holmström et al. (2010), who highlight that AM may lead to simpler (i.e. shorter and narrower) supply chains. However, the argumentations becomes consistent when considering the different objects of observation: while Berman (2012) refers to the possibility of separating design from manufacturing, the suggestions by Holmström et al. (2010) rather seem to focus on the degree of vertical integration within manufacturing. By including more functionality into products due to AM technology usage, the number of components and hence of suppliers can be reduced. This may not only eliminate sub-assembly activities, but also reduce and simplify manufacturing steps (e.g. instead of providing sub-components, suppliers might only need to deliver materials for AM). Moreover, AM's potential to increase manufacturing depth could lower the need for transport services. We expect that firms consider these implications on the supply-side when deciding about using AM technologies for the production of industrial parts.

2.2.2 Demand-side benefits

Previous research suggests that AM technology usage enables traditional manufacturing firms to infuse agility in their operations (Nyman and Sarlin 2014; Onuh and Hon 2001; Vinodh et al. 2009). This can benefit a firm's customers by increasing the customer service level and slashing lead times, e.g. due to a tighter integration of customers in the design and manufacturing process (customers as co-producers). Several studies, particularly in the area of spare parts supply chains, highlight AM's potential to move production closer to the customer through decentralization (e.g. Holmström et al. 2010; Khajavi et al. 2014; Mellor et al. 2014; Walter et al. 2004). Companies may also become faster in reacting to changing customer needs since AM does not require object-specific tools, punches or molds (Berman 2012). Consequently, product designs can easily be altered. As the tooling requirement is removed, firms that use AM technologies can distribute "manufacturing according to demand locations as in theory the only inputs required for production are CAD data and raw material" (Mellor et al. 2014, p. 197). Holmström et al. (2010) point out that in most cases, the motivation to pursue AM goes back to the technologies' ability to build custom products, which would otherwise not be possible or economical to make. This is why major hearing aid manufacturers, such as Sonova and Beltone, employ AM technologies for mass customization (Holmström et al.

2010). A lot of studies, particularly from the marketing and operations management literature, note that mass customization may not only increase profit margins of manufacturers (due to customer's higher willingness to pay), but also foster customer satisfaction (e.g. Du et al. 2006). Overall, it seems reasonable to assume that the potential benefits on the demand-side induced by AM technology usage are also relevant for the decision to adopt these technologies.

Figure 1 presents illustrative examples of the potential impact of AM technology usage on the supply- and demand-side of a firm's operations in comparison to a starting situation without AM. To our knowledge, no work on the inter-firm adoption of manufacturing technologies in a narrow sense (i.e. technologies to control manufacturing processes and build physical products) has specifically examined the role of supply chain-related factors. Previous research in this field

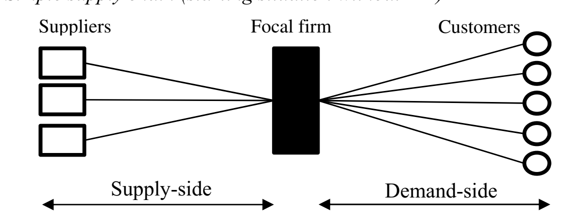
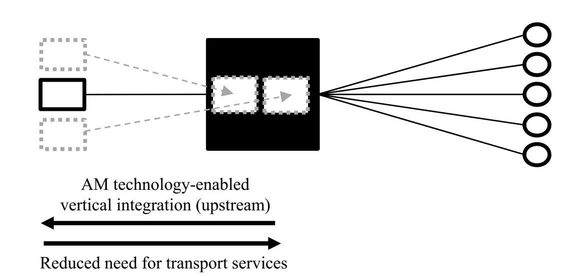
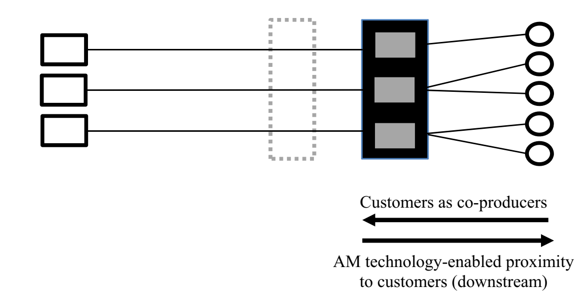
<table>
<tr><th>Scenario</th><th>Description</th></tr>
<tr><td>Simple supply chain (starting situation without AM)

</td><td>The focal firm receives raw materials and components from several suppliers to build standard products. Altering products according to changing customer needs would be time-consuming and costly because various suppliers have to be involved and tool changes are necessary.</td></tr>
<tr><td>Supply-side potential of AM

</td><td>The focal firm only sources raw materials or a small number of components from suppliers because more functionality can be integrated into the products. Thus, pre-assembly activities are eliminated and the need for transport services is reduced. Consequently, AM helps to reduce the complexity of the upstream supply chain (Holmström et al. 2010).</td></tr>
<tr><td>Demand-side potential of AM

</td><td>Production is geographically moved closer to customers and products can be individualized or quickly adapted to changing customer needs as no object-specific tooling is required. Customers may take the role of "co-producers", e.g. by being integrated in the product design process, because in AM, design and production can easily be separated (Berman 2012).</td></tr>
<tr><td colspan="2">supplier focal firm local unit situation before AM technology usage customer</td></tr>
</table>

Fig. 1 Supply- and demand-side potential due to AM technology usage (examples)

primarily focuses on the perceived benefits these technologies may generate for internal operations, such as cost reductions and improved product quality (e.g. Arvanitis and Hollenstein 2001; Small and Yasin 1997). There are a few studies on the adoption of communication-based AMT like RFID and EDI, which to some extent address inter-organizational aspects, e.g. customer service and communication with trading partners (e.g. Iacovou et al. 1995; Premkumar and Ramamurthy 1995; Reekers and Smithson 1994). However, these technologies are quite different from AM technologies, because they are not destined for building physical objects, but for data collection or data transfer.

2.3 Summary of the literature review and research gaps

Overall, the review of the literature reveals that innovation adoption research brings up various factors, which may also be relevant for the adoption of AM technologies. Apart from more generic theories or models, such as IDT and TAM, a limited number of studies on AMT adoption exist. However, none of these specifically addresses the determinants of AM technology adoption for the production of industrial parts. Additionally, there is reason to believe that supply chain-related factors (i.e. supply- and demand-side benefits) have an influence on AM technology adoption, too. So far, no study on the inter-firm adoption of a manufacturing technology (in a narrow sense) has included such a supply chain perspective. The aim of our paper is to fill these gaps in research by identifying the determinants of AM technology adoption. The impact of supply chain-related factors on the decision to adopt AM technologies for industrial parts production will thereby also be examined.

3 Conceptual model and hypotheses

3.1 Conceptual model

We argue that contextual, interdisciplinary factors have an impact on the adoption of AM technologies. These contexts can be classified into four different elements: (1) technology-related factors, (2) firm-related factors, (3) market structure-related factors, and (4) supply chain-related factors (see Fig. 2). The first three elements comprise potential determinants derived from the innovation and manufacturing technology adoption literature in general, whereas the supply chain-related factors reflect the specific relevance of including suppliers and customers in this matter.

Technology-related factors include the relative advantage and the ease of use (complexity) of AM technologies. Firm-related factors refer to absorptive capacity and the perceived compatibility of AM technologies with the organization. Market structure-related factors include external pressures and perceived outside support. Finally, supply chain-related factors summarize opportunities with regard to the supply- and demand-side. Thus, they add an inter-organizational perspective to the examinations.

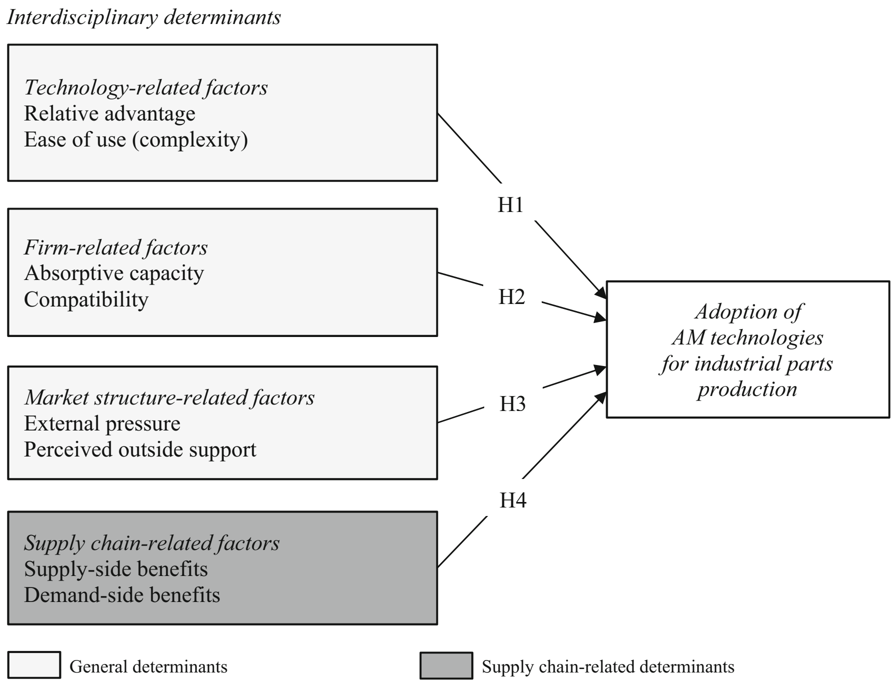


Fig. 2 Conceptual model: interdisciplinary determinants of AM technology adoption

We consider the various factors as "interdisciplinary determinants" of AM technology adoption, because they are all rooted in different academic streams. The technology-related factors are primarily based on technology management research. The firm-related factors reflect organization-specific aspects, such as a company's ability to learn and assimilate new knowledge. Therefore, they can predominantly be attributed to intra-organizational management literature (e.g. organizational learning). In contrast to that, the market structure-related factors rather pertain to the field of microeconomics. The supply chain-related factors rather build on logistics and operations management literature, because they take in an inter-organizational (supply- and demand-side) perspective, which is inherent to supply chain management. Innovation management and behavioral science literature, such as IDT, form the connecting elements between the factors, because the study of innovation adoption behavior lies at the heart of our examinations. In the following subsections, the hypotheses for the different interdisciplinary factors are developed.

3.2 Technology-related factors

3.2.1 Relative advantage

Following the large part of previous research on the impact of relative advantage on innovation adoption, we expect that firms, which see a high relative advantage in AM technologies, are also more likely to pursue AM. Hence, we hypothesize that:

H1a. Relative advantage is positively related to AM technology adoption.

3.2.2 Ease of use (complexity)

We argue that complexity is also a determinant for the adoption of AM technologies, because the harder a manufacturing technology is to understand, implement, use and maintain, the more knowledge needs to be build up and dispersed across the organization. This, in turn, could make firms more reluctant to use these technologies. As we code complexity positively so that it reflects ease of use, we hypothesize that:

H1b. The relationship between ease of use (complexity) and AM technology adoption is positive.

3.3 Firm-related factors

3.3.1 Absorptive capacity

The relevance of "absorptive" or "learning capacity" as a determinant of technology usage has already been shown for AMT (Arvanitis and Hollenstein 2001). Therefore, we suspect that it is also positively related to the adoption of AM technologies for industrial parts production. We hypothesize that:

H2a: Absorptive capacity is positively associated with AM technology adoption.

3.3.2 Compatibility

Investigations by Arvanitis and Hollenstein (2001) show the relevance of compatibility concerning the decision to adopt AMT: Besides human capital restrictions (e.g. lack of qualified personnel), compatibility issues (e.g. with the organization, product portfolio or installed equipment) were found to be the most impeding factors to the adoption of fabrication-related AMT. However, for the cluster of design-related AMT, to which RP was also attributed, compatibility problems did not depict a significant barrier to adoption (Arvanitis and Hollenstein 2001). Since we believe that the implementation of AM technologies for industrial parts production requires a tighter integration into existing systems (e.g. process flows, information technology) than for prototype construction, we hypothesize that:

H2b. Compatibility is positively related to AM technology adoption.

3.4 Market structure-related factors

3.4.1 External pressure

Within the area of AMT, Arvanitis and Hollenstein (2001) found that market conditions only have a limited impact on AMT adoption. They showed a significant, positive relation between the intensity of non-price competition in the product market and AMT usage, but did not yield significant effects for market concentration (expressed by the number of competitors) and the intensity of price competition (Arvanitis and Hollenstein 2001). Since AM technologies can infuse agility to a firm's operations (Onuh and Hon 2001; Vinodh et al. 2009), we find it reasonable to assume that AM is particularly attractive to firms in challenging (e.g. volatile) environments. Therefore, we propose the following:

H3a. External pressure is positively associated with AM technology adoption.

3.4.2 *Perceived outside support*

Previous studies indicate that innovation adoption is facilitated by (the perceived availability of) outside support (Cragg and King 1993; Yap et al. 1992). We claim that firms, which perceive that they can get access to outside support for employee training, AM technology implementation and operation, are also more likely to pursue AM. Consequently, we hypothesize that:

H3b. Perceived outside support is positively related to AM technology adoption.

3.5 Supply chain-related factors

3.5.1 *Supply-side benefits*

An example of the benefits that AM technology usage may bring to the supply-side, is its potential for simpler (i.e. shorter and narrower) supply chains (Holmström et al. 2010). By including more functionality into products, the number of subcomponents and assembly activities—and hence of suppliers—may be reduced. We propose that firms also consider implications on the supply-side of their operations when deciding about the adoption of a new manufacturing technology. Therefore, we hypothesize:

H4a. Supply-side benefits are positively associated with AM technology adoption.

3.5.2 *Demand-side benefits*

AM technology usage may also evoke changes on the demand-side of a supply chain. For example, customers can benefit from firms' faster reactions to changing customer needs since product designs can quickly be adjusted in AM due to the elimination of object-specific tooling (Berman 2012). We presume that firms, which expect greater demand-side related benefits from AM, are more likely to adopt these technologies. Hence, we propose that:

H4b. Demand-side benefits are positively related to AM technology adoption.

4 Methodology

4.1 Data collection and sampling

In order to empirically test our hypotheses, we conducted an online survey among 934 Swiss companies. Business activities in Switzerland can be interpreted as highly developed and representative for other Western economies (Wagner 2008). Moreover, as suggested by the World Economic Forum's Global Competitiveness Report 2014–2015, the business environment in Switzerland is highly conducive to innovative activities. It ranked sixth (out of 144 countries) in the categories "availability of new technologies" and "firm-level technology absorption" (Schwab 2014). Thus, Switzerland seems to be a suitable country for studying the adoption of novel technologies such as AM, because the number of adopters is likely to be higher there than in most other places. Since AM can be done with a wide range of materials (including metal, wax, plastics, and ceramics), all types of firms in the manufacturing sector were deemed relevant, e.g. the automotive, mechanical engineering and plastics industry. The sample also included a small number of logistics service providers and trading companies because although manufacturing is typically not part of their activity portfolio, we found evidence that several firms in these sectors have entered the AM market. For example, the Swiss Post (www.post.ch), Switzerland's largest logistics service provider, uses AM technologies to build personalized products like jewelry for its customers.

As our examinations focus on decision-making concerning the adoption of new manufacturing technologies, we targeted executive managers in the field of production, logistics and supply chain management. The contacts were selected from a total of 2,300 firms, which form the survey panel of the Logistics Market Study Switzerland—a study that is conducted by the Chair of Logistics Management of the University of St.Gallen in cooperation with GS1 Switzerland. Among the 934 persons who received the survey, 226 were no longer in the company, had an invalid e-mail address or declined to participate. This reduced the sample size to 708. 195 questionnaires were complete and usable, yielding a response rate of 27.5 %. This rate seems adequate compared to response figures from other survey research (e.g. Kaplowitz et al. 2004).

We evaluated the non-response bias by comparing the sales figures and number of employees of respondents and non-respondents. This analysis did not reveal any significant differences between the two groups. 83 of the responses were from "non-adopters" of AM technologies, who are neither planning nor interested in employing these technologies in the future. The remaining 112 responses were from companies who are already involved in AM or who are interested in using or planning to invest in AM technologies. More background information on the respondents can be found in Table 1, which displays the annual sales volume, number of employees and industry affiliation of the adopters and non-adopters of AM technologies.

All statistical analyses in this paper were carried out in SPSS Statistics, version 23.

4.2 Variable measurement

We classified our questionnaire items into adopted, modified, and proposed items. Adopted items were taken over from previous studies without any changes. Modified items were adapted in order to match the context of our research. Finally, proposed items were derived based on the condensed findings from the literature.

Table 2 provides an overview of the sources and origin (adopted, modified, proposed) of the different questionnaire items.

For measuring the multiple-item constructs, we employed five-point Likert scales with the anchors "strongly agree" and "strongly disagree". No reversed or negated items were used because although these may help to correct for agreement bias, there is evidence that scales with such items tend to be less reliable (e.g. Schriesheim et al. 1991). For the adoption decision, we introduced a dichotomous variable ("0 = resource commitment was not made and is neither planned nor of interest" and "1 = resource commitment was made, is planned or of interest").

4.3 Measure refinement and validation

In order to measure the multiple-item constructs, we employed formative as well as reflective scales (see Table 3). Relative advantage, ease of use (complexity), absorptive capacity, compatibility, perceived outside support as well as supply- and demand-side benefits were measured through reflective scales. Formative scales

Table 1 Sample profile of the responding firms

	Adopters		Non-adopters		Total	
	Count	%	Count	%	Count	%
AM technology adoption status	112	57.4	83	42.6	195	100
Annual sales (million CHF)						
<1	13	11.6	8	9.6	21	10.8
1–5	37	33.0	25	30.1	62	31.8
6–50	29	25.9	22	26.5	51	26.2
51–100	15	13.4	14	16.9	29	14.9
>100	18	16.1	14	16.9	32	16.4
Employee number						
<11	11	9.8	1	1.2	12	6.2
11–100	31	27.7	22	26.5	53	27.2
101–500	32	28.6	18	21.7	50	25.6
501–1000	9	8.0	3	3.6	12	6.2
>1001	29	25.9	39	47.0	68	34.9
Industry affiliation						
Trade	12	10.7	12	14.5	24	12.3
Consumer goods	10	8.9	23	27.7	33	16.9
Metalworking and mechanical engineering (incl. automotive)	52	46.4	4	4.8	56	28.7
Chemical, pharmaceutical and plastics	16	14.3	12	14.5	28	14.4
Logistics and transportation	7	6.3	14	16.9	21	16.9
Other (e.g. cement, glass)	15	13.4	18	21.7	33	10.8

Table 2 Sources of questionnaire items

Scale	Item	Source	Origin
Relative advantage	RA1	Arvanitis and Hollenstein (2001)	Adopted
	RA2, RA4	Holmström et al. (2010)	Proposed
	RA3	Mellor et al. (2014)	Proposed
	RA5	Grzesiak et al. (2011)	Proposed
Ease of use (complexity)	CX1	Verhoef and Langerak (2001)	Modified
	CX2, CX3	Beatty et al. (2001)	Modified
	CX4	Ungan (2004)	Modified
Absorptive capacity	AC1, AC2	Arvanitis and Hollenstein (2001)	Modified
	AC3	Cohen & Levinthal (1990)	Proposed
Compatibility	CP1, CP2	Verhoef and Langerak (2001)	Modified
	CP3, CP4	Beatty et al. (2001)	Modified
External pressure	EP1, EP2	Arvanitis and Hollenstein (2001)	Modified
	EP3	Carr et al. (1996)	Modified
	EP4	Nadler et al. (1995)	Modified
	EP5, EP6	Ungan (2004)	Modified
Perceived outside support	OS1, OS2, OS3	Ungan (2004)	Modified
Supply-side benefits	SS1, SS2, SS3, SS4	Holmström et al. (2010)	Proposed
	SS5	Berman (2012)	Proposed
Demand-side benefits	DS1	Holmström et al. (2010), Walter et al. (2004)	Proposed
	DS2	Berman (2012), Vinodh et al. (2009)	Proposed
	DS3	Holmström et al. (2010), Vinodh et al. (2009)	Proposed
	DS4	Berman (2012)	Proposed

were used for external pressure. Since associational-based validation approaches are not applicable for formative scales (Bollen and Lennox 1991), the reliability and validity of reflective and formative scales needs to be assessed in different ways. In the following, the outcomes of our reliability and validity assessment for the reflective and formative scales are described in greater detail.

4.3.1 Reflective scales

We used Cronbach's α together with item-to-total-correlations (ITC) to evaluate the reliability of our reflective scales. In the social sciences, alpha values above 0.65 are generally deemed acceptable. Moreover, scale items should have ITC above 0.5, otherwise they should be removed (Churchill 1979). In order to assess construct validity of the measures, we conducted a factor analysis. We used principal components analysis as extraction technique and direct oblimin as rotation method

Table 3 Measurement items of the independent variables

Variables	Measurement items
Relative advantage	RA1: Cost reduction
	RA2: Improved material usage
	RA3: Freedom of design
	RA4: Ability to build lightweight products
	RA5: Ability to optimize products for function and integrate more functionality into an object
Ease of use (complexity)	CX1: In general, AM technologies are rather uncomplicated
	CX2: Implementation of AM technologies would be a simple process
	CX3: Operating AM machines would be easy for our employees
	CX4: Maintenance of AM machines would be easier than for other manufacturing machinery
Absorptive capacity	AC1: A significant share of our capital expenditure goes into R&D
	AC2: We extensively cooperate with other companies or (research) institutions in R&D
	AC3: A major share of our employees has education at tertiary level
Compatibility	CP1: AM (as a concept) fits our company well
	CP2: The implementation of AM technologies would require few firm-specific adaptations
	CP3: The physical integration of AM technologies into our company would be unproblematic
	CP4: We could integrate the software necessary for AM with little effort into our existing IT-landscape
External pressure	EP1: High competitive pressure due to a large number of competitors
	EP2: High competitive pressure due to various substitution possibilities for products
	EP3: Volatile customer needs
	EP4: High legal requirements
	EP5: Frequent technological changes
	EP6: Changing business areas
Perceived outside support	OS1: There is a wide range of professional training opportunities available about AM technologies
	OS2: There is a sufficient number of experts that could help us to implement AM technologies
	OS3: We could get outside support to help us troubleshooting with little effort
Supply-side benefits	SS1: Reduction and simplification of manufacturing steps
	SS2: Elimination of pre-assembly activities
	SS3: Reduction of the supplier base
	SS4: Reduced need for transportation services
	SS5: Facilitated separation between product design and manufacturing tasks
Demand-side benefits	DS1: Production closer to the customer
	DS2: Customized production
	DS3: Faster reaction to changing customer needs
	DS4: Higher customer service level

because we assumed that at least some of the factors would be correlated with each other. Typically, primary factor loadings should be higher than 0.5. Moreover, there should not be any cross-loadings greater than 0.4 (Hatcher 1994). Six items (RA1, RA2, CP4, SS1, SS2) were eliminated due to factor loadings below 0.5. For the remaining items, factor loadings were clearly above this threshold and all cross-loadings were below 0.4. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy yielded 0.809 and Bartlett's test of sphericity turned out significant ($p < 0.001$), indicating that the data is adequate for factor analysis. The alpha coefficients and factor analysis results are displayed in Table 4.

4.3.2 Formative scales

We employed formative scales in our study to measure external pressures. When constructing indices for formative scales, content and indicators should be specified carefully and multicollinearity among the scale items should be avoided (Diamantopoulos and Winklhofer 2001). As we derived our content and indicators based on an in-depth review of the literature, we claim that they were specified appropriately. To assess collinearity, we used variance inflation factors (VIF). The VIF values for all external pressures items were far below the common cut-off value of ten (see Table 5). Thus, there seem to be no serious multicollinearity issues, which is why all items are retained.

5 Results

5.1 Univariate analysis

In this section, we examine the impact of each interdisciplinary factor on the decision to adopt AM technologies. It is analyzed whether the different mean values between the group of adopters and non-adopters are significant for a specific independent variable (e.g. compatibility, supply-side benefits). *t* Tests would not be appropriate for our examinations since they require normally distributed data and an equality of error variances within each group (adopters/non-adopters). Tests for normality suggest that all our variables violate the assumption of normality at $p = 0.01$. Therefore, we conduct logistic regressions as these neither require normality nor an equality of variances. Table 6 displays the outcomes of the univariate tests.

The results indicate that AM technology-related factors are linked with the decision to adopt AM technologies because significant differences are found for both, relative advantage and ease of use (complexity). Moreover, supply chain-related factors also seem to have an impact on AM technology adoption. Adopters more than non-adopters perceive that AM technology usage provides supply- and demand-side benefits. One the supply-side, users of these technologies expect from a switchover to AM a greater potential to reduce the supplier base and the need for transportation services. Moreover, they seem to be more convinced that AM technology adoption facilitates the separation between product design and

Table 4 Factor analysis results and α coefficients

Item	RA	CX	AC	CP	OS	SS	DS
RA3	0.67						
RA4	0.76						
RA5	0.71						
CX1		0.76					
CX2		0.74					
CX3		0.67					
CX4		0.75					
AC1			0.80				
AC2			0.81				
AC3			0.80				
CP1				0.80			
CP2				0.85			
CP3				0.72			
OS1					0.82		
OS2					0.83		
OS3					0.82		
SS3						0.69	
SS4						0.71	
SS5						0.65	
DS1							0.73
DS2							0.82
DS3							0.75
DS4							0.67
Cronbach's α	0.79	0.79	0.77	0.82	0.81	0.68	0.82

Kaiser–Meyer–Olkin measure of sampling adequacy: 0.801. Factor loadings above 0.5 are shown

RA relative advantage, *CX* ease of use (complexity), *AC* absorptive capacity, *CP* compatibility, *EP* external pressure, *OS* perceived outside support, *SS* supply-side benefits, *DS* demand-side benefits

Table 5 Variance inflation factors

Item	VIF
EP1	1.236
EP2	1.431
EP3	1.464
EP4	1.142
EP5	1.493
EP6	1.603

manufacturing tasks. One the demand-side, adopters not only perceive that AM offers greater opportunities for increasing the service level and the responsiveness to customer needs, but also for a decentralized fabrication of customized products. The results also suggest a positive relationship between a firm's absorptive capacity and the adoption of AM technologies. Moreover, a link between compatibility and AM technology adoption can be seen. Additionally, a significant difference between adopters and non-adopters is found for perceived outside support. In contrast to that,

Table 6 Results of the univariate logistic regression analysis

Variable	Chi square	Group means		
		Adopters	Non-adopters	Significance level
RA	5.64	3.92	3.65	*0.018*
CX	19.14	2.92	2.50	*0.000*
AC	11.62	2.62	2.13	*0.001*
CP	110.82	3.10	1.81	*0.000*
EP	1.85	3.24	3.09	0.147
OS	7.84	2.51	2.18	*0.005*
SS	4.00	3.53	3.32	*0.047*
DS	66.16	3.89	3.03	*0.000*

RA relative advantage, *CX* ease of use (complexity), *AC* absorptive capacity, *CP* compatibility, *EP* external pressure, *OS* perceived outside support, *SS* supply-side benefits, *DS* demand-side benefits

external pressures do not seem to be a discriminating factor for the adoption of AM technologies.

5.2 Multivariate analysis

All variables, which yield significant results in the univariate tests ($p < 0.05$), are considered for the multivariate analysis. These are: relative advantage, ease of use (complexity), absorptive capacity, compatibility, perceived outside support, supply- and demand-side benefits. As multivariate tests are sensitive to correlations among variables (Tabachnik and Fidell 1996), we conduct a collinearity analysis prior to the logistic regression. According to Johnston (1984), intervariable correlations should not be higher than 0.5, otherwise the regression model might get biased. We find a significant correlation between relative advantage and supply-side benefits ($r = 0.54$, $p < 0.01$), which exceeds this threshold value. Consequently, we exclude relative advantage from the multivariate regression as we consider the other variable more relevant for our research. The VIF values are much lower than the cut-off value ten: The highest VIF value is 1.67 and pertains to compatibility. Therefore, we can assume that (after elimination of relative advantage) multicollinearity does not depict a serious issue in our analysis.

The outcomes of the multivariate logistic regression are shown in Table 7. The findings suggest that demand-side benefits ($p < 0.001$) together with compatibility ($p < 0.001$) have an impact on the decision to adopt AM technologies. Even when choosing a stricter critical significance level than 0.05, as suggested by the Bonferroni method (see e.g. Bland and Altman 1995), the two effect sizes remain significant ($p < 0.001$ is still lower than the Bonferroni corrected p value of 0.008). Ease of use (complexity), absorptive capacity, perceived outside support, and supply-side benefits also seem to be positively linked to AM technology adoption. However, the results for these variables are not significant. The non-significant

Table 7 Results of the multivariate logistic regression analysis

Variable	β coefficient	Wald statistics	Significance level
Ease of use (complexity)	0.643	0.957	0.328
Absorptive capacity	1.216	0.663	0.415
Compatibility	9.207	32.093	*0.000*
Perceived outside support	0.886	0.158	0.691
Supply-side benefits	0.893	0.095	0.758
Demand-side benefits	5.061	15.251	*0.000*

Actual	Predicted		% Correct
	Non-adopters	Adopters	
Non-adopters	68	15	81.9
Adopters	13	99	88.4
Overall			85.6

value yielded from Hosmer and Lemeshow's test statistic ($p = 0.428$) and relatively high values for Cox and Snell's ($R^2 = 0.494$) as well as Nagelkerke's ($R^2 = 0.663$) goodness of fit statistics indicate the good fit of the model. Moreover, the classification table reveals that in 85.6 % of the cases, the regression model correctly classifies adopters and non-adopters into their respective groups (adopters: 88.4 %, non-adopters: 81.9 %). This suggests that our model provides a good fit with the data.

6 Discussion

In this study on AM technology adoption, the role of supply chain-related factors—beside other potential determinants—was explicitly examined. In the univariate analysis, significant differences were found between adopters and non-adopters of AM technologies with regard to both, perceived supply- and demand-side benefits. This is in line with hypotheses H4a and H4b, suggesting that inter-organizational aspects are relevant discriminators between the two groups. In the multivariate tests, supply side-benefits did not turn out as a significant predictor for the decision to adopt AM technologies. It is possible that its significant correlations with demand-side benefits ($r = 0.36$, $p < 0.05$) and compatibility ($r = 0.18$, $p < 0.05$) reduced its effectiveness. In contrast to that, the perceived opportunities on the demand-side of a firm's operations were found to be influential predictors of AM technology adoption. Thus, adopters distinguish themselves from non-adopters due to their stronger perception that a switchover from traditional to additive manufacturing enables firms to move production closer to the customer and to fabricate customized parts. Moreover, users of AM technologies tend to see a greater potential in AM for fostering the customer service level and the responsiveness to changing customer needs. The relevance of these demand-side benefits may be attributed to the rising importance of supply chain management, which follows the ultimate aim of generating competitive advantages to (end) customers (Mentzer et al. 2001).

Relative advantage and ease of use (complexity) of AM technologies yielded significant results in the univariate analysis. Thus, adopters distinguish themselves from non-adopters because they perceive that AM technologies are less complex and have higher relative advantages compared to other manufacturing technologies. Hypotheses H1a and H1b are therefore supported. It seems that users of AM technologies think more positively about the technologies, because both technology-related determinants help to distinguish between adopters and non-adopters. This might indicate that technology-minded companies tend to be more prone to pursue AM than less technology-minded firms. However, our research cannot provide proof for this possible linkage, as we do not have any information about the responding firms' general attitude towards technologies. Surprisingly, our multivariate tests did not reveal significant effects for the two technology-related variables. Compatibility may have had an influence on ease of use (complexity), because a significant and positive correlation between the variables exists ($r = 0.39$, $p < 0.01$). Respondents might think that if AM technologies are compatible with their business (e.g. existing process flows, IT-infrastructure), then they are also easier to use, implement or maintain. Significant links of relative advantage with supply-side benefits ($r = 0.54$, $p < 0.01$) and demand-side benefits ($r = 0.32$, $p < 0.05$) suggest that the special characteristics of AM technologies may not only create advantages over other manufacturing technologies, but can also provide opportunities on the supply- and demand-side of a firm's operations.

Firm-specific factors, expressed by a company's absorptive capacity and compatibility, were found to be positively associated with AM technology adoption. In our univariate tests, both variables depicted significant discriminators. Therefore, adopters of AM technologies tend to be better at assimilating new information and commercially seizing that knowledge than non-adopters. This supports hypotheses H2a and H2b. The positive link between compatibility and adoption suggests that firms, which believe that AM technologies provide a good fit with their business, are more likely to use the technologies for the production of industrial parts. This is in line with IDT, which suggests a positive relationship between an innovation's compatibility and its adoption rate (Rogers 1962). Compatibility also yielded significant effects in the multivariate regression, indicating the variable's predictive power concerning the decision to adopt AM technologies. This confirms our assumption that although compatibility problems do not seem to be a relevant barrier for AM technology usage in RP (Arvanitis and Hollenstein 2001), they would inhibit AM technology usage in industrial parts production. An increased need to integrate AM technologies into existing systems (e.g. process flows, information technology) when pursuing AM instead of RP could explain this phenomenon.

Market-structure-related factors, operationalized through perceived outside support and external pressures, only appear to have a limited impact on the adoption of AM technologies. The univariate analysis indicates a significant, positive relationship between perceived outside support and AM technology adoption, which supports hypothesis H3b. Adopters more than non-adopters perceive that they can get access to outside support for employee training, AM technology implementation and operation. The (perceived) availability of external support, e.g. from vendors or consultants, may reduce uncertainty concerning AM technologies' relative advantage and therefore make adoption more likely. However, the multivariate analysis did not show significant effects for perceived outside support. The variable's significant correlation with compatibility ($r = 0.21$, $p < 0.05$) might have reduced its effectiveness. Moreover, our analyses reveal that external pressures do not depict a relevant discriminating factor between adopters and non-adopters of AM technologies. Therefore, hypothesis H3a is not supported. Firms seemingly do not use AM technologies because they feel these might help them withstand in a challenging business environment. Instead, perceived benefits at an organizational and inter-organizational level appear to be the main motivational factors for pursuing AM.

Table 8 summarizes the results of the hypotheses tests. The findings highlight the interdisciplinary nature of our research: not only firm-related factors, which are typically addressed in intra-organizational management literature, are relevant for AM technology adoption, but also supply chain-related factors, which are inherent to logistics and operations management studies. We could show that perceived benefits on the demand-side can better explain AM technology adoption than potential company-internal benefits. Moreover, the empirical results indicate that a manufacturing technology is more likely to be adopted if it is able to reduce the complexity of the upstream supply chain. However, we could not entirely prove this assumption. Overall, our work gives reason to regard the constructs "relative advantage" (from IDT) and "perceived usefulness" (from TAM) in a wider scope, because the speed of an innovation's adoption may not only be accelerated by the gains it is expected to generate for a focal firm, but also by those it may bring to a company's supply chain.

Table 8 Results of hypotheses on AM technology adoption for industrial parts production

	Main effects on AM technology adoption for industrial parts production	Prediction	Univariate analysis	Multivariate analysis
Technology-related factors				
H1a	Relative advantage	+	+ ($p < 0.05$)	Not significant
H1b	Ease of use (complexity)	+	+ ($p < 0.001$)	Not significant
Firm-related factors				
H2a	Absorptive capacity	+	+ ($p < 0.01$)	Not significant
H2b	Compatibility	+	+ ($p < 0.001$)	+ ($p < 0.001$)
Market structure-related factors				
H3a	External pressure	+	Not significant	Not tested
H3b	Perceived outside support	+	+ ($p < 0.01$)	Not significant
Supply chain-related factors:				
H4a	Supply-side benefits	+	+ ($p < 0.05$)	Not significant
H4b	Demand-side benefits	+	+ ($p < 0.001$)	+ ($p < 0.001$)

7 Conclusion

The aim of this paper was to identify the determinants of AM technology adoption for the production of industrial parts. Significant differences were detected between adopters and non-adopters of AM technologies with regard to relative advantage, ease of use (complexity), absorptive capacity, compatibility, perceived outside support, supply- and demand-side benefits. Additionally, we found that compatibility and demand-side benefits are relevant predictors for the decision to employ AM technologies. Thus, users distinguish themselves from non-users due to their stronger perception that AM provides a fit with their company in terms of processes and (IT) structures. Another discriminating factor is the fact that adopters see more potential in AM for enabling a decentralized, customized production as well as for increasing the customer service level and the responsiveness to changing customer needs. Overall, the results suggest that not only firm- but also supply chain-related determinants may explain the adoption of AM technologies.

Our work sheds more light on the business implications of AM technologies, a still widely unexplored field. Thus, we follow Holmström and Romme (2012), who call for more basic research on how and where to introduce novel technologies. Existing studies mainly focus on economic aspects of AM technologies, e.g. Hopkinson and Dickens (2003), Ruffo et al. (2006) and Ruffo et al. (2007). Our investigation on the adoption of AM technologies has a wider scope, because besides internally-focused (cost) considerations, the role of inter-organizational factors is examined. To our knowledge, no other research has specifically analyzed the impact of supply chain-related factors (i.e. supply- and demand-side benefits) on the adoption of a manufacturing technology. Therefore, our work adds new insights to adoption literature by highlighting the relevance of inter-organizational aspects for the adoption of new manufacturing technologies. By combining knowledge from technology, innovation, behavioral science and operations management research, we take an interdisciplinary perspective. This approach helped us to identify relevant determinants of AM technology usage. Now, in return, we hope to contribute to interdisciplinary research by encouraging scholars to include supply chain-related factors in future studies on the adoption of innovations.

Vendors of AM equipment may use the findings to get more insights in companies' motives to use additive technologies. This can help them improve their offerings and target customers more effectively. Potential users of AM technologies may benefit from this research by identifying capabilities of AM in different contexts. Moreover, industrial firms are stimulated to reconsider their make-or-buy decisions before adopting new manufacturing technologies, because usage of these technologies could make vertical integration more attractive.

Limitations of this study arise, because it investigated the adoption of a specific innovation. Therefore, the findings cannot easily be generalized. Moreover, the group of AM technology adopters did not only contain companies that are currently using AM technologies, but also likely adopters (i.e. firms, which are interested in or planning to use AM technologies for industrial parts production). Although this can be justified by existing insights from the adoption literature, such as the linkage between attitude towards using and actual usage of a technology (e.g. Davis et al. 1989), it somewhat limits the explanatory power of our analysis.

Future research should provide more differentiated insights in the drivers of AM technology adoption. Especially the role of supply chain-related factors in different areas of AM technology application seems worth exploring. For example, it is possible that demand-side benefits are a particularly important adoption determinant in a mass customization environment, whereas supply-side benefits may be more relevant in the production of complex objects, which have a high potential for functional integration. Last but not least, the role of different supply chain configurations (e.g. centralized vs. decentralized) and a firm's positioning within the supply chain should be investigated. AM technologies' demand-side benefits could be particularly relevant for companies operating on higher levels of the supply chain, because they are more exposed to (end) customers' needs.

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