Additive manufacturing value chain adoption

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Abstract

Purpose – Adopting additive manufacturing (AM) on a large-scale requires an adoption in company value chains. This may happen through product innovation and require interorganizational cooperation, but the value-adding potential of cooperation and application recognition is still poorly understood. This study aims to investigate the progress of AM adoption in innovation projects featuring AM application recognition and interorganizational cooperation in the value chain.

Design/methodology/approach – A multiple-case study was implemented in successful metallic AM adoption examples to increase the understanding of AM adoption in value chains. Primary data were collected through interviews and documents in three AM projects, and the data were analyzed qualitatively.

Findings – All three AM projects showed evidence of successful AM value chain adoption. Identifying the right application and the added value of AM within it were crucial starting points for finding new value chains. Interorganizational collaboration facilitated both value-based designs and experimentation with new supply chains. Thereby, the focal manufacturing company did not need to invest in AM machines. The key activities of the new value chain actors are mapped in the process of AM adoption.

Research limitations/implications – The cases are set in a business-to-business context, which narrows the transferability of the results. As a theoretical contribution, this paper introduces the concept of AM value chain adoption. The value-adding potential of AM is identified, and the required value-adding activities in collaborative innovation are reported. As a practical implication, the study reveals how companies can learn of AM and adopt AM value chains without investing in AM machines. They can instead leverage relationships with other companies that have the AM knowledge and infrastructure.

Originality/value – This paper introduces AM value chain adoption as a novel, highly interactive phase in the industry-wide adoption of metallic AM. AM value chain adoption is characterized in multi-company collaboration settings, which complements the single-company view dominant in previous research. Theory elaboration is offered through merging technology adoption with external integration from the information processing view, emphasizing the necessity of interorganizational cooperation in AM value chain adoption. Companies can benefit each other during AM adoption, starting with identifying the value-creating opportunities and applications for AM.

Keywords Manufacturing technology, 3D printing, Additive manufacturing, Value chain

Paper type Research paper

Introduction

The metallic additive manufacturing (AM) industry has been growing over the years, and technology has developed into a considerable alternative when firms select manufacturing methods for their products. The adoption of AM (i.e. incorporating AM into commercial use) happens at different levels: as a concept, as a process innovation and as a product innovation

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(Steenhuis *et al.*, 2020). Therefore, metal product manufacturers that choose AM as a manufacturing method will face all these adoption tasks. This paper focuses on AM adoption in the value chains of large companies.

The process of AM adoption is not limited to a single company but potentially spans the value chain (Steenhuis and Pretorius, 2017). Technology companies have adopted the concept of AM and have started to produce AM machines (Steenhuis *et al.*, 2020). After the market introduction of AM machines, pioneering companies, mostly start-ups, purchased these machines and developed specialized skills for AM, adopting AM as a process innovation (Martinsuo and Luomaranta, 2018). Simultaneously, engineering and design companies have explored AM technology from the perspective of design (Luomaranta and Martinsuo, 2020). As design companies tend not to have their own production capacity or product brands, they need to sell their design services to companies that do. This paper argues that before adopting AM as a manufacturing method for certain products, metallic AM must be adopted as the chosen manufacturing technology not only by larger product manufacturers but also more broadly in their value chains, and both processes and products require innovations.

Previous studies already recognized that manufacturing companies have different options when adopting AM; they can directly procure AM-manufactured components (Oettmeier and Hofmann, 2016), develop and contract AM-manufactured components through a new or existing supply chain (Luomaranta and Martinsuo, 2020) or start AM production internally by investing in AM machines and procuring the required materials (Oettmeier and Hofmann, 2016). Any of these options may require innovations in the supply chains compared to firms' ordinary manufacturing approaches (Luomaranta and Martinsuo, 2020). However, cooperation becomes particularly necessary if a large firm does not invest in AM machines. Involving organizations across the value chain in adopting AM is both challenging and time-consuming, requires targeted efforts by focal firms and requires research that spans the network of firms.

This study investigates metallic AM technology adoption in process and product innovation projects involving different firms in the value chain and is positioned at the intersection of manufacturing technology adoption and value chains. Metallic AM was chosen as the context for its potential centrality in manufacturing firms' value chains (Bogers *et al.*, 2016; Holmström and Partanen, 2014; Weller *et al.*, 2015) and the level of complexity concerning suitable application areas (Azteni and Salmi, 2012; Luomaranta and Martinsuo, 2020). The main goal is to generate insights into the progress of AM adoption during collaborative innovation projects. The focus is on the main research question: How and why do companies adopt AM in their production value chain? The "how" concerns understanding the AM value chain adoption process, and the "why" deals with the benefits and added value of the adopted AM technology. Theory on technology adoption applied to AM will be elaborated and expanded through an information processing view (Galbraith, 1977; Tushman and Nadler, 1978) by acknowledging the uncertainty and centrality of external integration in companies' value chains during AM adoption.

This multiple-case study focuses on innovation projects where large companies require innovations for a certain product and related processes, find partners for the project and recognize AM as the most suitable technology and process solution for manufacturing the product. The companies themselves do not have AM machines or the skills to utilize them, but the partners in the innovation project do.

Next, the relevant literature on AM and innovations, adopting AM in the value chain, and AM product innovations are reviewed. Then, the case study approach is explained, including the introduction of the three cases, data collection and analysis. Analytical case narratives describe how the adoption of AM unfolded from introducing the idea of AM to establishing a new AM supply chain. The findings then report how AM adoption changed operations and added value and how activities were carried out in collaborative settings in the innovation projects. The discussion and conclusions reveal the need to view the adoption of radical new manufacturing technology as value chain adoption.

Literature review

AM and innovations

Innovation, following Schumpeter's (1934) definition, means the introduction of a new good, feature or method of production; the opening of new markets; the acquisition of new material sources; or the implementation of a new organization in an industry (Schumpeter, 1934). AM covers multiple dimensions in the Schumpeterian innovation definition as it is a new technological solution that enables a novel method of production to produce new goods in existing or new market segments. AM as an umbrella term refers to many types of technological approaches that allow building objects by increasing material, such as metals, ceramics, plastics or composites, usually layer-by-layer, directly from digital 3D designs (ASTM, 2012; Holmström and Partanen, 2014).

Besides technology innovation, AM can be viewed as a systemic innovation as its large-scale benefits can be achieved only when the technology is complemented with various product, process and service innovations (Martinsuo and Luomaranta, 2018). AM has the potential to impact value chains by much more than simply replacing one machine with another in the production process (Stentoft *et al.*, 2016). Systemic innovations involve multiple mutually influencing, interconnected innovations as part of a broader system (Mulgan and Leadbeater, 2013) that require collaboration in the business network (Chesbrough and Teece, 2002). Reaching competitiveness requires that companies join forces in a broader national or local innovation system where resources, demand conditions, competition and supportive industries jointly drive innovation throughout the value chain (Porter and Stern, 2001). Systemic and fast-developing technologies allow firms to collaborate and build on the strengths of other firms and, thus, legitimize the new technology, establish new industry standards and create a bandwagon effect (Chesbrough, 2003; Garud *et al.*, 2013; Van de Ven, 2004).

Adopting AM in the value chain

AM, as a systemic innovation, has different stages in which it must be adopted (Steenhuis *et al.*, 2020). After the invention of AM technologies, materials and software, the concept of AM is adopted by companies that produce AM machines commercially. They then sell these machines to companies that adopt them into their production of prototypes or commercial goods. The final stage is for customers to adopt products manufactured with AM (Steenhuis *et al.*, 2020).

Despite the growing number of studies on AM adoption, the actual organizational process for adopting AM is poorly understood. Several studies map certain factors and drivers of or barriers to industrial AM adoption (Chaudhuri *et al.*, 2018; Cohen, 2014; Delic and Eyers, 2020; Fontana *et al.*, 2019; Marak *et al.*, 2019; Martinsuo and Luomaranta, 2018; Oettmeier and Hofmann, 2017; Schniederjans, 2017; Schniederjans and Yalcin, 2018; Sobota *et al.*, 2021; Tsai and Yeh, 2019; Yeh and Chen, 2018). These studies do not, however, explain the process of adopting metallic AM technology in interorganizational settings. Also, a recent meta-study by Ukobitz (2021) concluded that (perhaps due to the novelty of AM technology in companies) most previous studies have concentrated more on the intention to adopt AM in firms and the barriers preventing it instead of the actual adoption.

Only a few studies cover the actual organizational adoption of AM, focusing merely on a single firm and non-processual albeit metallic AM (Mellor *et al.*, 2014) or polymer AM technology (Sandström, 2016). One study covered an actual metallic AM adoption case in depth and as a process. Rylands *et al.* (2016) concluded that external sources for acquiring knowledge and cooperatively generating new value with a local university by co-creating product innovations with existing products explain the success of AM adoption in firms. Firms may lack the knowledge needed for AM adoption, and collaborating with other organizations with different knowledge and skills could be helpful (Luomaranta and Martinsuo, 2020).

When AM value chains include multiple firms, there is a need to understand the interorganizational cooperation and flows of information necessary for AM adoption. The information processing view of organizations (Galbraith, 1977; Tushman and Nadler, 1978) acknowledges that organizations face various degrees of uncertainty in their tasks and, consequently, experience information processing needs. External (or supply chain) integration – manufacturers' collaboration with supply chain partners and collaborative management of processes (Flynn *et al.*, 2010) – represents one possible means for organizations to increase their information-processing capacity (Srinivasan and Swink, 2015). External integration concerning customers and suppliers has been positively associated with the comprehensiveness of planning (Srinivasan and Swink, 2015) and some aspects of manufacturers' performance (Flynn *et al.*, 2010; Srinivasan and Swink, 2015). Kim and Schoenherr (2018) differentiated between external integration for products and processes and tested their effects on return in contract manufacturing, showing somewhat contradictory results. While none of these studies deal with technology adoption or AM specifically, external integration in line with the information processing view could potentially explain some challenges in AM adoption and help in developing new knowledge, particularly on AM value chains.

To conclude, previous studies on the organizational adoption of metallic AM are limited to single organizational settings and the intention to adopt instead of adoption progress or success. This research fills the gap concerning completed AM value chain adoption in interorganizational settings by elaborating and expanding the theory of AM adoption with external integration in line with the information processing view and thereby responding to calls by Ukobitz (2021) and Rylands *et al.* (2016).

Product innovations for AM

The task causing uncertainty and requiring information processing in AM adoption deals with the product intended to be manufactured. "Product" is used generally by AM manufacturers as anything they manufacture for their customers, whereas for the purchasing customer, it can be a component or part of a broader solution. Finding suitable products to be produced with AM and creating value for the customer have been recognized as crucial for the adoption of AM in the value chain (Luomaranta and Martinsuo, 2020; Martinsuo and Luomaranta, 2018; Rylands *et al.*, 2016; Sobota *et al.*, 2021). A value-focused approach to AM adoption and product innovations means concentrating on the value the new technology can create for the organizations involved. For example, Fontana *et al.* (2019) and Rylands *et al.* (2016) studied the adoption of AM from a value-driven perspective, considering product development and operations levels for a focal firm.

Opportunity recognition and concept development represent key activities for product innovation (Kirzner, 1997; Shane, 2000; Koen *et al.*, 2001). Existing proprietary knowledge plays an influential role in recognizing the potential opportunities of AM technology, and knowledge of customer problems is important in discovering the right products and services with which to exploit new technology (Shane, 2000). These kinds of activities in development projects can be outsourced (Quinn, 2000), but when collaborating with partners in the value chain, trust between organizations becomes an important aspect of AM-related product innovations in the early phase of adoption (Luomaranta and Martinsuo, 2020; Stentoft *et al.*, 2021).

In the case of AM, the phenomenon of opportunity recognition is referred to as application recognition (Fontana *et al.*, 2019), indicating the specific purpose to which AM technology is applied. This is the concept employed in this study. By recognizing the applications, new product (part, component or end-use product) innovations become possible.

With AM technologies, there is an ongoing debate as to whether applications should be recognized and selected based on a need to develop and replace existing traditionally manufactured goods or to produce completely new products. Previous research reports processual models for recognizing suitable existing parts to be converted for manufacturing with AM (Chaudhuri *et al.*, 2021; Knofius *et al.*, 2016; Lindemann *et al.*, 2015). In a top-down process, the search covers the database of a company's products (especially spare parts) and other commonly available databases; key indicators are assessed; and the best part candidates are selected based on their technological and economic feasibility to be converted into AM manufacturing (Knofius *et al.*, 2016). In a bottom-up process, a company's personnel use their knowledge, skills and creativity in a specially designed workshop to assess existing components' functional, geometrical, manufacturability-related and economical aspects to identify possible AM-converted parts (Lindemann *et al.*, 2015). The top-down and bottom-up approaches can also be combined, as illustrated by Chaudhuri *et al.* (2021).

The existing approaches to application recognition do not explain how and why companies decide to use these part identification frameworks, and our study fills this need. Future research directions deal with the limited data availability of products, design for AM and its influence on innovation and combining conventional and AM technologies in product innovations (Frandsen *et al.*, 2020). The systemic nature of AM-related innovations indicates an evident need for further research on AM adoption and application recognition. A systematic analysis of AM value-adding potentials can reveal radically new domains (covering prototyping, enhanced designs, incremental product launch, custom products, improved delivery, production tools and process concentration) and more versatile possibilities for AM adoption across firms in the value chain (Fontana *et al.*, 2019).

This study expands the view of a focal firm to networks of multiple firms. We employ the value chain concept to emphasize the actions and activities during AM adoption (Hansen and Birkinshaw, 2007) but widen the perspective to cover the network of companies in production supply chains.

Research method

Research design

A multiple-case study design was used to develop a new understanding of AM adoption in the value chain. This strategy was chosen because it enables studying the phenomenon in its natural, real-life context with many possible data sources (Piekkari *et al.*, 2009) and provides a holistic explanation of the cases under study (Ragin, 1992). Multiple cases can be jointly studied to compare and complement each other and to offer information on the core phenomenon (Stake, 2005).

Three cases were intentionally selected as they represent ordinary AM innovation projects, concern both product and process innovations and involve multiple firms in the value chain. We sought recently completed AM innovation projects that featured a specific product and included a company network or at least a dyad. Another selection criterion was that AM technology was used in production (i.e. adopted) and not just in development, so the focus is on the end-use components instead of only prototypes. Also, voluntary participation was sought – the key persons were willing to share their first-hand experiences in AM-related innovations.

Cases

Altogether, seven companies were involved in the two innovation projects. Each project includes a focal firm (i.e. a customer who needed the innovated product as part of its core processes) as well as other companies involved in product innovation and manufacturing. The first project (Case 1) concerns the radical re-engineering of an already-existing component that was functionally critical in its final assembly. The component was completely re-engineered for a radically new manufacturing solution of AM; involved four companies (CU1, ID1, AM1 and MM1; Table 1); and used services from one external company (MM2) to post-process the component.

Company	Key informant title	Interview information	Case
CU1 Process plant technology manufacturer Employs 13,000+ people	Development manager	75 min, provided additional documents	1
	Senior chief engineer	35 min	1
CU2 Mass transport and logistics vehicle maintenance and lifecycle company Employs 1,000+ people	Purchasing manager	90 min, provided additional documents	2a and b
	Chief specialist	76 min, provided additional documents	2a and b
ID1 Industrial design and technology development company Employs 400+ people, ca. 10 in the AM team	Head of AM team, AM designer	1st interview 68 min, provided additional documents 2nd interview 61 min	1, 2a and b
	AM designer	80 min	1, 2a and b
AM1 AM contract manufacturer Employs 10+ people	Sales, metals specialist, and industrial designer	43 min	1
	Sales manager	30 min	1
AM2 AM contract manufacturer Employs 5+ people	Founder, technology director and industrial designer	43 min, provided additional documents	2a
	Founder, CEO	76 min, provided additional documents	2a
MM1 Contract manufacturing company specializing in metals Employs 30+ people	Sales director	25 min	1

Table 1. Background information of interviews

The second project includes two subcases (Case 2a and Case 2b) representing two different innovations where obsolete parts were re-engineered. Subcase 2a involved three companies (CU2, ID1 and AM2) in the innovation project, whereas subcase 2b involved only two firms (CU2 and ID1) and used sourcing from one external company (AM3) to manufacture the re-engineered component.

In Case 1, CU1 is a global process plant technology manufacturer selling its own products. CU1 has its own design, manufacturing and assembly units but also sources components, designs and engineering consultations from other firms. In Cases 2a and 2b, CU2 is a mass transport and logistics vehicle maintenance and lifecycle company that repairs and maintains customer vehicles. It usually purchases, or in some cases manufactures, spare parts and does the installation and repair. CU1 and CU2 are in a central position in adopting AM components in their value chain as they fund the project, engineering and design services and finally purchase the new AM components or subcontract their manufacturing.

ID1 has acquired special skills and knowledge about design and engineering for AM and provided expertise in application recognition and product innovation to help CU1 and CU2 in the studied innovation projects. In Cases 1 and 2a, AM contract manufacturing companies (AM1 and AM2, respectively) also took part in the innovation project. In Case 1, two contract manufacturing companies with traditional machinery were additionally involved in the innovation project. All seven companies are headquartered in Europe and operate globally. We focused only on the companies active in the innovation projects and purposely excluded the other possible organizations involved in the supply chains, such as transport firms, material and software suppliers and customers of companies CU1 and CU2.

Data collection

The innovation projects were studied retrospectively. Data were collected from past events by interviewing the persons involved in the projects, as suggested by Thomas (2011). The data were collected using 12 semi-structured interviews and supplementary open-ended discussions after formal interviews with 11 key informants from the involved companies. The interviews were conducted using video conference calls, which allowed the key informants to provide internal company documents to visualize with screen sharing the product innovations and the different phases that took place in the innovation process. These interviews were recorded, resulting in digital video/audio files.

Table 1 summarizes the interviews and background information of key informants and companies. It also explains the companies' involvement in the cases. The key informants all participated in the product innovations and were key specialists and decision-makers in the projects. Additionally, each company's webpages, blogs, videos and webinars were reviewed before the interviews as secondary data and documented in memos.

Data analysis

The data analysis takes the point of view of product innovation and value chain-level actions from the perspective of both intra- and interorganizational processes. Coding was done inductively (Tavory and Timmermans, 2014), acknowledging that the codes and themes emerged from the data, but the researcher's previous knowledge was also acknowledged as influencing the emerging codes. During each interview, handwritten notes of initial ideas for codes and preliminary ideas for analysis were documented to take advantage of the original situation and the situational intuition of the interviewer (Tessier, 2012).

The analysis was conducted using Atlas.ti software, which allowed coding of the interviews directly from the recorded video conference call files. In this way, additional material could be coded, too, which is suggested by Tessier (2012). The most illustrative phrases of codes were then transcribed for the purpose of reporting the findings and giving transparency to the data.

Coding started by identifying actions, events and context (organizational) and existing problems and the value-adding solutions of AM in the value chain important for the innovation projects. Example codes include "proprietary knowledge," "sourcing/creating knowledge," "starting of cooperation," "cooperation," "seeking partners," "industrial context," "AM added value" and "value chain position," which represent ingredients in the adoption of AM into the value chain of product manufacturing company.

Then, the coded actions were organized chronologically into a timeline (Eveland and Tornatsky, 1990). The analysis then proceeded to writing a narrative of each case to serve as analytical presentations of the cases (Munksgaard *et al.*, 2014). The intention was to preserve the in-depth richness of the cases in the analytical descriptions to increase the insights relevant to the cross-case analysis. This approach also enables readers to conduct further interpretations of the cases and enhances the transferability of results (Stake, 2005).

The analysis then proceeded into the cross-case analysis. First, the added value of AM was analyzed inductively. Then, from the timeline of analytical case descriptions, three distinct phases emerged where events and actions took place. The events regarding network structure changes were further inductively coded as "before AM adoption," "during AM product innovation" and "new AM supply chain structure" to address the evolutionary stages of innovation (Eveland and Tornatsky, 1990). The activities were further coded, and the categories that inductively emerged from the data are presented in Table 3. This analysis enabled revealing how the AM adoption proceeded and what drivers and value-adding aspects influenced AM adoption.

In the findings section, analytical case narratives are first presented case-by-case, followed by the cross-case analysis of the value-adding features of the AM. The cross-case analysis then proceeds thematically, concerning the main phases, value chain changes and activities of interorganizational collaboration during AM adoption.

Findings

Case 1: re-engineering essential parts for the process plant machines

CU1 has many complex parts in their machine systems. Most of these parts are hard to manufacture, and their performance can be low due to design compromises and manufacturability issues. CU1 collaborates actively with local universities. Case 1 started when a highly compromised component, a flow manifold (among others), was given to students as a part to be improved in a course assignment. One student group introduced AM to improve performance and enable redesign.

At that time, the component had become too costly, but CU1 continued the development in a strategic AM project. Consequently, a thesis project was started with a local university of applied science. The thesis identified the 10 most promising components where AM could provide extra value for the whole value chain. Eventually, the flow manifold was prioritized and became the first AM component for the process plant machine.

An industrial design and technology development company, ID1, later recruited the thesis worker. After recruitment, CU1 contracted ID1 to develop the AM component idea further as they had already collaborated in other projects. ID1 had collaborated with a local AM contract manufacturer, and they proposed including AM1 in the innovation project. AM1 experimented with hybrid manufacturing, which was only a hypothetical option at the time, which was introduced to them by the manufacturer of their AM machine. AM hybrid manufacturing here meant that two high-tolerance mounting flanges were manufactured from flat metal using computer-controlled machining, and the bigger flange was set up as the building platform of the powder bed AM machine. ID1 then used this approach in the re-engineering process.

According to the key informants in AM1, ID1 and CU1, this was a groundbreaking technical solution to the problem of creating new value with AM. This way, the cost of the component was decreased by 30%, the power loss of the component was decreased by 70%, and a 25% higher volume output was achieved through the AM-manufactured flow manifold. Part consolidation reduced the number of components needed in the assembly from seven to three. Originally, the processing machine required two mirrored parts on the different sides of the machine, but the new design allowed the same part to be used on both sides. This way, the part consolidation resulted in an actual component count reduction from 14 to 3, reducing the assembly complexity.

ID1 was the project leader in that they served as the link between CU1 and AM1; all contributed to the radical re-engineering of the component. MM1 was chosen from among the existing suppliers of CU1 to produce CNC-milled flanges. When the part was developed, tested and ready for production, ID1 helped arrange the new supply chain agreements between CU1 and MM1, AM1 and MM2. The help for arranging the new supply chain included the transaction of final digital designs and specifications for each manufacturing phase in the supply chain.

At this point, CU1's sourcing unit experienced problems because its sourcing processes and information systems were based on blueprints and a single subcontractor per part. Ordering the new AM part would require using a digital 3D design, and this single part was manufactured by three different subcontractors. MM1 then solved the issue with CU1 by scaling down the original 14 lines in the information system into a one-line order. MM1 became responsible for overseeing this new supply chain. This way, the sourcing process in Company C1 was simplified even though they perceived themselves to be in active collaboration with all the companies involved.

Cases 2a and 2b: spare parts redesigned for AM

Cases 2a and 2b have similar features, thus they are reported together. In Case 2a, the product innovation where AM was adopted was a special swivel joint used as a transport vehicle spare part. The swivel joint was originally manufactured outside the EU by casting it in a steel foundry that no longer existed. The quality of the casted spare part for this application was poor, and establishing a new casting supply chain would require batch sizes too large. CU2 wanted to scale down their spare parts warehouse due to these specific vehicles approaching their end of life.

CU2 contracted ID1 to seek a solution for the quality- and supply-chain-related problem of this spare part after ID1 had marketed their AM services to them. The part was considered suitable for AM. ID1 redesigned the part by scanning and measuring the last spare parts in the inventory and modified the designs to improve AM manufacturability. ID1 then sourced an AM contract manufacturer, AM2, to run simulations of the part and propose final design changes to achieve better manufacturability with its AM machine. The first AM-manufactured part was already functional and was tested by customer CU2.

The new AM spare part resembled the original part in costs due to added redesign costs, reduced warehousing and logistics costs and the elimination of customs costs. Its quality exceeded that of the original part. After testing, ID1 handed over the new 3D designs and helped their customers set up the new supply chain with the AM2. The order batch size was reduced from 100 to 4, and CU2 decided to keep one batch of four swivels in its warehouse as the controlling unit for new orders. AM2 now stores the spare part 3D design, and the order is simply and effectively placed digitally.

Case 2b started simultaneously with Case 2a. In Case 2b, ID1 and CU2 together recognized another spare part to be converted to AM as they were running out of the original spare parts. This already-obsolete spare part was a complex mixing wheel with blades used in the vehicle. The last stored spare part was of too-poor quality for the contemporary specifications, and existing blueprints were insufficient. ID1 then re-engineered the part, and as the part was approximately 30 cm in diameter and complex in geometry, AM was soon determined as the suitable manufacturing approach. To design for AM manufacturability, ID1 and CU1 cooperated to measure and model the assembly interfaces for the spare part and added missing information to the blueprints. The challenging geometry of the mixing wheel also required ID1 to run both AM-manufacturability simulations and functional simulations of the assembly.

Consequently, ID1 explored contract manufacturers that could deliver the quality needed. The best option was found in North America. The transportation distance increased, but the lead time decreased considerably, costs were lower and the quality and performance of the spare part were higher. After completing the development phase and arranging the supply chain, ID1's involvement in the project was over. CU2 now has a new supply chain in place, and they will source further spare parts when needed.

Added value of AM

As described above, each case had a problematic component or spare part. Innovation projects considered and exploited AM as potential solutions to the problems. Additionally, new AM value-adding potential was recognized and successfully delivered. Table 2 summarizes the AM added value in each case.

Case 1 suffered from the original component's difficult manufacturability and low performance. AM added value was received through the manufacturing of complex geometry, which eventually led to cost reduction and functionality increase. Case 2a received AM added value through batch size reduction, which resulted in cost savings in purchasing and

Table 2. Cross-case analysis of AM added value

Case 1	Old component	AM component
	• Difficult to manufacture (basically manually)	• Easier to manufacture, 30% cheaper than old component
	• Low performance (bottleneck in its process)	• Higher in performance, power loss decreased 70%, output volume increased 25%
	• Assembling required manual fitting every time	• Parts consolidation: 3
	• Parts consolidation: 14	• Easy design scalability for other configurations in the future
Case 2a	Old part	AM spare part
	• Low quality	• High quality
	• No existing supply chain but the possibility to establish a new supply chain	• Cost per spare part same (in a batch of four) compared to casted spare parts (in a batch of 100) resulting in substantial savings (as estimated needed spare parts somewhere between 10 and 30)
	• In potential new supply chain batch size too large for end-of-life maintenance of vehicle fleet	
Case 2b	Old part	AM spare part
	• Obsolete spare part, no good blueprints existing	• Ensures future availability of the spare part
	• No existing supply chain nor the potential for new supply chain	• Viable solution to ensure availability of spare parts, as original spare parts could no longer be purchased or could not easily be sourced as manually custom-made spare part
	• Hard to manufacture and much manual welding and grinding would become costly	• Quality and lead time great
	• Last spare part in the warehouse was very low quality	• Cost acceptable

warehousing. Case 2b achieved AM added value through replacing obsolete spare parts and producing them in low quantities. In this way, the cases differed in the main value driver, but they also had commonalities, such as higher quality and functionality compared to the old counterpart.

The different contexts of the cases disclose why the AM added value was decisive. The informants from CU1 explained that all possible savings were sought from production costs due to competition. Also, the continuous development of process plant machines is necessary for the company to retain its market-leader position. CU2, in turn, operates mainly with publicly owned transportation companies. The lifecycles of the vehicles are 30–60 years, and the maintenance activities and spare parts availability of CU2 are expected to serve throughout these lifecycles. However, over time, the availability of spare parts may be endangered. Consequently, the spare parts may need to be sourced from different suppliers using the same manufacturing technologies or, as in this study, be replaced with completely new technologies, as was done in the cases involving CU2.

Value chain changes during AM adoption

Each part chosen for AM design already had a preexisting supply chain set up for ordinary supply and manufacturing, but in Cases 2a and 2b, the product and related supply chain was becoming obsolete. After the innovation project, the old supply chain was discontinued and a new supply chain was established. Figure 1 illustrates the changes in company networks from before AM adoption to the latest version of the supply chain.

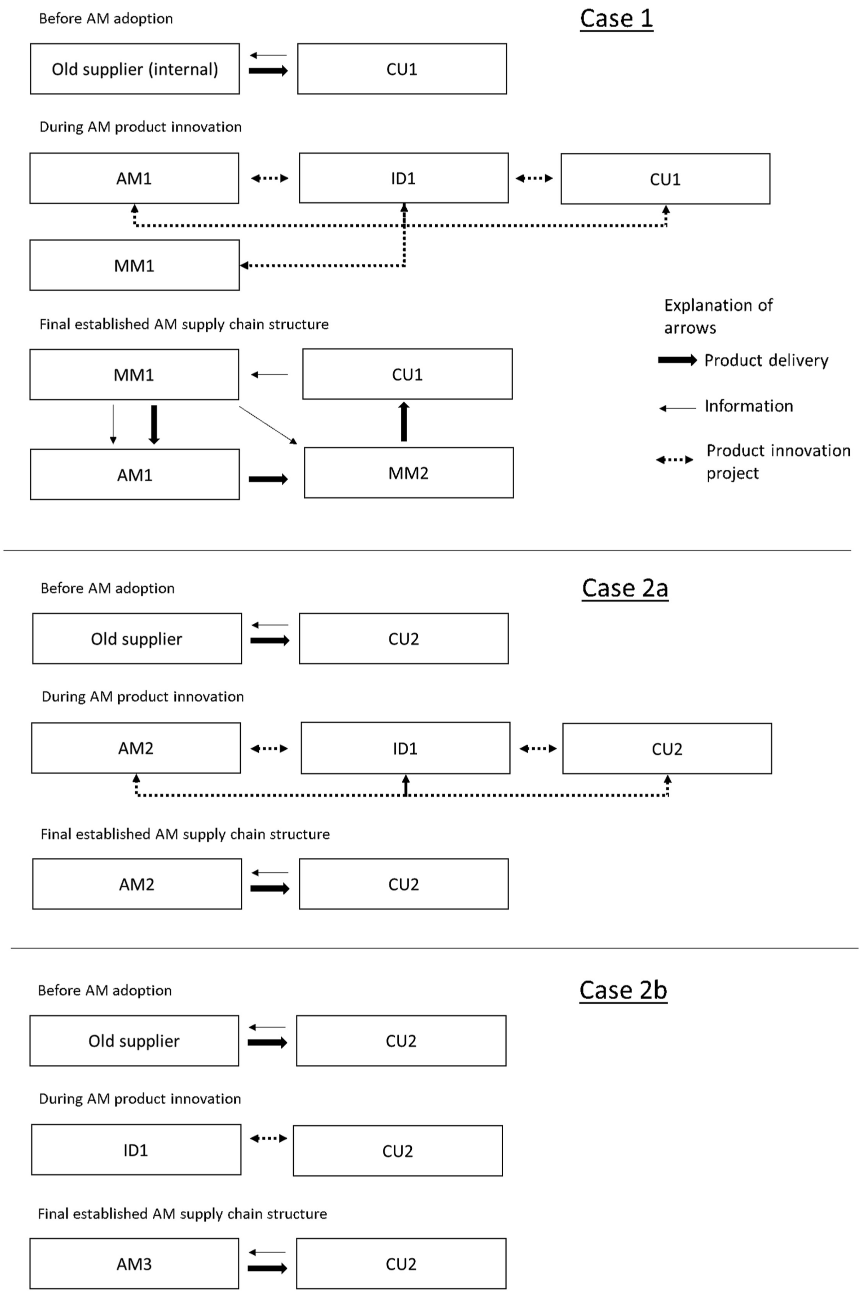

Figure 1.
Illustration of the network structures and the changes

Figure 1 illustrates that ID1 has been in a central position in these innovation projects. Also, other companies (AM1, AM2 and MM1) participated in Cases 1 and 2a, and this highlights the collaborative work that led to the adoption of AM into the value chain of the large manufacturing companies CU1 and CU2.

Activities and interorganizational collaboration during AM adoption

Table 3 clarifies the organizations' cooperation in Figure 1 and activities during the AM innovation project. The innovation projects had approximately the same activities but slightly different involvement and collaboration by companies.

Table 3. Activities during the AM innovation projects and interorganizational cooperation

	Activities during the AM innovation project (presented in sequential order, but each activity may have feedback loops to other activities)				
Active companies involved	Starting of collaboration and application recognition	Collaborating for value-based design, potential supply chain partners' identification	Material testing*, prototyping**, demo part testing**	Accepting the design and part characteristics	Establishing supply chain with necessary design and sourcing specifications
Case 1	ID1, CU1	ID, CU1, AM1	ID1, CU1, AM1, MM1	CU1	ID1, CU1
Case 2a	ID1, CU2	ID1, CU2, AM2	ID1, CU2, AM2,	CU2	ID1, CU2
Case 2 b	ID1, CU2	ID1, C2		CU2	ID, CU2

Note(s): * in Cases 1 and 2a, ** in Case 1

Starting of collaboration and application recognition. Before starting the AM innovation projects, CU1 and CU2 increased awareness about the technologies outside their own organization; as the informant from CU2 stated: *"We have the willingness to keep up-to-date and try different options in the organizational level."* Informants in CU1 and CU2 explained they had gathered information about AM before these innovation projects to offer services to recognize the applications where AM can provide value through design. CU1 gained experience through university-related collaborations and internal development projects. CU2's informants had participated in local universities' seminars to scout AM possibilities.

For ID1, a knowledge base was built before these projects. Both informants of ID1 expressed that they had a personal interest in the new technology, and through their insights, ID1 was persuaded to establish the AM team. Neither informant at ID1 had received AM-related basic education in their engineering studies, so they educated themselves extensively about AM. Various technology fairs and seminars were useful in exploring new technological alternatives and organizations in the AM industry.

The starting point for collaboration was previous technological knowledge about AM. When ID1 contacted CU1 and CU2, they knew enough about AM to initiate an AM-innovation project once the potential applications were jointly recognized. According to a key informant from ID1: *"To find out the critical aspects where AM can be beneficial is the most demanding part of this process but also the area where our expertise shines."* This statement highlights the necessity to discover where AM can contribute additional value to even initiate a development project.

Collaborating for value-based design, identifying potential supply chain partners. In the design (or re-engineering) phase, ID1 cooperated closely with their customers, CU1 and CU2, to ensure the functionality and quality of the AM part. With its creative AM design skills, ID1 built on the parameters for the key functionalities from the customers. The product owners (e.g. CU1 and CU2) then had the product, assembly and component-level knowledge.

When these can be aligned between ID1 and either CU1 or CU2, there is a possibility to find out where AM can add value. According to a key informant from ID1, "*the most demanding part of these cooperative projects is to find out what are the actual necessities of the components, is it aesthetics, weight, certain functionality, or cost of manufacturing?*"

As neither CU1 and CU2 nor ID1 expressed an interest in investing in metallic AM machines, ID1 contacted potential AM service providers. AM1 and AM2 were then introduced to the projects and contributed with their AM manufacturability expertise. The informant from AM1 explained: *"we are focusing on the operating of this new technology of AM, and we want to be seen as the experts of this technology,"* and continued, *"if the customer request is a simple task, we do it from scratch to the end. Otherwise, a company like (ID1) is in an important role, a link between us and complex design job."*

Demonstrating, testing and accepting the design. Trust in the new technology was something that had to be gained. The second informant from ID1 explained the centrality of technology trust and the importance of testing in Case 1: *"Customers are quite reserved regarding this new technology (AM) and regarding material properties . . . this customer (CU1) was also reserved regarding the components made with AM, but they were curious, too. So, this was resolved by extensive testing of demo parts and drawbars. All the tests were conducted, the customer tested tensile strengths, examined the fractions, they even grinded them with angle grinder, tested welding and exposed the demo part to extreme conditions, and compared all the results to standard parts. Eventually, the result of these tests corresponded to our machine and material supplier's data sheets."* Drawbars are test pieces manufactured simultaneously with the part or demo that produce the same internal microstructure. Drawbars can then be predisposed to structural testing.

Another example concerning technology trust deals with evidence about product quality. The second informant from ID1 explained this through their experience in collaborating with CU2 in Cases 2a and 2b: *"With them (CU2), we had the data sheets to provide the data that these AM parts actually are very good quality, and we proceeded directly to manufacturing as these spare parts required no prototypes, but the first prints were directly ready for use."*

The difference between CU1 and CU2 concerning trust in AM might stem from the different natures of their businesses. CU1 designs and sells its own solutions – large process plants – that its customers use in conducting their main business. Each solution builds on the proprietary knowledge of CU1. The component re-engineered for AM is an important component in the process. The customer's business would be interrupted if faults occurred, so CU1 had to be certain that the quality was high. CU2, in turn, maintains its parent company's vehicle fleet and has non-proprietary components. The AM spare part was a wearing part anyway, and if it were to break in action, it would be replaced with a spare vehicle while in repair, unlike the case in CU1, where an AM component breaking would lead to the malfunction of a large process plant machine. Consequently, the reputation risks differ between these business environments.

After the completion of the desired value-adding designs, the customer companies (CU1 and CU2) accepted the parts for production. The informant from CU2 confirmed this: *"The designs and data provided looked good, and the manufacturer (AM2) simulated the results of the AM process. We then proceeded directly to ordering the spare parts . . . they are now in use, and we painted them with bright colors, and the routine maintenance pays closer attention to them, but so far everything seems to work fine."*

Establishing the supply chain with necessary design and sourcing specifications. New supply chains were established for AM manufacturing. As AM service providers AM1 and AM2 were already part of the project, they took the role of AM manufacturing after the AM manufacturing contracts were signed. In Case 2b, ID1 arranged a manufacturer for the spare part as AM service providers did not participate in the innovation project. The informant from ID1 explained their coordination role: *"We help in establishing the supply chain so that* *there will be no gaps in, for example, in quality assurance after the component or spare part is design-wise ready and ready for production.*"

The industry of AM service providers and contract manufacturers, however, is still emerging and in transition. Manufacturing standards and operational practices are still underdeveloped, and it is project-dependent who bears the responsibility for quality and what is expected to be delivered by these contract manufacturers. "*At the moment, we are in the situation where if we source a single part with similar 3D models from six different contract manufacturers, we get six different parts. This is not a huge problem per se, but in practice it creates a lock-in situation with one AM contract manufacturer, with whom we did the R&D, if we want to proceed to serial production*," said the informant from ID1. Through these activities, the AM innovation projects were carried out and ended with functioning new AM value chains.

Discussion

The main goal of this study was to generate new insights into how AM adoption takes place when adopted in the production value chains of companies that do not invest in AM machines and why AM is adopted into the value chain. This study contributes to the knowledge on the adoption of AM through the value-driven potential of AM and answers the call for studies to illustrate successful cases of AM adoption (Luomaranta and Martinsuo, 2020; Rylands *et al.*, 2016; Ukobitz, 2021). We explored companies that cooperate in the value chain to generate new opportunities and analyzed innovation projects as platforms that enable the companies to benefit from each other when identifying value-adding applications and establishing new supply chains. Technology adoption was purposely connected with external integration building on the information processing view to complement single-organization studies of AM adoption.

AM adoption in the production value chain

The main theoretical contribution adds an important stage for the large-scale adoption of AM, namely, the adoption of AM value chains, which connects technology adoption with external integration based on the information processing view of organizations (Galbraith, 1977; Tushman and Nadler, 1978) and lends support to and complements AM adoption research (Steenhuis *et al.*, 2020). For large-scale AM adoption, metallic AM must be selected and adopted in the supply chains of larger product manufacturers, as shown in our empirical study. The studied successful innovation projects showed how such product manufacturers proceeded in AM value chain adoption through a series of activities of problem identification, AM application opportunity and value recognition and value chain changes in collaboration with suitable partner companies.

AM value chain adoption takes place between process and product innovation adoption, where product problem recognition enables the process innovation of utilizing the new technology and developing a possible new structure of the supply chain and where the innovative concept of AM and its process innovations enable value-adding product innovations. The empirical study offers evidence on the temporal order of developing products and processes during AM adoption and related collaboration and, thereby, witnesses complexities identified in external integration in other contexts (Kim and Schoenherr, 2018). This modified illustration of AM adoption stages builds upon Steenhuis *et al.* (2020) and is presented in Figure 2.

The studied innovation projects showed that it is not necessarily large firms but rather pioneering companies (usually smaller) that first adopted AM and purchased metallic AM machines to experiment with the technology, start a new business and acquire new

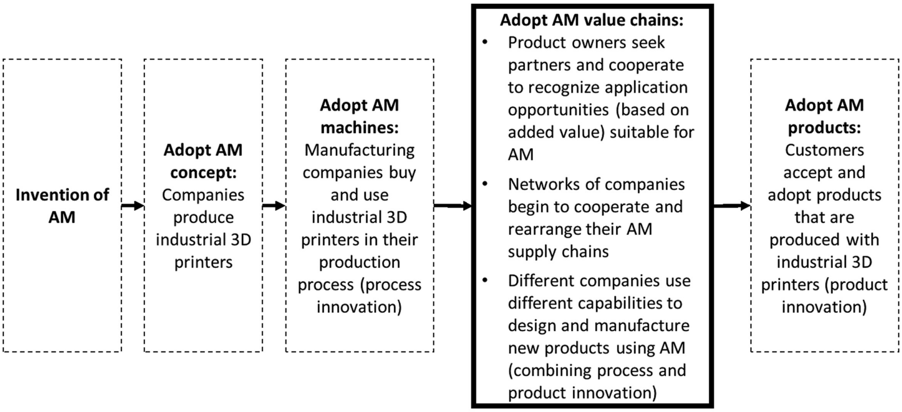

Figure 2.
Different stages of AM adoption and the main contribution of this study

Note(s): Modified from Steenhuis *et al.* (2020), dashed line boxes in the original conceptual figure

capabilities to succeed in the competition. These activities fall into the stage of companies adopting AM as a process innovation (cf. Steenhuis *et al.*, 2020). However, companies that do not seek to create a new market with new technology have a completely different perspective, and their AM adoption requires extensive movement in their value chains. For them, the technology and its potential markets are not the reasons for adopting AM into their value chains; rather, their interest is in the value of AM. They need to recognize the right value opportunities for products offered by AM technology compared to alternative manufacturing methods and establish the right fit for their value priorities and situations.

The findings concerning the first part of the research question (how companies adopt AM in their value chain) offer a new understanding of the innovation adoption process, specifically in connection with external integration. The cases revealed the simultaneous occurrence of product and process innovations when firms that did not invest in AM machines decided to adopt AM in their value chains. This indicates that successful AM adoption requires comprehensive planning, seen as an important mechanism for uncertainty reduction when integrating external partners in the supply chain (Srinivasan and Swink, 2015). Before customers adopt AM products, metallic AM value chains require significant innovation steps in cooperation between brand-owning manufacturing firms and their partner companies. While the product re-engineering that took place in the cases might be considered incremental innovation, the required process innovation is radical, as it is new to the industry and potentially also to the technology supplier, requiring intensive cooperation between the firms (Chaoji and Martinsuo, 2019). Radically new approaches were needed for recognizing the value potential of serving customers in a new way, recognizing and selecting the application suitable for AM and designing the manufacturing process and production value chain for AM.

The findings for the second part of the research question (why companies adopt) – specifically, companies' motivation to adopt AM – concentrate on the value AM can add. The identified value drivers dealt with the companies' unique business contexts and problems concerning previous components or spare parts. The solutions for these problems and other benefits (i.e. added value) were possible to realize with AM, lending support to other AM-value-related research (Fontana *et al.*, 2019; Rylands *et al.*, 2016).

Interorganizational cooperation for product innovation

The findings showed successful examples of innovation projects that featured an evolutionary process of interorganizational cooperation (Figure 1 and Table 3), the value-driven recognition and design of AM products (Table 2) and establishing new supply chains for new AM products (Figure 1). Thereby, the examples offer evidence of the unfolding of adoption processes for systemic innovations in interorganizational networks (cf. Garud *et al.*, 2013; Chesbrough and Teece, 2002) and the benefits of external integration in the form of better information processing capacity for manufacturing firms when the task of product and process innovation is highly uncertain (Flynn *et al.*, 2010; Srinivasan and Swink, 2015). AM was completely new to companies CU1 and CU2, and eventually, they adopted AM into their value chains successfully. However, AM value chain adoption required the involvement of multiple actors in innovation projects. AM application recognition, value-driven design for AM, design for AM manufacturability and establishing supply chains were central activities in driving success in AM value chain adoption for these larger companies.

This finding contributes to Fontana *et al.* (2019), who emphasized the importance of finding the right applications and recognizing AM added value. In Case 1, the AM added value stemmed from the possibility for AM to manufacture complex geometries, leading to cost reduction and increased functionality (supporting Fontana *et al.*, 2019 on enhanced designs, process concentration and improved delivery). In Case 2a, the AM added value dealt with batch size reduction, which resulted in cost savings in purchasing and warehousing (improved delivery in Fontana *et al.*, 2019). In Case 2b, the AM added value was AM enabling the production of a low quantity of highly complex obsolete spare parts where there was virtually no other option left (improved delivery, process concentration and enhanced design in Fontana *et al.*, 2019). Depending on the whole value chain and the context, there might be the possibility (or need) to cover multiple value-adding prospects of AM.

When designs of process plants are established, radically re-engineering components or converting obsolete parts for AM will likely offer many future application opportunities for AM. In this sense, replacing already-existing parts and components can, based on our findings, enable companies to build knowledge about AM, and this is relevant for the early phase of AM value chain adoption. This replacement requires the re-engineering of parts and components (Frandsen *et al.*, 2020). The exploration of the potential of AM in future industries will also create radical product innovation possibilities for AM as completely new products are yet to be invented (Fontana *et al.*, 2019).

The analysis of the cases offered additional information on the challenges of application recognition and design for AM, contributing to Fontana *et al.* (2019). The existing frameworks for recognizing AM products (Chaudhuri *et al.*, 2021; Knofius *et al.*, 2016; Lindemann *et al.*, 2015) were to some extent known by ID1 and helpful for building knowledge, but the innovation processes proceeded in a much more *ad hoc* manner than suggested by the frameworks. Application recognition requires the expertise of design companies as they have the knowledge and skills to design AM and the knowledge of their clients' products. This competence base is useful for executing customized application recognition processes that are currently out of reach for manufacturing firms or companies specializing in operating AM machines. Stentoft *et al.* (2021) similarly found that other organizations in the adopting companies' networks are a good source of knowledge required for AM adoption. The expertise and skills needed for AM are not only in the operation of the actual machines but also in being able to design new products and innovate new applications, which will benefit from the technological possibilities of AM technologies (Luomaranta and Martinsuo, 2020).

Companies adopting AM in their value chains face the legacy of earlier technologies, both as a possibility to extend product lifecycles and as a necessity to replace outdated components and related supply chains (Ballardini *et al.*, 2018). Cases 2a and 2b herein illustrate this kind of situation, where the lifecycle of the repaired vehicles with AM spare parts can now be extended by several years, and the quality of AM spare parts is superior to that of old spare parts. Various issues will need to be resolved in spare parts production for systems with long lifecycles. AM spare parts can be a feasible solution for repairing or extending the lifecycles of machines where the spare parts supply has become obsolete, but it may introduce new quality problems or increase costs (Ballardini *et al.*, 2018). Although the cost per part might be higher for AM spare parts in their small batch sizes compared to casted spare parts, the actual need for so few spare parts favors AM. Ballardini *et al.* (2018) and Frandsen *et al.* (2020) also raised the topic of missing computer-aided designs of spare parts, which needs to be resolved. Cases 2a and 2b also offer insights into how a dedicated design company (ID1) was able to re-engineer parts in a situation where there was only an old paper drawing and one low-quality spare part left for demonstration.

Conclusion

For the large-scale adoption of AM, AM concepts, products and processes need to be broadly accepted in the production value chain. Case studies of successful AM adoption have been called for (Luomaranta and Martinsuo, 2020; Ukobitz, 2021) to overcome managers' AM technology trust issues and further advance the adoption of AM. Our multiple-case study generated new knowledge on application recognition and interorganizational cooperation during innovation projects when adopting AM in companies' production value chains. The findings showed that the adoption of AM happens through successful innovation projects that cover both product and process innovations and take place in a collaborative project setting.

The first theoretical contribution extends and elaborates the process of technology adoption specifically in AM. We propose the new stage of AM value chain adoption for the existing framework of AM adoption (to add to Steenhuis *et al.*, 2020). This stage is necessary to bridge the gap between consumers' product adoption and manufacturers' technology adoption because AM alters production value chains and requires simultaneous process and product innovations. Firms within AM value chains will need to realize the potential of cooperation when adopting AM. As not all manufacturing firms are procuring and installing AM machines themselves or replacing their existing technologies, they will benefit from cooperating with other AM firms in selecting, designing and manufacturing products optimized for AM and also offer new value to customers.

The second theoretical contribution elaborates the information processing view (Galbraith, 1977; Tushman and Nadler, 1978) specifically in the context of AM innovations. Merging technology adoption with external integration from the information processing view enabled emphasizing the necessity for interorganizational cooperation in AM value chain adoption, which is a complex process and an uncertain innovation task spanning across organizational boundaries (Garud *et al.*, 2013; Chesbrough and Teece, 2002). The collaboration with other companies allows a company with little knowledge of AM to leverage the knowledge of other companies and combine it with proprietary knowledge (supporting Chesbrough, 2003; Van de Ven, 2004). This external integration through collaboration enhances the company's information processing capacity and enables managing the uncertain task of product and process innovation (in line with Srinivasan and Swink, 2015).

The third contribution is in explicating and showing evidence of the technical and business value of AM as a driver of successful AM value chain adoption. We showed how AM was able to add value compared to the alternative manufacturing methods in terms of cost, functionality, quality and availability, and this identification of added value was required for the successful adoption of the AM value chain. These findings add to earlier research on the application selection and value-driven innovation in AM (Ballardini *et al.*, 2018; Fontana *et al.*, 2019; Rylands *et al.*, 2016) by explicating the necessity to consider processes and value chains simultaneously with product innovations.

As a practical implication, this study encourages companies to educate themselves about the characteristics of AM, which will help in recognizing applications where AM can generate value for value chains. The cases illustrated how such innovation projects can be carried out in collaborative settings where project partners' knowledge and skills contribute to the application recognition and value-driven design of AM products and establishing the new AM supply chain. Regarding novel AM technology, companies that know the possibilities of AM and have the skills to identify possibilities for adding value to the application are potential collaboration partners for companies pursuing AM adoption.

The case study approach as a research design has its limitations, including those concerning the choice of cases, limited qualitative data and the framework chosen for the analysis. This study was conducted in two different industrial settings between companies accustomed to subcontracting and collaborating with other companies, and the transferability of the results primarily concerns such environments. Future research might consider conducting further case studies of successful AM adoption through innovation projects in other types of business environments and potentially focusing specifically on the knowledge, capabilities and skills of the organizations. Another interesting venture would be to study the completely new unique manufacturing context that AM opens.

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