Supply chain innovations for additive manufacturing

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Abstract

Purpose: Additive manufacturing (AM) involves the renewal of production systems and also has implications for firms' supply chains. Innovations related to AM supply chains are, so far, insufficiently understood, but their success will require firms' awareness of their systemic nature and their firm-specific implications. The purpose is to explore the supply chain innovations dealing with AM in business-to-business supply chains.

Design/methodology/approach: An exploratory qualitative research design is used. Interviews were conducted in 20 firms, workshops were organized to map AM-related processes and activities, and supply chain innovations were analyzed.

Findings: This study reveals practical changes in supply chains and requirements for AM-related supply chain innovations. While earlier research has centered on technology or firm-specific AM implementations, this study shows that fully leveraging AM will require innovations at the level of the supply chain, including innovations in business processes, technology, and structure, as well as supportive changes in the business environment. These innovations occur in different parts of the AM supply chain and are emphasized differently within different firm types.

Research limitations/implications: This research was conducted in one country in the context of the machine building and process industry with a limited dataset, which limits the generalizability of the results. The results offer an analytical framework and identify new research avenues for exploring the innovations in partial or complete AM supply chains.

Practical implications: The results offer a framework to assess the current state and future needs in AM-related supply chain innovations. Practical ideas are proposed to enhance AM adoption throughout firms' supply chains. These results are important to managers because they can help them position their firms and guide the activities and collaborations with other firms in the AM supply chain.

Originality/value: This study draws attention to the supply chain innovations required when firms adopt AM in their processes. The generic supply chain innovation framework is enhanced by adding the business context as a necessary component. Implementation of AM is shown to depend on the context both at the level of the supply chain and the firm's unique role in the supply chain. The holistic view taken reveals that successful AM technology adoption requires broad involvement from different firms across the supply chain.

Keywords: Additive manufacturing, manufacturing technology, supply chain innovation, radical innovation

Introduction

Additive manufacturing (AM) implies the use of digital product designs and a process of joining and adding layers of material (ASTM, 2012) to produce goods. It can challenge traditional removal and molding-centric manufacturing and either revolutionize entire processes (D'Aveni, 2015; Weller *et al.*, 2015) or complement traditional manufacturing (Holmström *et al.*, 2016; Rylands *et al.*, 2016; Sasson and Johnson, 2016). Earlier conceptual studies showed that AM has great potential to enhance operations. For example, with AM, almost any shape can be manufactured without tooling, which allows parts to be made independently at no extra cost. This can potentially simplify supply chains, shorten lead times, and reduce inventories, consequently enhancing flexibility and improving customer satisfaction (e.g., Holmström *et al.*, 2010; Weller *et al.*, 2015). The majority of previous research has focused on AM in single large early adopter firms in consumer goods industries, whereas less is known about the possibilities of AM more broadly in supply chains in business-to-business industries and the involvement of small and medium-sized enterprises (SMEs).

This paper focuses on the supply chain innovations concerning AM in industrial firms' supply chains. Supply chain innovation represents the possibility for manufacturing firms to enhance their competitiveness by changing their supply chain network, technology, process, or a combination of these (Arlbjørn *et al*., 2011). Implementing AM can have a significant effect on manufacturing firms' supply chains (Holmström and Partanen, 2014) and potentially requires the re-engineering of business logics (Weller *et al*., 2015). Each firm may have a very different role in the supply chain, and it is not yet clear which firms should implement AM, how their partners can support AM adoption, and what kinds of structures will emerge for AM supply chains (Rogers *et al.*, 2016).

Implementing AM technology not only affects the firm using AM machines for producing goods, it changes the supply chain process and requires involvement in the upstream of the supply chain. Additive manufacturing requires specially processed raw materials (Khajavi *et al.*, 2014), which requires the involvement of raw material manufacturers. Designers need to consider the new production process during the product development and design stages (Martinsuo and Luomaranta, 2018). After AM, , parts need post-processing (Khajavi *et al.*, 2014) before product assembly or final use. Although this could be done by the AM machine operator, it could involve another firm, machine shop, or similar, that has a large variety of traditional machining equipment (Strong *et al*., 2018). This implies that AM could influence the downstream supply chain.

For example, a machine shop with traditional manufacturing equipment and methods based on paper blueprints now has to convert to very accurate material removal from an almost-finished part based on a digital file. Previous studies have generated a conceptual illustration for the metallic AM supply chain (Holmström *et al*., 2016) and an empirical illustration of a business-to-consumer metallic AM supply chain from the point of view of a single firm (Rylands *et al*., 2016), but they do not offer empirical evidence concerning multi-firm supply chains for metallic AM in the context of business-to-business industries of machine building and industrial processes.

The purpose of this study is to explore the supply chain innovations that take place when AM is adopted in the supply chain. Firms need to respond to the changes in the business environment and take part in supply chain innovations in order to successfully complete the implementation of AM. The goal is to create knowledge about AM supply chain innovations and the related activities in the different firms in the AM supply chain. The study focuses on three research questions:

1) What kinds of contextual changes take place in business-to-business AM supply chains?

2) How—through what kinds of activities—do different firms participate in the AM supply chain process?

3) How can firms leverage AM through innovations in their supply chains?

To address to these questions, this study focuses on industrial goods manufacturing and, more specifically, on firms with different roles in the AM supply chain.

The paper reviews previous research on AM as an innovation in manufacturing systems, supply chain innovations, and related activities and roles of firms involved in them. The exploratory research approach, the interview and workshop data focusing on AM in the machine and process industry, and the data analysis approach are then introduced. The findings include mapping of the relevant contextual changes when implementing AM, a categorization of phases in the AM supply chain process, and required supply chain innovations. Finally, the contributions are discussed in light of previous literature and a conclusion is provided. This study contributes to the existing knowledge by revealing the contextual changes in the industrial inter-organizational supply chain during the implementation of AM, suggesting context as a necessary component in forthcoming analyses of supply chain innovations, and identifying various means that firms can use to enhance their operational efficiency through the AM supply chain. The results offer evidence that understanding AM through supply chain innovations can help firms connect with other firms in the supply chain and thus leverage AM more effectively. As practical contributions, these results help managers position their firms, guide the activities and collaborations with other firms in the AM supply chain and enhance AM adoption by means of supply chain innovations.

Literature review

Additive manufacturing as an innovation in manufacturing firms

Innovation, in its classical sense, 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). Innovations can be divided into incremental and radical changes (Freeman and Soete, 1997), and their classification depends on the innovation adopter's perspective (Johannessen *et al*., 2001). Innovations can be divided into intra-organizational and inter-organizational (Santosh and Smith, 2008), and they must aim to create new value (new products, services or structures) (Arlbjørn *et al*., 2011). In this study we focus on inter-organizational innovations specifically dealing with AM.

Additive manufacturing represents a radical innovation in terms of manufacturing technology (Oettmeier and Hofmann, 2016; Rylands *et al*., 2016), and in many cases AM technology advancements have been seen as enablers of new benefits in products, batch sizes, and waste reduction (Holmström *et al*., 2010). These and later studies called AM a groundbreaking innovation, where AM technology has pushed the implementation, but regarded it as a complementary innovation for the manufacturing industry or its supply chains (Oettmeier and Hofmann, 2016; Rylands *et al*., 2016; Steenhuis and Pretorius, 2017; Durach *et al*., 2017).

There are indications that a single firm cannot achieve the full benefits of AM alone and that AM adoption requires the involvement of multiple stakeholders in the supply chain (Oettmeier and Hofmann, 2017). *Supply chain* in this study is defined as a network of firms that transfer and process materials and information between them to create value (Heikkilä, 2002). Adopting AM technology might affect the interactions between supply chain firms (Durach *et al*., 2017) because firms' roles in the supply chain may change, new firms may enter the field with completely new capabilities, and some current supply chain relationships may be substituted by new AM-specific relationships (e.g., AM material suppliers, service providers, designers). Previous research suggests viewing AM as a systemic innovation that requires complementary innovations to achieve the expected large-scale benefits (Martinsuo and Luomaranta, 2018).

Supply chain innovations and required activities

Manufacturing firms often operate in networks of firms that need to collaborate to produce a product or a service, and to innovate (Manceau *et al.*, 2012). The concept of supply chain innovation deals with firms' innovation efforts to achieve a competitive advantage through and for their supply chain by developing operational and service efficiency and increasing both the firm's revenue and the supply chain's joint profits (Bello *et al.*, 2004). Supply chain innovation can be defined as "a change (incremental or radical) within a supply chain network, supply chain technology, or supply chain process (or a combination of these) that can take place in a firm function, within a firm, in an industry or in a supply chain in order to enhance new value creation for the stakeholder" (Arlbjørn *et al*., 2011, p. 8).

Supply chain innovations take place through a series of activities that help a firm deal with uncertainty in its business environment, respond to its customer demands, and enable more efficient supply chain management (Lee *et al.*, 2011). Supply chain innovation can therefore be used as a tool to enhance supply chain performance through interaction with up- and down-stream supply chain firms (Lee *et al*., 2014) and creation of collaborative relationships, especially when implementing new technologies that can be beneficial to several firms in the supply chain (Storer *et al*., 2014).

According to Bello et al. (2004) and Lee et al. (2011), supply chain innovations are operationalized through a set of activities, which can be divided into multiple categories. Two conceptual studies (Bello *et al*. 2004; Wong and Ngai, 2019) identified similar categories with a sales-oriented focus. Arlbjørn *et al*. (2011) identified three categories with a focus on operations management: 1) supply chain business processes, 2) supply chain technology, and 3) the supply chain network structure. The empirical study of Munksgaard *et al*. (2014) noted that supply chain innovations can originate from any of these three categories separately or combined. Due to our focus on AM supply chains directly dealing with manufacturing systems, we will build on the supply chain innovation framework of Arlbjørn *et al.* (2011).

Previous empirical studies have examined supply chain innovation activities in consumer goods manufacturing, specifically hearing instruments and shoe manufacturing (Munksgaard *et al*., 2014), and car manufacturing and pharmaceuticals (Ageron *et al.*, 2013).

Most of the earlier supply chain innovation studies have focused on analyzing the individual and organizational level of supply chain innovations (Wong and Ngai, 2019), implying a further research possibility concerning the inter-organizational level. Supply chain innovations are also considered as very context dependent and cross-organizational (Ojha *et al.*, 2016), which suggests a research gap, as supply chain innovations have not been covered in business-to-business settings, specifically in the context of AM.

Supply chain innovations for additive manufacturing in different types of firms

Two supply chain types are particularly relevant in the AM industry. The first type concerns AM equipment, proceeds from the machine supplier to the machine owner and user, and involves project business. The second type concerns goods manufactured using AM equipment, is product business, and extends from material suppliers through AM manufacturers and their design and software partners to their customers and other suppliers (Mellor *et al.*, 2014). In this study, we focus broadly on product-related supply chains.

Supply chain innovations have not been covered purposely for AM, but their indications appear in some previous studies. Many conceptual studies summarize the possible impacts of AM implementation on supply chains (Holmström *et al.*, 2010; Petrick and Simpson, 2013; Steenhuis and Pretorius, 2017; Sasson and Johnson, 2016). The nature of AM (with improved product-level integration) can enable simpler supply chains, shorter lead times, and lower inventories, likely resulting in cost reductions (Holmström *et al*., 2010). Reliance on digital designs can shorten and simplify physical sections of the supply chain (Campbell *et al*., 2011). For example, an assembled multi-component part can be digitally modeled and manufactured as a complete part with AM. This single-step manufacturing could reduce the physical transportation needs, which would have an impact on inventory and logistics costs (Holmström *et al*., 2010; Holmström and Partanen, 2014).

Only a few empirical studies have taken supply chain impacts into consideration (Rogers *et al.*, 2016; Rylands *et al.*, 2016; Thomas, 2016; Oettmeier and Hofmann, 2016), they are summarized in Table 1, and these have typically emphasized the viewpoint of large firms or a single SME, not a complete supply chain. AM is a rapidly emerging industry where service providers are gaining a foothold (Rogers *et al.*, 2016), and smaller firms need to rely on their networks when they are adopting AM (Martinsuo and Luomaranta, 2018).

Table 1. Summary of previous empirical research on AM-related supply chain innovations

Source	**Context and method**	**Findings on supply chain innovation activities**	**Gap or motivation driving this study**
Oettmeier and Hofmann, 2016	Impact of AM adoption on supply chain management, two case studies (plastic AM from the hearing aid industry), SME firms operating their own AM machine	Processes such as order fulfillment, manufacturing, and supply chain management are affected by the adoption of AM	Future research should study the relationships between firms in the AM supply chain
Rogers *et al*., 2016	3D printing services, evaluation of 404 3D printing service providers' offerings, different service providers (AM machine operators and AM designers)	Different kinds of AM service models are emerging	How will the future supply chain configuration strategies, structures and operations change?
Rylands *et al*., 2016	Value stream changes after the adoption of AM, two case studies (consumer products), metallic AM, two small firms producing filters and wallpapers, sourcing AM manufactured parts	AM changes the value stream so customers can engage in the design process better than before	Supply chains are areas where AM could cause disruption and change
Thomas, 2016	Comparative single assembly supply chain cost analysis, metallic AM, car steering systems as a whole assembly	AM affects both manufacturing process level and system (supply chain process) level	How will the whole supply chain benefit from AM?
Martinsuo and Luomaranta, 2018	Adoption of AM in the SME sector, exploratory research, metallic AM, 19 SME firms from supply chains in the machine building and process industry	SMEs rely on their networks when adopting AM	What kind of innovations could complement AM adoption?

Many of the benefits expected of AM assume that some supply chain innovations take place during AM adoption. Manufacturing firms should therefore consider the potential effects of AM on supply chain processes and management both within the firm and in partner firms (Oettmeier and Hofmann, 2016). For AM to fully deliver its potential, it is argued that such process technology innovations require restructuring of the relationships with suppliers and customers, increasing collaboration (Mellor *et al*., 2014).

Some production features in the current AM technologies need to be considered to reach the volume-related benefits of AM and may potentially be resolved through supply chain innovations. In AM technologies, manufacturing capacity does not refer to the number of components but rather to the building platform fill rate, meaning the amount of space a component takes up on a building platform where components are then produced. Ultimately, batches of one may not be economically feasible if the component is much smaller than the building platform (Piili *et al*., 2015). Also, AM currently has a significant need for post-processing (Khajavi *et al.*, 2014) and components need to be machined, heated, or polished after manufacturing. Therefore, AM supply chains should also consider operations and firms outside of the bespoke AM processes.

Different types of firms will have their own ways to contribute to AM through supply chain innovations. The empirical studies in Table 1 have primarily taken the perspective of certain types of firms, such as AM producers (Oettmeier and Hofmann, 2016; Rylands *et al*., 2016) or service providers (Rogers *et al*., 2016), whereas one study takes a more systemic view (Thomas, 2016) and another study draws attention to the different firms' different experiences with AM adoption (Martinsuo and Luomaranta, 2018). So-called supercenters are predicted to arise from large manufacturing firms that implement AM alongside their traditional mass manufacturing technologies to serve internal or external customers (Sasson and Johnson, 2016). Strong *et al*. (2018) propose that strategically placed AM hubs would feed AM components for post-processing to nearby SMEs that have traditional manufacturing machines. Adding AM hubs to the traditional manufacturing supply chain could promote both AM adoption and the performance of machinery SMEs by harnessing excess capacity to post-process AM components (Strong *et al*., 2018).

Research gaps

The literature review and analysis in Table 1 portray AM as an emerging manufacturing innovation that will require supply chain innovations for better performance. There is a research gap in the area of partial or complete AM supply chains as the different firms collaborate to create value through AM, making this research focus important and complementary to single-firm studies. The second research gap is in the business-to-business context of AM, as its supply chains may be more complex than those in consumer goods manufacturing. As supply chain innovations are context dependent, an AM-focused study will offer novel knowledge in connection with modern manufacturing systems. The third research gap is the context-dependent understanding of AM implementation, and for that, further knowledge is needed about the types of changes occurring in AM supply chains, the types of innovations needed for AM supply chains, and the complementarity of different types of innovations.

Research methods

Research design

This research employs an exploratory research design to study supply chain innovations in firms in different positions in AM-related supply chains. This approach was chosen because of the emergent nature of the phenomenon and limited previous research in this domain. The industry context was selected with the intention to access a complex AM supply chain—the machine manufacturing and process industry—where brand-owning manufacturers commonly use subcontractors and external industrial designers, which are very often SMEs. In this supply chain, the AM technology is metal-based AM, since mainly metallic components are used. This context is useful for the study of anticipated and ongoing changes in supply chains and the supply chain innovations needed to fully leverage AM.

Different types of firms involved in machine and process industry supply chains were enlisted through a list of technology industry firms in Finland in a region active in these industries, and by inviting the firms to participate in interviews and an AM supply chain-related workshop series. The initial list contained about 70 firms with different supply chain roles, and they were contacted by e-mail and/or telephone to seek volunteers for participation. Collecting data from different firms was seen as a means to achieve the best possible holistic understanding of supply chain innovations. The firms were selected based on their interest in AM and because they all had experience using AM or were in the adoption phase of AM technology. Altogether, 20 firms were willing to participate in the study, and this was considered suitable for an exploratory study. Alphabetical codes are used to differentiate the firms (A…U), as anonymity was promised to the interviewees during the study. Numerical codes (1…5) are used to cluster and differentiate the firm types involved in the study based on their scope of business, and to enable comparisons.

The firms vary in their supply chain roles, and different roles in potential AM-related supply chains are covered. The firms include some large firms and some medium OEMs/ODMs that can be considered to have a central position in the supply chain because they are the product users of metallic components. Most of the other firms are directly linked with the supply chains of these large/medium brand-owner manufacturing firms. Background information on the included firms is presented in Table 2.

Table 2. Background information on firms included in the study

Firm type	Firm	Approx. no. of personnel	No. of interviewees	Firms displaying additional internal document-based data	Respondents' position, total years of experience and AM experience in years	Firm experience in AM: years and specific areas
1: Large manufacturing brand owner firms	R	5000	1		Senior designer, 20+ total, 5 AM	5 years: Sources AM parts for prototyping and uses AM tooling in production
	U	45000	1	x	Vice president of technology, 25+ total, 5 AM	10 years: Has an AM machine and an AM department, sells AM products and uses AM parts in products
	S	19000	1	x	Sourcing manager, 25+ total, 7 AM	7 years: Uses AM tools in production and AM parts in products
	T	12500	1	x	AM lead designer, 10+ total, 7 AM	7 years: Has an AM machine and an AM department, uses AM parts in products and as replacement parts
2: Medium-sized manufacturing brand owner firms	A	200	1	x	Manager of production development, 10+ total, 5 AM	5 years: Sources AM prototypes for product development
	H	50	1	x	Vice president of technology, 15+ total, 5 AM	5 years: Sources AM prototypes for product development
	I	200	2	x	General manager, 35+ total, 3 AM; Vice president, 10+ total, 3 AM	3 years: Sources AM prototypes for product development and uses AM parts in products
	K	150	1	x	Manager of R&D, 25+ total, 3 AM	3 years: Sources AM prototypes for product development, planning to use AM tools in production and AM parts in products
	M	60	2		Vice president of R&D, 20+ total, 3 AM; R&D design engineer, 15+ total, 3 AM	3 years: Sources AM prototypes for product development, planning to use AM tools in production and AM parts in products
3: Small or medium sized OEMs and ODMs	B	50	1		General manager, 30+ total, 3 AM	3 years, Seeks information on how AM would influence their business, production developed to enable AM when customers ask for it
	E	15	2	x	General manager, 30+ total, 4 AM; Lead design engineer, 15+ total, 4 AM	4 years: Is post-processing parts that have been manufactured with AM
	F	160	1		Production development engineer, 25+ total, 2 AM	1 year: Is post-processing parts that have been manufactured with AM and uses AM tools in production
	J	20	1		General manager, 10+ total, 1 AM	1 year: Seeks information on how AM would influence its business

Firm type	Firm	Approx. no. of personnel	No. of interviewees	Firms displaying additional internal document-based data	Respondents' position, total years of experience and AM experience in years	Firm experience in AM: years and specific areas
4: AM service and machine operators	N	5	1	x	General manager, 25+ total, 4 AM	3 years: Has an AM machine, produces AM prototypes, tools, and parts for its customers
	Q	5	1	x	Manager of sales & marketing, 10+ total, 6 AM	4 years: Has an AM machine, produces AM prototypes, tools, and parts for its customers
5: Engineering and industrial design	C	1	1		Entrepreneur, 25+ total, 6 AM	2 years: Designs AM prototypes and parts
	D	5	1		Financial manager, 25+ total, 2 AM	1 year: Designs AM prototypes
	G	280	2	x	Vice president, 25+ total, 5 AM; Lead design engineer 15+ total, 5 AM	5 years: Designs AM prototypes, tests AM parts with its customers
	L	70	1	x	Vice president, 25+ total, 3 AM	3 years: Designs AM prototypes
	P	1	1	x	Entrepreneur, 20+ total, 5 AM	2 years: Designs AM prototypes, AM tools, and AM parts. Sells AM products

Data collection

Primary data were collected through 3 workshops and 25 semi-structured interviews in 20 firms (Table 2). Interview duration ranged from 40–108 minutes. Of these 20 firms, 13 also displayed internal documents (in-depth firm and strategy presentations), and this additional information was documented as approximately 1–2 pages of written notes per firm. Secondary data were collected from the target firms' websites to get background information about the firms and from 2 workshops to validate the results. The workshop contents and data included:

WS1 – AM value and supply chains: primary data, 18 participants, 2 pages of notes, and 4 posters

WS2 – Future scenarios: Primary and secondary data, 14 participants, and 7 pages of notes

WS3 – Future scenarios: Primary and secondary data, 12 participants, and 6 pages of notes

WS4 – New AM markets: Secondary data, 5 participants, 1 page of notes, and 3 posters

WS5 – New business possibilities: Secondary data, 5 participants, and 2 pages of notes

The interviews took place after the first three workshops. The contact persons from target firms were asked to identify a person from the managerial level with the best knowledge about AM in their firm. The interviewees were managers and directors from engineering, design, business development, sourcing, or general management (CEOs). At the beginning of each interview, the interviewees were asked whether there was another person in their firm who had better or different knowledge about AM. When another person was identified, a second interview was conducted. One additional interview was also conducted with an AM machine supplier. That interview is used as a secondary source to validate the results, together with the secondary data from the workshops.

An interview outline was formed with the help of the preliminary analysis from the first three workshops. The interview outline included questions concerning the background and position of the respondent; the firm's experience and plans for implementing AM; identified challenges in implementing AM; possible industry-specific needs for AM; opportunities to add value for the business and its customers by using AM; and production and supply chain changes required by AM. This paper concentrates on opportunities to add value for the business and its customers by using AM; and production and supply chain changes required by AM. The recorded interviews were transcribed for further analysis. After the preliminary analysis, two more workshops were organized with industry experts and firm representatives to present the preliminary results, to validate them, and to check whether anything was missing.

Data analysis

The analysis of the first three workshops took place first. Handwritten notes from the researchers were compared and rewritten analytically so each observation was retained. Posters from the first workshop represented the AM actor network and supply chain process. All four posters were compared and combined to identify a complete AM supply chain process. This is presented in Figure 1 in the Results section. Notes from the internal documents of the firms targeted for interviews were used in the further analysis of the AM supply chain process and to analyze the firms' strategic focus on that process. Each interview response was then coded in terms of whether and how the firm (i.e., a firm with a certain supply chain network role) was involved in the different phases of the supply chain process. We then cross-tabulated these results with an analysis of the internal documents, revealing the involvement of each firm in the different phases of the supply chain process. This is presented in the results in Table 4. As secondary data, the firms' websites were explored and used where possible, particularly to improve the validity of the results.

The subsequent more detailed analysis of interview data started by exploring the data and marking four themes to structure the analysis: a) How does the market change when AM is a feasible alternative? b) How does the business environment change when AM is a feasible alternative? c) Important issues in AM subcontracting, and d) Important issues for AM supply chain structure formation. Each theme's citations were inductively coded with more detail to condense the interviewees' experiences and retain the terms that the interviewees used. These findings were then pattern coded and structured thematically under two main topics: contextual changes in the supply chains preceding or after the implementation of AM (themes a and b), and required supply chain innovations (themes c and d). Pattern coding the expected changes in AM supply chains and in the business environment resulted in five categories, presented in Table 3, which includes the dominant changes in AM supply chains repeated in the interviews, explanations for these, and interviewee quotes. Changes that were expressed by only a single interviewee were excluded from the table. Since business environment changes are an important component of supply chain innovations (Lee *et al.*, 2011), this was considered an important intermediate phase in the analysis of supply chain innovations, for revealing the innovation context.

For the interview analysis, the needed supply chain innovations were grouped into innovations in supply chain business processes, technologies, and network structures, based on the thematic framework proposed in Arlbjørn *et al*. (2011), due to its appropriateness for operations management-oriented innovations and, thus, for the core focus of this study. We then mapped how each of these supply chain innovation types appeared across the different types of firms. These results were validated with the results from workshops 2 and 3. The results are presented in Table 5, which shows the categories of supply chain innovations, needed activities, example quotations, and the number of different firm types in which the innovation was expected.

After discovering the needed supply chain innovations from interviewees with the support of workshops, another analysis was performed to reveal the relations between firm types, supply chain process positioning, and supply chain innovation needs. This was done by identifying patterns from Table 4 and analyzing the reasons behind these patterns. In the findings section, we first introduce the contextual changes experienced in AM supply chains, then map the supply chain process and different firms' roles in it, and then categorize the supply chain innovations and experiences of them across different firms.

Findings

Overview of contextual changes in AM supply chains

Based on the previous literature, the introduction of AM in the manufacturing industry was expected to cause changes in the business environment, with implications for firms' supply chains. Interviewees were asked to describe what kinds of changes had already occurred and what future changes they expected in the context for AM-related innovations.

The interviewees from large firms had the most insight into how AM has changed their business environment. All four interviewees stated that their new product development cycles have shortened. Three of the four large firms had already replaced some traditionally manufactured components in their products with AM components. Interviewees from two large firms said the reason their firms' own AM machines is that AM-manufactured components are cheaper to produce. According to them, integrating multiple components into one—which was previously impossible—has made the parts and the parts production more effective. The same digital models are used throughout the manufacturing process, and the firms are planning to replicate this for other critical components, regardless of the actual manufacturing technology.

An interviewee from one large firm said that due to the tightening regulations concerning their end product, the manufacturing time for one product has shortened and the batch size has decreased. Therefore, they have given up on molds for manufacturing certain components and have started to produce them using AM. The interviewee further explained that: "About ten years ago, we had one product variant in the production for years, but nowadays we need to adjust our product every year or every two years. There is no sense anymore to order expensive molds, as the batch sizes have gotten so small it is cheaper to manufacture these small series additively. This has actually been one answer to manage the ever-tightening regulations affecting the product development in our industry" (Large manufacturing firm). This has also led to a challenge for their former logistics providers, who were not able to make small deliveries on short notice, and in some cases, some of the firm's employees had to pick the components themselves.

Even though some changes have occurred, most respondents indicated that traditional manufacturing still dominates, and operating AM technology is primarily the concern of specialized AM firms. According to one interviewee, "There are so many new areas in metal printing that it currently is not and most expectedly will not be the business of every firm" (Engineering and industrial design firm).

For this study, anticipating possible future changes was considered important, as changes may have implications for supply chain innovations. Table 3 summarizes the changes that some interviewees had already noticed in their firms' business environment and the changes expected in supply chains due to AM, grouped into five categories, further described below.

Table 3. Expected changes in AM supply chains and in the business environment

Change in AM supply chains and the business environment	**Explanation**	**Example quotations**
Digitalization of the entire design-to-manufacturing chain	Using the same digital model from the designer in every phase of the supply chain process	"The whole supply chain must start using digital plans and the key issue is to agree on roles. It must start from designing so that manufacturing can start leveraging digitalization." (Firm B)
Digitalization increasing the need for trusted business partners	Digital files and data transmission may be more vulnerable than working based on paper plans	"Trust and security are emphasized in digital services." (Firm N)
AM features complement traditional manufacturing	Changes due to "economies of one": Orders only on demand, no need for big batches to gain a cost advantage from the economies of scale	"The supply chain is going to be faster when you don't need to order big batches because of the price." (Firm D) "AM decreases the need for machining but increases the value of the machining needed." (Firm T)
Changes in operations management	Some steps will be left out from the manufacturing process, and the flexibility of batch sizes challenges traditional production management	"Of course AM will cause significant changes. Manufacturing steps are left out, quite a lot of them, I presume. And, indeed, the whole environment of the enterprise resource planning changes." (Firm A) "This will change operations management because every part can be different—it brings flexibility—but on the other hand, it can be quite slow compared to machining. There will be

Change in AM supply chains and the business environment	**Explanation**	**Example quotations**
		possibilities for new product development, testing, and ramp-up that no one has utilized yet." (Firm G)
Changes in logistics and with suppliers	Integration of components reduces the need for logistics and multiple suppliers or changes how logistics has to be managed	"… if integration within one engine reduces the need for 855 parts to 12 parts, then it has a strong impact on supply chains and logistics." (Firm L)

Digitalization of the entire design-to-manufacturing chain is a change that was experienced in all types of firms. It is an ongoing change enabled by recent technological developments, and an opportunity to streamline supply chains. The interviewees expressed that full digitalization increases the need for trusted business partners to be addressed in the supply chain definition and in partner selection. Also, firms that operate with traditional manufacturing technology rely heavily on their partner firms, for example, to offer research and development and post-processing capacity or services. Some of these firms act as subcontractors for other firms, and research and development for their products is initiated and/or even implemented by their customers. Two SME interviewees (B and F) said that that they had to renew their production software to be able to continue the work with their customers who required post-processing for their AM parts.

According to the interviewees, AM is a flexible manufacturing method that complements traditional manufacturing. Additive manufacturing allows production based on "economies of one," which enables firms to manufacture orders only on demand. Consequently, the need for big batches to gain a cost advantage from economies of scale decreases. This opens up possibilities for entirely new operational models. Interviewees suggested that the small batch orientation will also lead to changes in operations management because some steps will be left out of the manufacturing process and the production type will change. This again creates an opportunity to develop operational activities and new innovations.

Changes in logistics mean there is a possibility for reduced or simpler logistics due to integrated parts. Lighter parts may also reduce costs if logistics costs are calculated based on weight. One interviewee predicted that the use of metal parts casting would decrease when AM replaces it, which means the number of suppliers may also decrease due to AM. Despite reduced logistics, the interviewees mentioned that the need to post-process components still requires transportation, since AM service providers currently do not have advanced post-processing capabilities. Therefore, it would be useful to locate post-processing firms within close proximity of AM service providers. Additive manufacturing service providers considered this to be important because part of their value promise is speed of production. With delivery times of one or two days, they cannot wait for transport for a very long time.

The AM supply chain process in the machine and process industry

The supply chain process includes the business operations across time and place, the beginning and the end, and the inputs and outputs of a supply chain (Mentzer *et al.*, 2001). Classically, supply chain processes include manufacturing raw materials, designing the product, manufacturing the product, warehousing the product, and lastly, distributing the product to customers.

To understand the nature of AM in the machine building and process industry and its specific nature, we mapped the core AM-related supply chain process. Figure 1 illustrates this process and its key activities as discovered through empirical data in the machine manufacturing and process industry, compared to a generic supply chain. This study suggests that supply chain innovations can occur in any phase of the supply chain process and across the phases.

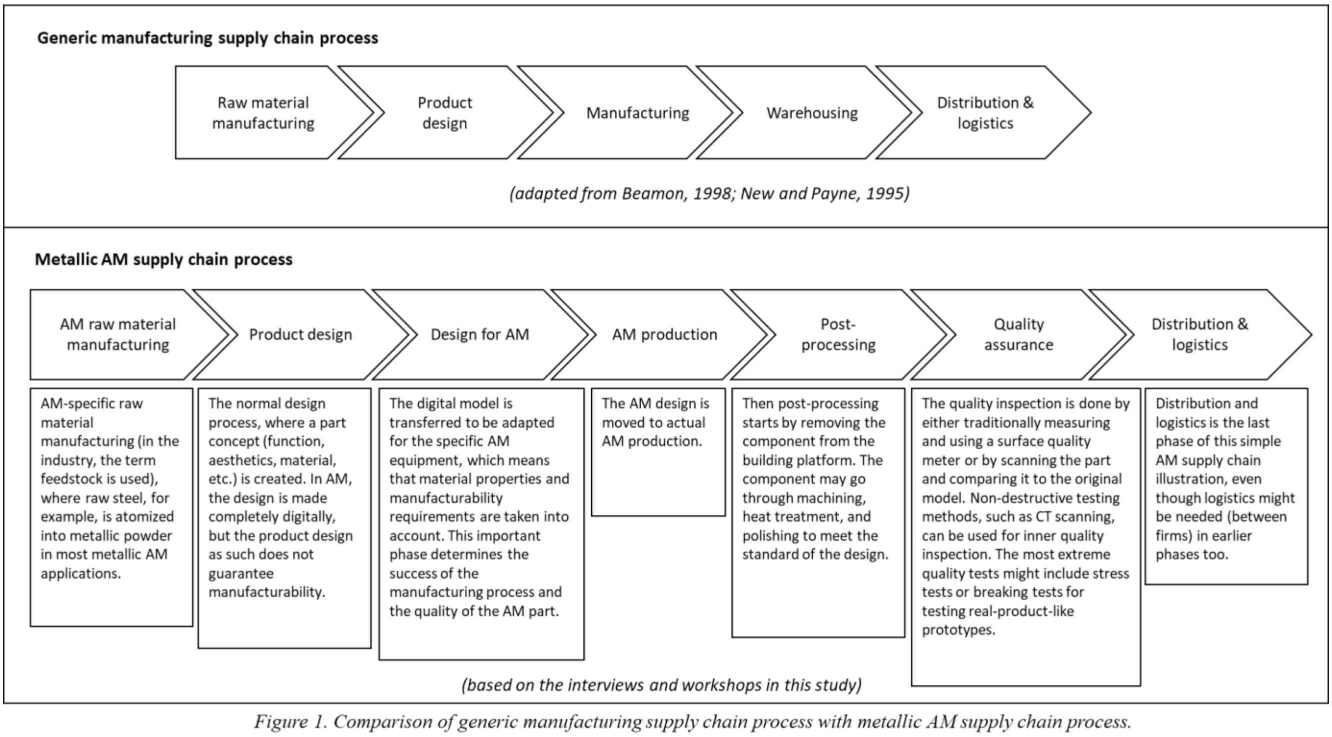

Figure 1. Comparison of generic manufacturing supply chain process and metallic AM supply chain process

After distribution, components go to be assembled in customer or OEM premises because, in the context of the machine and process industry, AM parts are mostly used as components for larger assemblies or products (such as spare parts used within a piece of equipment), instead of as final AM products after manufacturing (such as hearing instruments).

Because a supply chain is comprised at the highest level of two root processes: 1) the production planning and inventory control process, and 2) the distribution and logistics process (Beamon, 1998), it differs from traditional manufacturing processes at the root process level of production planning and inventory control. Additive manufacturing needs much more design work than traditional manufacturing due the complexity of AM technology. On the other hand, AM has the potential to reduce or even entirely remove post-production warehousing processes. Additive manufacturing also needs one extra step in the raw material manufacturing phase as well as in the post-production and quality assurance phases.

Roles of the different firms in the AM supply chain processes

The interviewees were asked to describe (and offer secondary data on) what kinds of activities their firms are involved in with regard to AM generally and the AM supply chain specifically. The roles of the studied firms in the supply chain process were mapped and are summarized in Table 4. This map reveals that every process phase of the AM supply chain is covered through the firms involved in this study. All but two (B and J) of the firms are currently working with AM, and their positions in the AM supply chain process are marked with x. The two firms not yet involved in an AM supply chain clearly indicated where they would be positioned in AM processes, and these are marked as o. At this point, distribution and logistics are excluded from the analysis because all of the firms is taking part have outsourced them to external logistics firms.

Table 4. Roles of interview target firms in the AM supply chain process

Firm type	Firm	AM raw material manufacturing	Product design	Design for AM	AM production	Post-processing	Quality assurance
1: Large manufacturing brand owner firms	R		x				
	U	x	x	x	x	x	x
	S		x			x	x
	T		x	x	x	x	x
2: Medium-sized manufacturing brand owner firms	A		x				
	H		x				
	I		x			x	
	K		x				
	M		x				
3: Small or medium sized OEMs and ODMs	B					o	
	E					x	
	F		x			x	
	J					o	
4: AM service and machine operators	N			x	x		x
	Q			x	x		
5: Engineering and industrial design	C		x				
	D		x	x			
	G		x				
	L		x				
	P		x	x			
x = current role in the AM supply chain process o = expected/planned role in the AM supply chain process, not yet implemented							

Table 4 shows that large product brand owners (type 1), small and medium OEMs/ODMs (type 3), and AM machine operators (type 4) have distinct supply chain process roles based on their activities, whereas medium-sized brand owners and industrial designers show some similarities. Two of the four large firms (U and T) are active almost throughout the AM supply chain process, and they have implemented their own AM machines for in-house applications. The other large firm (U) also produces AM-specific metallic powder for internal use and external sales. In the smaller firms, AM machines are implemented by only two AM service providers, which have also invested in knowledge of AM design. As machine operators, this was seen as crucial by the interviewees from these two firms. Two of the four OEMs/ODMs that operate mainly with traditional manufacturing technology are actively taking part in the post-processing of AM components, meaning that they had to develop their capabilities for very accurate machining operations to almost net-shaped parts (close to the dimension of the ready-to-be-used parts). Otherwise, the majority of the firms concentrate on their own product design and on assembling the products, but many of the AM phases have been outsourced to smaller firms specializing in AM.

Required supply chain innovations and activities to leverage AM

In order to leverage AM in their firms, interviewees expected that various innovations were required, and these are presented in Table 5. The most frequently expressed needs deal with new practices in product development, investments in digital systems in the supply chain, and a partnership approach in the supply chain, expressed by over half of the respondents. Each of the other topics was discussed by fewer respondents.

Requirements for supply chain innovations during AM adoption depend on the strategies of certain leader firms that decide to invest in either machinery or AM manufactured goods. The interview data suggest that it is not clear who should own the AM machines. Currently, two large firms have implemented their own AM machines, but these are solely for internal use. Two service providers are the only smaller firms that had implemented industrial-scale AM so their capacity would be accessible to others as well, but they will need a strong and co-operative supply chain for AM to become competitive. The interviewees anticipated that new firms may be emerging in AM-oriented supply chains. Also, possibilities for other firms to implement AM machines may open up as the technology improves.

Based on the interviews, *supply chain business process innovations* deal with product development, order fulfillment, demand management, customer/supplier relationship management, and service capacity.

Innovations in product development processes are expected because of the faster iteration cycles with real components instead of mock-ups or weak quality prototypes. The capacity fill rate of the building platform plays a crucial role in terms of costs. Optimizing the fill rate is, therefore, a goal for firms that have implemented AM, and it will require innovation activities in order fulfillment, demand management, and service capacity. In current practice, one AM machine operates with only one material, since material changes are currently very expensive due to the required cleaning process of the machine. Therefore, interviewees suggested that at least in the beginning there should be a handful of machines with different material set-ups that firms could load with different materials, and an agreed-upon way to share the production resources.

Supply chain technology innovations were expected in terms of investing in digital systems that promote digitalization in the entire design-to-manufacturing chain and changes in manufacturing methods and open up the possibility to effectively streamline the design-to-manufacturing chain and enhance transparency. The change in manufacturing methods means that with AM technology, supply chain management has new tools to make manufacturing processes more flexible. One important question to solve is how to integrate AM in the supply chain of a product that consists mostly of traditionally manufactured components with only a few AM components.

Supply chain structure innovations and, more precisely, innovations with suppliers and customers, deal with models of cooperation, specialization, and co-location of expertise; the emergence of new actors and job profiles; and alternative initiators of innovations. According to the interviews, a suitable operations model in the supply chain structure is cooperation, which requires finding the right partnerships. Additive manufacturing technology is new and complex, and cooperation between the customer and the supplier is needed to maximize R&D innovations. Some interviewees thought specialization would be the best operating model for cooperation, whereas others indicated that expertise centers should be formed for AM. Expertise centers were described as multiple specialized firms within the same building—or at least in very close proximity—where partnership is close and several firms can work as one firm. An interviewee in one of the AM service provider firms revealed that they have already started to implement this kind of model by acquiring premises large enough for multiple firms and negotiating with promising partner firms. More actors and new job descriptions are expected to emerge in the supply chains in each scenario. New actors could emerge in the field of total AM supply chain management that would optimize all steps in the value chain and handle quality assurance. According to one interviewee, this would be the best way of managing expertise centers.

Regarding who should be the leader of AM implementation and network innovators, one interviewee in a medium-sized OEM firm said they would like to source AM parts or services traditionally from the subcontractor with the lowest bid. Interviewees in other OEMs saw collaboration or cooperation as a better model, although they mentioned that they would expect their subcontractors to be the initiators in providing new technology capacity to them. Subcontractors, on the other hand, are waiting for their customers to ask them to provide AM capabilities or, ideally, to start to co-develop AM with them. Two of the large firms that had implemented their own AM machines had also defined AM as an important new technology in their strategy. Their interviewees stated that the implementation of AM began when they discovered some of their important components were easier or faster to manufacture with AM. Now their strategic aim is to educate their designers so AM will not only be a special manufacturing method for special parts but could also be used for more general purposes. This is expected to be a wise way to generate product design innovations. Interviewees in two other large firms said their subcontractors implemented AM based on their requests, and then the required capabilities were co-developed. They also stated that intellectual property rights were the most important thing in selecting subcontractors for co-development.

Table 5. Expected innovation requirements in supply chains to leverage AM

Element of supply chain innovation	**Description: Domains where innovation activities are expected**	**Specific innovation example**	**Example quotations**	**The number of the firms (within the five firm types) where innovation was expected**				
				1	**2**	**3**	**4**	**5**
Innovations in supply chain business processes	Product development	Possibility to manufacture working prototype components for testing a complex product or assembly	"Design schedules have become so short nowadays. After our designer has designed the component, it needs to be integrated into the product to be tested within three weeks. We don't have any other possibility but to have the components additively manufactured so that they are real working components, not just weak prototypes. (Firm U)	4	1		2	2
	Order fulfillment	A new real-time pricing system based on delivery times, with online quotations for customers	"We had to come up with a new pricing system with online quotations to ensure that our building platform is always filled to the acceptable rate and that the customers have fast delivery times if needed, because that is what we promise." (Firm Q)			1	2	

	Demand management	A new tool to estimate and forecast both the demand and manufacturing time	"Our main goal has been to maximize the machine utilization rate. We have gathered a lot of know-how to excel in forecasting the manufacturing schedule, to handle incoming orders by promising the right delivery times." (Firm N)				2	
	Customer/ supplier relationship management	A new tool for quality management and quality documentation requested by the customer, developed together with the customer, AM producer, and supplier	"We demanded that our AM supplier had to develop new systems to guarantee the quality of AM parts. Eventually we developed new systems for quality management with our supplier, and they took care of the documentation and access to all the material data from their feedstock supplier." (Firm U)	3	3		2	
	Service capacity	Overall innovation needed to create a new front-end supply chain business process for AM services to fulfill customers' expectations (delivery time, multiple batch sizes, quality assurance, and reasonable costs)	"Good service capacity is expected from our AM suppliers, meaning that we must know when we get the part, how the quality is assured, and how much it costs, since these differ from the traditional sourcing." (Firm A)	2	1			
Innovations in supply chain technology	Investments in digital systems in the entire design-to-manufacturing chain	Using the same digital model throughout different manufacturing phases and technologies making development and production more efficient and of better quality	"We have developed our systems so that our designers make the design model in a certain way and we have integrated systems to use the same model in each phase from R&D to product assembly. We can now use the same model in digital simulations, printing the part, post-processing it, and measuring the part to inspect the quality […]." (Firm U)	4	3	1		3
	Change in manufacturing methods creates opportunities for new tools for the supply chain and operations management	New supply chain and operations management tools to take advantage of AM benefits and integrate the AM technology to production, i.e. a tool to optimize cost, delivery time and forecast benefits of faster delivery	"Because of the tough competition, the design cycles and new product cycles are so short that it does not make economic sense to utilize the mass production method for small batches of certain components." (Firm U)	4		2	1	1
Supply chain structure: Innovation with suppliers/ customers	Partnership, cooperation	Open and cooperative relationships between the different companies in the supply chain, i.e. suppliers are expected to raise new ideas for production to the customer	"We definitely take up ideas from our subcontractors, and we constantly try to improve co-operation with our subcontractors. Cooperation with subcontractors is what makes us successful, and we can trust that our subcontractors also develop their competences to have the latest methodological expertise in AM." (Firm K)		4	2	2	4

	Specialization	Seeking and adding new companies to the supply chain and share production resources of the different firms	"None of our established suppliers have started to provide us the possibility of AM, so we had to seek those smaller companies specialized in AM. It seems that this is the case of how we need to operate. Of course there are many new methods in AM, so one company cannot handle them all." (Firm M)		1	1	2	2
	Expertise centers: clusters of specialized firms in the same or a close location	Innovative way of relocating companies near to each other for more efficient supply chain structure	"Although the digitalization level of firms is growing and AM operators can basically be anywhere in the world, post-processing is very important for the manufacturing industry. It requires a geographically relatively tight ecosystem to benefit, for example, from the relative speed of the AM method." (Firm N)			1	2	1
	New supply chain roles and job descriptions	A new role for design chain management that carries the original idea and requirements through different phases of design, manufacturing with different technologies, and quality management	"New professions are emerging as we speak. Part of it is formed from old quality assurance or material management, and in this whole manufacturing process there will be, for example, design management professions related to the design chain that have to carry the idea through to the end with certain criteria. And there's a lot of designer stuff to think about through different stages. Now we try to take care of those responsibilities, but it is complicated because we are just a small company and our customers are big companies." (Firm N)			1	1	2

We further analyzed participating firms' experiences concerning supply chain innovations to identify potential patterns of innovations according to firm type. Table 5 implies that different types of firms experience different kinds of innovation needs. Table 5 shows four distinctive clusters of participation, which provide evidence about the supply chain innovation within the specific context of a supply chain process phase.

First, product development process innovations are expected widely in different firms (firm types 1, 2, 4, and 5, that is, in all firm types except small/medium OEMs/ODMs). Product development innovations concern mostly the early parts of the supply chain, from material development to product design. Here, the collaboration between traditional product designers and designers with advanced AM design skills is crucial because in many cases traditional product designers do not know what is possible with AM and, on the other hand, AM designers do not have the product-specific knowledge to implement AM ideas.

Second, AM service providers (firm type 4) are experiencing innovations throughout supply chain business processes. These innovations mainly include the latter part of the supply chain, from manufacturing to delivery. This pattern may stem from the emerging nature of business and business models for AM service provision.

Third, innovations in supply chain technologies are expected evenly throughout the supply chain positions. Supply chain technology innovations are linked with process and structure innovations, as they can be seen to support each other. Product development innovations will benefit from the increased accuracy of digital designs. Order fulfillment and service capacity will benefit from the increased use of digital systems and new operations management tools.

Fourth, interviewees in the smaller firms (and in medium firms to some degree) particularly emphasized supply chain structure innovations, while large firms did not. This pattern may reflect the advantage that large firms have in term of capabilities and possibilities to invest in the whole AM supply chain process. Small and medium firms are restricted in terms of their capital and capabilities, which leads to the need for partnerships or cooperation with firms as complementary capability sources.

Discussion

This paper inspected AM in industrial goods manufacturing and its inter-organizational supply chains holistically, and supply chain innovations when firms are implementing AM into their processes. This innovation process should not be seen as only a linear process where one aspect of AM has a direct effect on the supply chain, creating opportunities for supply chain innovations. Innovation can also happen the other way around, where supply chain innovations have an effect on the adoption, implementation, or utilization of AM.

The first research question inquired: *What kinds of contextual changes take place in business-to-business AM supply chains?* While earlier empirical research on AM supply chains has primarily taken a consumer goods-centric, intra-organizational, and single-firm perspective (e.g., Oettmeier and Hoffmann, 2016; Rogers *et al*., 2016; Rylands *et al*., 2016), this study covered the AM supply chain broadly, particularly in machine manufacturing and process industries. Five major contextual changes were identified, as reported in Table 3. The general finding that AM complements rather than replaces traditional manufacturing lends support to Rylands *et al*.'s (2016) ideas. As a contrast to previous research that portrays AM as a means to simplify the supply chain and improve its efficiency (e.g., Holmström *et al*., 2010), our findings highlight the complexity of the supply chain transformation associated with AM, drawing attention to the new kinds of firms (i.e., partners), material flows, and digital information flows within the supply chain.

The most frequently expressed change concerned the digitalization of the entire design-to-manufacturing chain, which links directly with the firms involved and with changes in the material flow, and also confirms the centrality of the digital transformation pointed out in earlier AM-related research (Campbell *et al*., 2011). However, this digitalization trend and its implications have not been analyzed sufficiently in previous supply chain research or in AM specifically. Although digitalization is not solely an AM-specific change, AM and other digital manufacturing technologies are driving industries in a more digitalized direction. On the other hand, fully leveraging digital manufacturing technologies will require adopting a holistic view of the digitalized supply chain. This may have far wider effects than just for manufacturing processes. For example, product designers with different roles in the supply chain can benefit from the possibility of co-designing products in real time using suitable design software. Digitalization also has the possibility to enhance the response time in customer relationships.

The second research question asked: *How—through what types of activities—do different firms participate in the AM supply chain process?* Its response required mapping the AM supply chain process (Figure 1) and different firms' involvement in it (Table 4). The findings revealed that different types of firms have different roles across the supply chain process. The findings contribute to research that acknowledges the supply chain implications of AM (Rogers *et al*., 2016; Rylands *et al*., 2016; Thomas, 2016; Oettmeier and Hofmann, 2016) by showing evidence that AM is not an isolated innovation within one firm and gaining its benefits requires and enables the involvement of different types of firms in the supply chain. In particular, SMEs with traditional manufacturing equipment are actively seeking to be part of the AM supply chain in the post-processing phase, which reflects Strong *et al*.'s (2018) prediction that post-producing is a way for machinery SMEs to join the AM supply chain.

The description of the AM supply chain process includes the phases and activities needed in the AM supply chain context of this study (goods manufacturing, metallic AM) and provides a starting point for studies in other fields. Respective supply chains in different contexts may need some additional phases.

For the third research question—*How can firms leverage AM through innovations in their supply chains?*—the interviewees' experiences of required AM supply chain innovations were mapped. We identified a total of 11 required innovation expectations (Table 5) that were divided into 3 categories, based on the framework of Arlbjørn *et al*. (2011). The findings suggest that manufacturing technology innovations such as AM cannot be seen as isolated innovations that could be leveraged merely as a technology adoption task. Instead, they need to be viewed as a systemic innovation requiring complementary innovations to realize their benefits at full scale (Chesbrough and Teece, 2002; Martinsuo and Luomaranta, 2018). Martinsuo and Luomaranta (2018) raised the question about what kinds of innovations could be complementary for AM adoption stemming from the systemic innovation nature of AM, and Thomas (2016) asked how the whole supply chain would benefit from AM. This study provides evidence that supply chain innovations complement AM technology and, thereby, support the technology's adoption. Supply chain innovations are also a means for the entire supply chain to benefit from AM and to help firms leverage AM effectively.

Based on a further analysis, four different patterns were identified concerning the depth and focus of the firms' perceived innovation requirements for leveraging AM. The broad expectation across the supply chain regarding the possibility of enhanced product development is consistent with a previous study that pointed out the need to develop product design activities to promote AM adoption (Martinsuo and Luomaranta, 2018). Another broad requirement spanning the supply chain addresses the need to invest in digital systems and supply chain operations management tools, which Campbell *et al.* (2011) predicted. The digitalization of production and supply chains affects entire industries, not just single firms. Additive manufacturing service providers' specific expectations regarding innovations in business processes reflect the emergent phase of AM service business models, thereby lending support to findings in Rogers *et al.* (2016).

Implementing an AM machine and processes is demanding both financially and operationally. It requires new expertise within a firm, as well as supply chain innovations that emphasize cooperation, coordination, and specialization. A collaborative approach has been emphasized in this study as a means to benefit from AM-driven changes, especially in the SME context, confirming Oettmeier and Hofmann's (2017) predictions. A consortium of smaller firms co-locating, forming expertise centers, and having a strong network with each other could promote the increased speed through AM production. This finding is in contrast with Sasson and Johnson (2016), who predicted that large firms would evolve into AM supercenters. While larger firms may indeed evolve according to this prediction in the future, SMEs in particular require complementary capabilities from their broader networks. The perspective of an entire supply chain in AM-related innovations reveals that firms in different supply chain positions will have different ways to support AM adoption and leverage the novel technology in their networks.

The thematic framework of Arlbjørn *et al.* (2011) was used in the analysis to map supply chain innovations, and it was found useful for AM supply chains. However, the interviewees often linked their needs and the implementation of supply chain innovations to changes in the AM supply chain and the broader business environment. Also, the business-to-business context appeared as more complex in its supply chain operations than ordinary consumer goods manufacturing. Changes in the supply chain context and the business environment generally can, therefore, be seen as key factors in supply chain innovations. Therefore, the results of this exploratory study offer evidence to elaborate the framework of Arlbjørn *et al*. (2011) by adding the context of supply chain innovations as a new analytical dimension. This could enhance the further usefulness of the framework by providing a broader contextual view of supply chain innovations, which has already been recognized as important by Ojha *et al.* (2016).

Conclusion

Contributions

Since AM technologies are being considered in various industries, firms need information about how they can promote and speed up AM adoption and succeed with the new technologies. The results of this study provide a process model of the AM supply chain, offering evidence of the activities and firms involved in producing goods through metallic AM. The specific involvement of different types of firms in the AM supply chain process was described, indicating that AM adoption takes place very differently for different supply chain firms. Since AM machines are purchased and implemented only by certain firms, the implications of AM implementation are spread throughout the supply chain and require an understanding of multiple perspectives to become effective for all supply chain firms.

Firms experience various practical changes in their supply chains when considering and implementing AM. These changes can also be drivers for AM, for example, the digitalization of the whole design-to-manufacturing chain. Successful AM adoption requires complementary supply chain innovations in business processes, technology, and structure. They also need awareness and sensitivity to the specific context in which AM supply chain innovations are implemented, and we have proposed adding the innovation context to the framework of supply chain innovations.

The findings provided evidence on using the framework of supply chain innovations to acquire a holistic view of the possible effects of AM and revealed the effects of AM on supply chains and inter-organizational relationships. Supply chain innovations can complement AM technology innovations during AM adoption and offer practical mechanisms for the entire supply chain to benefit from AM, which can help firms leverage AM more effectively.

Practical implications

Engaging the supply chain more broadly in AM-related discussions will help the different firms justify their investment decisions, negotiate their network position, and access other firms as sources of complementary capabilities. The results serve as an inspiration for practitioners to view the implementation and leveraging of AM from a wider perspective through the framework of supply chain innovations. Practitioners can use the ideas to map the relevant changes stemming from AM, generate supply chain innovations, improve their supply chains, and, consequently, enhance AM adoption.

Different companies in the supply chain have specific expectations of AM. Some expectations, such as those concerning a certain service capacity, can be solved by creating a new front-end supply chain business process for AM services that would inform customers and other partners about the implications and requirements of AM (e.g., delivery time, quality assurance, cost). Furthermore, because the implementation of AM may influence the strategic location of manufacturing facilities and capability needs in a society, the results are useful for designing new training programs for SMEs or within larger firms, and when funding institutions screen the business plans of newly founded AM firms.

Limitations and avenues for further research

The exploratory research design enabled a broad exploration of the phenomenon but not in-depth observations or analysis of a specific case. All firms were from the machine and process industry, and the AM technology was metallic AM, which limits the findings to this context. In some firms, only one person was interviewed and additional documentation or website data were not available for triangulation purposes, which may limit the reliability of the data. However, efforts were made to identify knowledgeable key informants, use secondary data where possible, and test the main results in collaborative workshops to confirm the key findings. Not all relevant supply chain innovations were covered in this study, and further research is needed to delve deeper into other AM-related innovation scenarios in the future. Furthermore, the firms did not necessarily represent the same supply chains, so conclusions concerning a single supply chain cannot be made.

In the future, a single supply chain and its AM investment should be investigated to confirm this study's predictions and develop them further. Since cooperation between firms was considered important in this study, it would be beneficial to study to what degree large firms' support of their respective supply chains explains the successful adoption of AM throughout the supply chain.

References

Ageron, B., Lavastre, O., and Spalanzani, A. (2013), "Innovative supply chain practices: The state of French companies," *Supply Chain Management: An International Journal*, Vol. 18 No. 3, pp. 265–276.

Arlbjørn, J.S., de Haas, H., and Munksgaard, K.B. (2011), "Exploring supply chain innovation," *Logistics Research*, Vol. 3 No. 1, pp. 3–18.

ASTM Standard (2012), Standard Terminology for Additive Manufacturing Technologies, Vol. 10.04, ASTM International, West Conshohocken, PA.

Beamon, B.M. (1998), "Supply chain design and analysis: Models and methods," *International Journal of Production Economics*, Vol. 55, pp. 281–294.

Bello, D. C., Lohtia, R., and Sangtani, V. (2004), "An institutional analysis of supply chain innovations in global marketing channels," *Industrial Marketing Management*, Vol. 33, No. 1, pp. 57–64.

Campbell, T., Williams, C., Ivanova, O., and Garrett, B. (2011), "Could 3D Printing Change the World?" Technologies, Potential and Implications of Additive Manufacturing, Atlantic Council, Strategic Foresight Report, Washington, DC, USA.

Chesbrough, H.W. and Teece, D.J. (2002), "Organizing for innovation: When is virtual virtuous?" *Harvard Business Review*, Vol. 80 No. 2, pp. 127–136.

Durach, C.F., Kurpjuweit, S., and Wagner, S.M. (2017), "The impact of additive manufacturing on supply chains," *International Journal of Physical Distribution & Logistics Management*, Vol. 47 Issue 10, pp. 954–971.

Freeman, C. and Soete, L. (1997), The economics of industrial innovation, Continium, London.

D'Aveni, R.A. (2015), "The 3-D revolution," *Harvard Business Review*, Vol. 93 No. 5, pp. 40–48.

Heikkilä, J. (2002), "From supply to demand chain management: Efficiency and customer satisfaction," *Journal of Operations Management*, Vol. 20, pp. 747–767.

Holmström, J., Holweg, M., Khajavi, S.H., and Partanen, J. (2016), "The direct digital manufacturing (r)evolution: Definition of a research agenda," *Operations Management Research*, Vol. 9, pp. 1–10.

Holmström, J. and Partanen, J. (2014), "Digital manufacturing-driven transformations of service supply chains for complex products," *Supply Chain Management: An International Journal*, Vol. 19 No. 4, pp. 421–430.

Holmström, J., Partanen, J., Tuomi, J., and Walter, M. (2010), "Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment," *Journal of Manufacturing Technology Management*, Vol. 21 No. 6, pp. 687–697.

Johannessen, J.A., Olsen, B., and Lumpkin, G.T. (2001), "Innovation as newness: What is new, how new, and new to whom?" *European Journal of Innovation Management*, Vol. 4 No. 1, pp. 20–31.

Khajavi, S.H., Partanen, J., and Holmström, J. (2014), "Additive manufacturing in the spare parts supply chain," *Computers in Industry*, Vol. 65, pp. 50–63.

Lee, S. M., Lee, D., and Schniederjans, M. J. (2011). "Supply chain innovation and organizational performance in the healthcare industry," *International Journal of Operations & Production Management*, Vol. 31 No. 11, pp. 1193–1214.

Lee, V.H., Ooi, K.B., Chong, A.Y.L., and Seow, C. (2014), "Creating technological innovation via green supply chain management: An empirical analysis," *Expert Systems with Applications*, Vol. 41 No. 16, pp. 6983–6994.

Manceau, D., Kaltenbach, P-F., Bagger-Hansen, L., Moatti, V., and Fabbri, J. (2012), "Open innovation: Putting external knowledge to work," *Supply Chain Management Review*, Vol. 16 No. 6, pp. 42–48.

Martinsuo, M. and Luomaranta, T. (2018), "Adopting additive manufacturing in SMEs: Exploring the challenges and solutions," *Journal of Manufacturing Technology Management*, Vol. 29, No. 6, pp. 937–957.

Mellor, S., Hao, L., and Zhang, D. (2014), "Additive manufacturing: A framework for implementation," *International Journal of Production Economics*, Vol. 149, pp. 194–201.

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

Munksgaard, K.B., Stentoft, J., and Paulraj, A. (2014), "Value-based supply chain innovation," *Operations Management Research*, Vol. 7 No. 3-4, pp. 50–62.

New, S.J., and Payne, P. (1995) "Research frameworks in logistics: three models, seven dinners and a survey", *International Journal of Physical Distribution and Logistics Management,* Vol. 25 No. 10, pp. 60-77.

Oettmeier, K. and Hofmann, E. (2016), "Impact of additive manufacturing technology adoption on supply chain management processes and components," *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 944–968.

Oettmeier, K. and Hofmann, E. (2017), "Additive manufacturing technology adoption: An empirical analysis of general and supply chain-related determinants," *Journal of Business Economics*, Vol. 87, pp. 97–124.

Ojha, D., Shockley, J., and Acharya, C. (2016), "Supply chain organizational infrastructure for promoting entrepreneurial emphasis and innovativeness: The role of trust and learning," *International Journal of Production Economics*, Vol. 179, pp. 212–227.

Petrick, I.J. and Simpson, T.W. (2013), "3D printing disrupts manufacturing: How economies of one create new rules of competition," *Research-Technology Management*, Vol. 56 No. 6, pp. 12–16.

Piili, H., Happonen, A., Väistö, T., Venkataramanana, V., Partanen, J., and Salminen, A. (2015), "Cost Estimation of Laser Additive Manufacturing of Stainless Steel," *Physics Procedia*, Vol. 78, pp. 388–396.

Rogers, H., Baricz, N., Kulwant S., and Pawar, K.S. (2016), "3D printing services: Classification, supply chain implications and research agenda," *International Journal of Physical Distribution & Logistics Management*, Vol. 46 No. 10, pp. 886–907.

Rylands, B., Böhme, T., Gorkin III, R., Fan, J. and Birtchnell, T. (2016), "The adoption process and impact of additive manufacturing on manufacturing systems," *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 969–989.

Santosh, D.B.L. and Smith, L.S. (2008), "RFID in the supply chain: Panacea or Pandora's Box?" *Communications of the ACM*, Vol. 51 No. 10, pp. 127–131.

Sasson, A. and Johnson, J.C. (2016), "The 3D printing order: Variability, supercenters and supply chain reconfigurations," *International Journal of Physical Distribution & Logistics Management*, Vol. 46 No. 1, pp. 82–94.

Schumpeter, J. (1934), The theory of economic development, 1983 new edition, Transaction Publishers, USA.

Steenhuis, H-J. and Pretorius, L. (2017), "The additive manufacturing innovation: A range of implications," *Journal of Manufacturing Technology Management*, Vol. 28, No. 1, pp. 122–143.

Storer, M., Hyland, P., Ferrer, M., Santa, R., and Griffiths, A. (2014), "Strategic supply chain management factors influencing agribusiness innovation utilization," *The International Journal of Logistics Management*, Vol. 25, No. 3, pp. 487–521.

Strong, D., Kay, M., Conner, B., Wakefield, T., and Manogharan, G. (2018), "Hybrid manufacturing – Integrating traditional manufacturers with additive manufacturing (AM) supply chain," *Additive Manufacturing*, Vol. 21, pp. 159–173.

Thomas, D. (2016), “Costs, benefits, and adoption of additive manufacturing: A supply chain perspective,” *The International Journal of Advanced Manufacturing Technology*, Vol. 85 No. 5, pp. 1857–1876.

Weller, C., Kleer, R., and Piller, F.T. (2015), “Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited,” *International Journal of Production Economics*, Vol. 164, pp. 43–56.

Wong, D.T.W. and Ngai, E.W.T. (2019) “Critical review of supply chain innovation research (1999–2016),” *Industrial Marketing Management,* In press, https://doi.org/10.1016/j.indmarman.2019.01.017.