Adoption of additive manufacturing technology: drivers, barriers and impacts on upstream supply chain design

Alessio Ronchini, Antonella Maria Moretto and Federico Caniato
Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy

Received 30 December 2021
Revised 19 May 2022
28 September 2022
18 November 2022
8 February 2023
Accepted 16 February 2023

Abstract

Purpose – This paper investigates how the adoption of additive manufacturing (AM) impacts upstream supply chain (SC) design and considers the influence of drivers and barriers towards the adoption.

Design/methodology/approach – Ten case studies investigating AM adoption by Original Equipment Manufacturers (OEMs) in five industries were conducted. This research is driven by a literature-based framework, and the results are discussed according to the theory of transaction cost economics (TCE).

Findings – The case studies reveal four patterns of AM adoption that affect upstream SC design (due to changes in supply base or types of buyer–supplier relationships): make, buy, make and buy and vertical integration. A make or buy decision is based on the level of experience with the technology, on the AM application (rapid manufacturing, prototyping or tooling) and on the need of control over production. Other barriers playing a role in the decision are the high initial investments and the lack of skills and knowledge.

Originality/value – This paper shows how different decisions regarding AM adoption result in different SC designs, with a specific focus on the upstream SC and changes in the supply base. This research is among the first to provide empirical evidence on the impact of AM adoption on upstream SCs and to identify drivers of the make or buy decision when adopting AM through the theoretical lens of TCE.

Keywords Additive manufacturing, Supply chain design, Supply chain management, 3D printing, Make-or-Buy

Paper type Research paper

1. Introduction

Additive manufacturing (AM) technology, also called 3D printing, builds objects layer by layer, starting from a digital model. Patented by Charles Hull in 1984, it was initially used for prototyping (rapid prototyping, RP); in recent years, it has been deployed to produce tools (rapid tooling, RT) or final products (rapid manufacturing, RM) (Hopkinson *et al.*, 2006). Lately, companies' interest in AM has increased due to advances in the technology leading to improvements in accessibility, precision, speed and material range (Halassi *et al.*, 2019). Indeed, different materials are now available (plastics, polymers, metals, ceramics, carbon fiber) with several AM techniques (e.g. stereolithography, SLA; fused deposition modeling, FDM; selective laser sintering, SLS) (Hopkinson *et al.*, 2006). Yet it remains a niche technology with a long way to go before 'mass adoption'. Traditional manufacturing is still superior from a cost and time perspective for high volumes of standardized products (Attaran, 2017).

International Journal of Physical Distribution & Logistics Management
Emerald Publishing Limited
0960-0035
DOI 10.1108/IJPDLM-12-2021-0541

Moreover, another barrier to adoption is uncertainty regarding the impact of AM technology on supply chain (SC) structure (Martinsuo and Luomaranta, 2018).

The adoption of AM is not a single-firm change. It affects SC processes, practices, roles and relationships (Oettmeier and Hofmann, 2016). Indeed, a company adopting AM may decide on a centralized configuration, where several AM machines are deployed in a central hub, or distributed manufacturing, where a manufacturing network is created and printers are deployed in local hubs (Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Braziotis *et al.*, 2019). Among SC processes, supplier relationship (Oettmeier and Hofmann, 2016) and supply network management appear to be affected yet are underexplored. In fact, Kunovjanek *et al.* (2022) and Meyer *et al.* (2021) explored the topic with two structured literature reviews aimed at identifying AM's impact on the sourcing process, showing that there is a critical gap regarding the perspective of upstream SCs. Many papers have been published looking at the effects on distribution channels (Ryan *et al.*, 2017), but the adoption of AM has direct consequences on the upstream linkages as well (Ruffo *et al.*, 2007). Thus, this topic requires more theoretical and empirically based contributions. For this reason, this paper aims to highlight the impact of AM adoption on SC design, especially upstream, covering both a practical gap by offering empirical evidence regarding the effects of AM adoption on upstream SC linkages and nodes and a theoretical gap by using transaction cost economics (TCE) as a lens to interpret and discuss results.

This paper aims to study the impact of drivers and barriers in the adoption of AM and consequent effects on the upstream SC by pursuing the following research questions:

RQ1. How do drivers and barriers influence the adoption of AM technology?

RQ2. What is the impact of AM adoption on the upstream supply chain, according to Transaction Costs Economics?

Based on 10 case studies, we provide evidence about the impact of AM adoption on SC design in terms of centralization, make or buy decision and impact on the supply network. We discuss these elements according to three constructs of TCE: asset specificity, frequency and uncertainty. Our findings provide evidence of four patterns of adoption regarding make or buy decisions, namely *make*, *buy*, *make and buy* and *vertical integration*. Moreover, in contrast to the knowledge provided by the extant literature, we discovered that SC complexity may increase as the supply base is enlarged when AM is adopted and that the buyer-supplier relationship may result in a lock-in relation.

This paper describes the state of the art in the academic literature in section 2, presenting the research framework. Section 3 explains the research methodology. Section 4 describes and discusses results. Section 5 concludes the paper, providing theoretical and managerial contributions along with limitations and future research directions.

2. Theoretical background: literature review and research framework

2.1 Drivers and barriers to AM adoption

Herein, we define drivers as enabling factors that push towards the adoption of AM technology and barriers as the challenges that hamper its adoption.

Several studies focused on detecting drivers for AM adoption propose two categories: *exogenous events*, such as the expiry of critical patents (Ryan *et al.*, 2017) or the advent of the fourth industrial revolution (Industry 4.0) (Pfohl *et al.*, 2015; Nascimento *et al.*, 2019) and *expected benefits of adoption*. In Afshari *et al.*'s (2020) model, the achievable *expected benefits* are clustered into three different classes: *product level*, *process level* and *SC level*. In this paper, we use this same model to cluster the expected benefits of AM.

Barriers, meanwhile, were classified by Martinsuo and Luomaranta (2018) into six main categories: *technological*, *strategic*, *supply chain*, *operational*, *organisational* and *external barriers*.

Table 1 summarises and describes the drivers and barriers to AM adoption.

2.2 Supply chain design

The supply chain can be defined as a network of different business entities that work together to acquire raw materials, components and sub-assemblies, transform them into final products and deliver them to customers (Melo *et al.*, 2009; Song *et al.*, 2018). Therefore, supply chain

Drivers		Source	Barriers	Source
Exogenous events	*Strategic Factors* - Patents' expiration - Industry 4.0 advent	Pfohl *et al.* (2015), Ryan *et al.* (2017), Nascimento *et al.* (2019)	*Technological barriers* - Low production speed - High manufacturing costs for series production - Technical constraints: limited size and volume of the product - Quality issues and post-processing needs	Wagner and Walton (2016), Attaran (2017), Shukla *et al.* (2018), Thomas-Seale *et al.* (2018)
Expected benefits of adoption	*Product level* - Design freedom: possibility to produce complex-shaped items - Optimization of products and enhanced functionalities: creation of hollow spaces or grid structures inside an object	Mellor *et al.* (2014), Oettmeier and Hoffman (2016), Oettmeier and Hoffman (2017), Martinelli and Christopher (2019)	*Operational barriers* - Limited quality, accuracy and reliability - Limited available materials - Lack of technical standards and specifications	Colosimo *et al.* (2018), Chaudhuri *et al.* (2019)
	Process level - Cost-efficient manufacturing performance: reduction in manufacturing costs and lead time - Process simplification: fewer post-production and assembly procedures - Reduction in resource consumption and waste, with an impact on environmental performance - Shortening of the new product development process	Sun and Zhao (2017), Attaran (2017), Luomaranta and Martinsuo (2020)	*Supply chain-related barriers* - Uncertainty of the chain structure after AM adoption: changes in the SC design, new actors in the chain (e.g. new suppliers)	Martinsuo and Luomaranta (2018)

(*continued*)

Table 1.
Drivers and barriers to AM adoption

Drivers		Source	Barriers	Source
	SC level - Digitization of SC processes and linkages - SC complexity reduction: elimination of one or more tiers from SC structure - SC performance enhancement: inventory and transportation costs reduction, better environmental impact - Enabling customer-centric business models: demand-chain and value co-creation with customers	Holmström *et al.* (2010), Khajavi *et al.* (2014), Bogers *et al.* (2016), Ashour Pour *et al.* (2019), Muir and Haddud (2018), Martinelli and Christopher (2019)	*External barriers* - Lack of certifications and regulations - Intellectual Property Right protection of CAD files	Yampolskiy *et al.* (2018), Halassi *et al.* (2019), den Boer *et al.* (2020)
			Organizational challenges - Lack of skills and knowledge of AM - Lack of trained and skilled labour force	Shukla *et al.* (2018), Martinsuo and Luomaranta (2018), Öberg and Shams (2019)
			Strategic challenges - Lack of a strategy for AM introduction - High initial investments, capital expenditures (CAPEXs) and long payback time - High operational expenses (OPEXs)	Martinsuo and Luomaranta (2018), Tziantopoulos *et al.* (2019), Braziotis *et al.* (2019)

Table 1. **Source(s):** Created by author

design means defining the SC configuration, i.e. the structure of the SC and task allocation to its different stages. As suggested by Song *et al.* (2018, p. 3), designing an SC means defining *'the physical network structure'* and optimizing *'the links and inventory decisions among the network nodes'*.

Holmström *et al.* (2010) and Khajavi *et al.* (2014) established the basis for a research stream focused on understanding how to design an SC once AM is adopted. Focusing on the spare parts SC, they identified two possible SC configurations: *centralized* and *distributed manufacturing configurations*. In the first, a hub with a number of AM machines is used to aggregate demand and replace regional distribution centers. The second configuration deploys distributed local hubs (i.e. service locations) close to end-use customers where AM machines print products and serve local demand (Holmström *et al.*, 2010; Khajavi *et al.*, 2014; Liu *et al.*, 2014; Savastano *et al.*, 2016; Braziotis *et al.*, 2019). By adopting one configuration or the other, the SC structure is impacted as one or more tiers may be eliminated (Holmström *et al.*, 2010; Khajavi *et al.*, 2014), allowing a reduction in the number of suppliers (Ivanov *et al.*, 2019). Indeed, by adopting a distributed manufacturing approach, an original equipment manufacturer (OEM) can eliminate regional distribution centers by printing and distributing products locally. Thanks to this and to the digitisation of linkages (Holmström *et al.*, 2016), SC complexity reduces (Ashour Pour *et al.*, 2019) and SC performance improves (e.g. reduction in inventory, lowered transportation costs, environmental impact) (Muir and Haddud, 2018). Nevertheless, Martinsuo and Luomaranta (2018) showed that the uncertainty regarding the impact of AM adoption on SC structure may be a barrier, especially as perceived by small and medium enterprises.

AM adoption may also impact relationships regulated within these networks. On the upstream side, new actors may emerge (equipment producers, power and service providers), and roles and responsibilities may vary (Mellor *et al.*, 2014; Chekurov *et al.*, 2018). On the downstream side, customers can become the engine for the chain, transforming it from a supply to a demand chain (Martinelli and Christopher, 2019), triggering a new product development process that is shortened thanks to rapid prototyping (Luomaranta and Martinsuo, 2020).

Nevertheless, studies investigating the impact of AM adoption on SCs have not considered the entire SC. A research stream about the impact of AM on the downstream SC (i.e. distribution from the manufacturer to the final customer) exists (Eyers and Potter, 2015; Ryan *et al.*, 2017), but the upstream side remains underdeveloped. Few authors have attempted to narrow this gap. Kunovjanek *et al.* (2022) performed a systematic review that classified papers according to the Supply Chain Operations Reference (SCOR) model and therefore also considered the sourcing process, but they still uncovered little evidence. Meyer *et al.*'s (2021) systematic literature review, which classified papers according to the logistics, SC and procurement strategies, as well as sourcing process, confirmed this gap. In this last category, they investigated the impact of AM in terms of make or buy decisions, demand specification, supplier selection and contracting processes. Filling their framework with the retained papers, they found that no papers explored the *procurement strategy* and that only two analysed the make or buy decision. Friedrich *et al.* (2022) investigated the make or buy decision in industrial AM through the theoretical lens of TCE. They identified three ways to adopt AM: (1) using an in-house strategy, i.e. purchasing the machines; (2) using an outsourcing strategy, i.e. purchasing the printing service; or (3) using a mixed strategy by purchasing both the machines and the printing service. They found that the strategy depends chiefly on two variables: the maturity level of AM and the AM application (rapid manufacturing, prototyping, tooling or education and research).

2.3 Transaction Costs Economics: theory and application to AM adoption

Transaction Costs Economics (TCE) is an economic theory that dates back to 1937 when Coase published the first contribution with his *The nature of the field.* Developed later by Williamson (1979, 1981, 2008), the theory is based on the concept that since the market is not perfect, two actors entering in a transaction (i.e. the transferral of a good or service across a technologically separable interface) are subject to bounded rationality and may act opportunistically (Williamson, 1981). This leads to a rise in *transaction costs*, which include information, negotiation and monitoring costs. Thus, since the publication of Coase's article in 1937, this research stream has worked to identify the best governance structure possible to manage transactions and reduce costs. Such decisions are made according to three dimensions: the *uncertainty* of the market, the *frequency* with which the transaction occurs and the specificity with which transaction-specific investments, also called *asset specificity*, are required (Williamson, 1981). According to the degree of these dimensions, a firm may decide to *buy on the market*; build a hierarchical structure, i.e. *vertically integrate*; or adopt a *hybrid form* (e.g. joint ventures, alliances). In the first decade of the 2000s, researchers began to apply this theory to SC management and procurement (Ellram *et al.*, 2008; Williamson, 2008). In this case, the theory helps addressing the basic question in procurement: to make or to buy? For a company, this means either producing goods/services internally (make) or outsourcing production activities and buying products/services on the market (buy). Thus, the theory should provide companies with guidance as to whether *making* or *buying* is more advantageous (Williamson, 2008).

To our knowledge, TCE had never been applied in the realm of AM prior to Friedrich *et al.* (2022). More widely, the impact of AM adoption on procurement and supply management is extremely underexplored, as shown by the systematic literature review by Meyer *et al.* (2021). They indicated that only two papers (Ruffo *et al.*, 2007; Hedenstierna *et al.*, 2019) have addressed the issue of make or buy, to which is then added the paper by Friedrich *et al.* (2022), which is also the only one to have adopted TCE. Nevertheless, the adoption of AM impacts supplier relationship management processes and changes linkages upstream. Thus, there is a gap related to the impact of AM adoption on upstream SC that needs to be both filled with empirical evidence and supported theoretically. As abovementioned, TCE is a useful theory for studying potential changes in the supply network, such as the buyer-supplier relationship and the make or buy decision. Thus, we have decided to support our study with this theoretical lens.

Our research framework, illustrated below in Figure 1, aims to fill this gap. It relates the adoption of AM with variables that may either drive or hinder this process (drivers and barriers to adoption), investigating the impact of AM adoption on SC design in terms of centralization, governance structure (make or buy decision) and supply network. Moreover, our research framework aims to address a theoretical gap, adopting TCE to interpret the role of asset specificity, frequency and uncertainty in determining the impact of AM adoption on SC design.

3. Methodology

Aligned with our research questions, we have adopted a case study methodology. Yin (1984, p. 2) proposed a case study methodology when *'the focus is on a contemporary phenomenon within a real-life context'*. The adoption of AM is in its infancy and requires empirical investigations such as case studies. Therefore, we have developed explanatory case studies to study the impacts of drivers and barriers on AM adoption and, in turn, on upstream SC design. In our study, the unit of analysis is the company that adopts AM; we investigate the changes in its upstream SC. Our sample comprises 10 OEMs, as shown in Table 2.

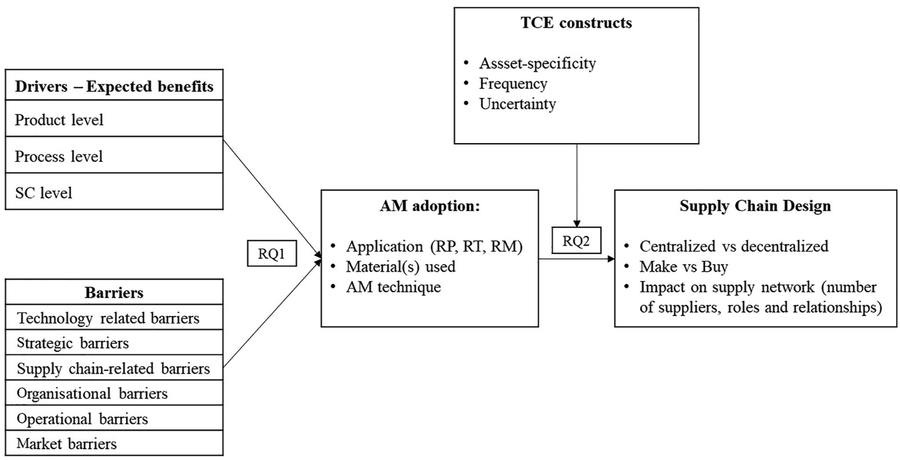


Figure 1.
Research framework

Source(s): Created by author

Table 2. Final sample of the interviewees

Company code	Interviewee(s) - job title(s)	Interviewee(s) code	Role	Position in the chain	Industry	Year of AM adoption	Size	Turnover
A	CEO	P1	OEM	First tier	Oil and gas	2017	SME	€ 3.8mln
B	Supplier Performance Manager	P2	OEM	Focal company	Aerospace	2017	Large	€ 64.78bn
C	Innovation Project Manager	P3	OEM	Focal company	Aerospace	2014	Large	€ 13.8bn
D	1. Product Engineer	P4	OEM	First tier	Medical	2014	SME	€ 7.66mln
	2. Project and Manufacturing Engineer	P5						
E	Additive Manufacturing and Technical Manager	P6	OEM	First tier	Industrial production	2017	SME	€ 3.91mln
F	NPI Industrial Leader – Additive Manufacturing	P7	OEM	Focal company	Aerospace	2007	Large	€ 1.7bn
G	R&D lead for AM development	P8	OEM	Focal company	Automotive	2008	Large	€ 1.87bn
H	1. Advanced R&D Engineer	P9	OEM	First tier	Automotive	2015	Large	€ 947.8mln
	2. Product Development Manager	P10						
I	Technical Functions Manager	P11	OEM	First tier	Industrial production	2013	Large	€ 1.5bn
J	Application Specialist 3D Printing	P12	OEM	Focal company	Tech	2017	Large	€ 49.73bn

Source(s): Created by author

These firms were selected because they have used the technology and, consequently, have gone through the process of adoption. After a scouting process that looked at OEMs' and providers' websites, we addressed firms that have published news, articles or business cases about their adoption of AM technology. To guarantee heterogeneity, we built our sample with firms that differ in terms of industry, role in the SC, size and AM application (RP, RT, RM). This choice was driven by a desire to create a diverse sample so that we could assess possible differences among cases and increase the representativeness of companies adopting AM.

Consistent with the qualitative nature of the methodology, data were collected mainly through direct interviews with companies' experts. A semi-structured protocol was used to guide the respondent to the topic while allowing for open answers. Two researchers participated in each interview, and interviews lasted between 30 and 86 min. Each was recorded with permission and then transcribed. Additional information was collected from secondary sources to complement and triangulate data and add depth to the cases. Companies' websites, press releases, reports and articles related to their use of AM were consulted to collect the following information: companies' revenues, year of establishment, year of AM adoption, expected benefits and, when available, data related to the use of AM technology (e.g. AM techniques, material used, AM application).

Following data collection, a within-case analysis was initially performed. For each case, interviews were transcribed and transcriptions were coded according to the variables of the research framework. If a respondent referred to a new variable that had not emerged from the literature review, this was added as a new code. The coding process is shown in Annex A. Then, additional information and data coming from secondary sources were added according to each variable they contributed to. Thus, the final output was a clear and deep understanding of each individual case of AM adoption., which was then used to perform the cross-case analysis. Indeed, the results of the within-case analyses were then used to compare cases. We performed cross-analysis among cases for every variable, which allowed us to identify similarities and differences among them. Moreover, variables that emerged from the literature and were mentioned as relevant by respondents were confirmed, while those variables not mentioned as significant by any interviewee were removed from the framework. Finally, we performed a cross-analysis to identify potential patterns among cases, which led to the identification of the four patterns of AM adoption. Cross-case tables were created based on the four patterns to identify the similarities and differences according to the variables of the framework.

4. Results

The within-case and cross-case analyses enriched the research framework as variables emerged during the interviews. Informants articulated drivers and barriers, providing evidence about their influence on AM adoption and the consequent impacts on upstream SCs.

4.1 Drivers of adoption

Our evidence suggests that companies adopt AM primarily to pursue ***expected product benefits***. Consequently, we removed ***expected process and SC benefits*** from the revised framework since companies' representatives stated that such benefits are perceived only after introducing AM and do not drive its adoption; they were simply unexpected.

At the product level, two drivers emerged as important: *enhanced functionality* and *design freedom*. All informants reported having adopted AM to improve the functionality of prototypes, components or products. Indeed, the ability to create the product layer by layer allowed new designs that enhanced the technical characteristics and the weight. This is especially significant in the healthcare sector, particularly for developing customized prostheses, as reported by P4: *'One of the great advantages of AM is that it is possible to create surfaces (known as trabecular surfaces) which allow very high levels of osteo-integration of the prosthesis on the bone'.* This driver also appears in the automotive sector, albeit with a slight nuance in meaning since the enhanced functionality includes aesthetics and improved performance that can result from a reduction in weight, as reported by P8. The other driver mentioned by all companies is *design freedom,* i.e. the possibility to design and print complex-shaped products without additional costs. P9 and P10, in the automotive sector as a supplier, stated, *'The biggest advantage of AM is the freedom of shape and the ability to make very complex geometries that do not have constraints linked to mechanical or casting technologies'.* The value of finding the optimal shape was also confirmed by P1, a supplier in the oil and gas sector: *'Let's take the example of this valve [...] With 3D printing, we have redesigned and created a valve that already has the ball inside, so it doesn't need to be plugged'.*

Freedom of design and enhanced functionalities align with many studies in the literature (Ghadge *et al.*, 2018; Tziantopoulos *et al.*, 2019) and seem to be general drivers for adopting AM.

Other case-specific drivers related to firm size emerged from the interviews (cases A, D and E). As small and medium-sized enterprises (SMEs), they adopted AM not only to enhance products' functionalities but also as a differentiation strategy to gain a competitive advantage. Company D decided to adopt AM to apply a *premium price* by customizing its products (prostheses) and offering a higher service level. Moreover, they could enter new markets and serve new customers. Similarly, P6 reported, *'We introduced AM because it was a technology that was well-suited for expanding our offerings'.* In this case, Company E adopted AM to increase the service level in terms of products' functionalities and overall lead time and, in turn, to find *new business opportunities (markets or clients)*. Although these are well-known drivers in the literature (Beltagui *et al.*, 2020), the links to company size that emerged from this study can be further analysed in future investigations.

Two other companies (A and F) reported having adopted the technology because it allows them to produce new products by leveraging *new materials* that can only be used with AM. P7 reported, *'Additive technology makes it possible to fuse materials that would have been difficult with traditional technology'.* This seems to be a case-specific product benefit and is perfectly aligned with Maresch and Gartner (2020, p. 10), who found that AM would be advantageous for companies only *'if the material used is that which best suits the firm's product and production processes'.*

4.2 Barriers to adoption

The first result is that companies do not perceive ***supply chain-related barriers*** since they are not concerned about possible implications regarding changes in SC design, roles and relationships. Most of them adopt AM as an additional manufacturing technology, often for rapid prototyping, and they do not forecast significant changes in terms of SC design. Even when it is adopted for rapid manufacturing applications, companies have adequate experience with the technology and also know how to deal with it from a managerial perspective. Hence, in contrast to the model by Martinsuo and Luomaranta (2018), we discarded SC-related barriers from our framework.

Moving to ***technological barriers***, *quality issues* are the most frequently recurring barrier highlighted by interviewees in all the investigated industries. Quality problems are related to post-processing activities, a problem that is well-known in the literature and that depends on the AM technique (Colosimo *et al.*, 2018). P6 stated, *'If we have to make a hollow object with reduced thickness, we cannot clean it with FDM (fused deposition modeling) technology, so we are forced to use other technologies or rely on other partner suppliers'.* The AM technique is, therefore, also important when considering impacts on upstream SCs: the barrier of *quality issues* related to the specific AM technique (fused deposition modeling, FDM) led this company to enlarge its supply base to new suppliers for post-processing activities.

Technological barriers also include extended *production times* and *volume limitations.* Informants reported that manufacturing times are still too long to adopt AM for mass production and that AM is profitable only for certain product categories. Indeed, P6 highlighted that in the case of production in series, the most competitive and best technology will continue to be the traditional one. Moreover, P7 explained that, to grow quickly in volume, there needs to be a high number of identical machines. However, not all companies can afford several machines due to high investment. Thus, according to these interviewees, AM should be deployed for producing parts or components with low volume and for which production speed is not relevant.

Finally, P2 reported another barrier regarding *size limitations*: *'There is a major dimensional constraint, because the manufacturing chambers for metal powders are still relatively small [. . .] This clearly restricts the type of parts that can be made for the structure of an aircraft'.*

Strategic barriers entail *high initial investments and operational costs* and are shared by all companies. They are experienced especially by companies that have bought metal printers, which entail significant investments, ranging from a half million euro upwards. Other expenses must also be borne when AM is adopted, including investments in new spaces and personnel (Companies E and J), high operational expenses for raw materials (powders, coils) and other related services. Relatedly, P1 stated, *'Initially, we bought the raw material (wire) from the same supplier as the printer, but this was very expensive, although we avoided waste, downtime and scrap because of its high quality'.* The company was locked into the buyer–supplier relationship, and due to the high quality of raw materials, costs were significant, and the company attempted to end the relationship. However, there were no substitute products on the market, and they were forced to maintain the relationship. Companies that purchase 3D printers may be particularly impacted by the barrier of *high costs.* Hence, this barrier may lead companies to change purchasing strategies and opt for outsourcing additive production to gain greater flexibility.

Three of the companies included in the present study identified two additional strategic barriers: the *lack of a defined strategy* and *top management resistance.* For the first, P11 reported that, when they adopted AM, they lacked a clear strategy, which led to under-exploitation of the technology. Moreover, this informant explained that the main difficulty experienced was convincing top management. This barrier was reinforced by P8: *'The biggest difficulty was explaining to management why they should spend €25,000 on a plastic printer'.*

Regarding ***operational barriers***, P3 reported that *limited available materials* were problematic. This may be industry-specific as this company is in the aerospace industry, where the selection of materials is highly relevant in terms of the quality of the final products and the safety of end users.

By contrast, a cross-case ***operational barrier*** is related to the fact that *products are not designed for AM production.* Hence, companies experience difficulties adapting product or component designs for additive production. According to P2, *'The difficulty we have is that to really achieve savings by using AM [. . .] it is necessary that the part is designed for AM [. . .] Trying to match or compete the price of a part designed for traditional technologies and then converted to AM will never be economically viable'.*

Moving to ***organisational barriers***, companies struggle with the technology due to a lack of skills and knowledge. Company F has had difficulty hiring AM-qualified personnel because of the labour shortage. Company I, by contrast, did not share this concern since, due to its large size, its bargaining power on the job market led to recruiting AM-skilled workers without difficulty, contrary to Company A (a small firm). Hence, P1 reported that the *lack of* *skills and knowledge* was a barrier to entry because employees had to study and acquire hands-on experience with the printers and raw materials before understanding the parts using AM. This barrier is linked to the strategic barrier of high initial investment since companies reported having to invest in the machinery as well as in new skilled employees. Consequently, organisational and strategic barriers may be related to the *make or buy* decision. As expressed by several informants, companies may decide to outsource metal production and not purchase metal printers to avoid high investments regardless of company size, which appears irrelevant in this decision (i.e. even large companies decided to outsource production).

Finally, the ***external barriers*** concern mainly the *lack of regulations and certifications* in AM. Indeed, companies are hindered since AM is a single-batch production process, i.e. components and parts are replicated, but printing can differ based on several factors, e.g. the single machine, contingencies, etc. Hence, contrary to traditional manufacturing, it is difficult to certify the production process and the manufactured products. This is a cross-case barrier, especially valid for companies associated with human safety, such as the aerospace, automotive and medical industries, that require certified products. P8 explained, *'One of the problems is related to the validation of the components produced in AM, so for example, durability tests or tests related to the materials used'*. Company C, which instead outsources AM production to an external service provider, expressed difficulties assessing production quality when performing the qualification and selection process of the provider. The *lack of regulations and certifications* is among the most relevant reasons the technology is not adopted for mass production. The literature (Wagner and Walton, 2016; den Boer *et al.*, 2020) discusses this barrier, but we provide significant evidence about its practical impacts on AM adoption.

4.3 AM adoption

Evidence common to all the companies in our sample is related to two aspects: (1) all companies have a central hub in which printers are used to produce components, tools or prototypes. None of the firms has a distributed manufacturing network since companies use AM for production volumes that are not large enough to justify creating a structured decentralized network, as suggested by Holmström *et al.* (2010) and Khajavi *et al.* (2014), (2) nine companies in the present study have complemented traditional manufacturing with AM, choosing a hybrid approach as suggested by Braziotis *et al.* (2019). Company D is the only company that has produced exclusively with AM since they adopted AM.

Looking at the materials used, companies have adopted AM with metal and plastics. Generally, plastic is associated with prototyping applications and the production of components. Companies tend to adopt AM first with plastics since it costs less than metal. This economic advantage led eight of 10 companies to internalize the production of plastic AM. By contrast, four of the nine companies using AM for metal production have decided to outsource production. The reason is linked to high operational and capital expenses (as reported in the barrier section) as well as to the increased need for competencies and experience with the material. Some barriers appear to be perceived more often when AM is adopted with metals compared to plastics, involving also a choice linked to buying or making.

4.4 Impact of AM adoption on upstream SCs

Our results show four patterns in adopting AM: (1) *buy*, i.e. purchase the printing service; (2) *make*, i.e. purchase printers; (3) *make and buy,* i.e. purchase plastic printers and buy metal printing services; and (4) *vertical integration,* i.e. acquire suppliers that use AM.

Buy was chosen by only one company, Company C, which purchases AM production from qualified suppliers in metal printing. The decision to purchase the service instead of printers was driven by the high initial investment the company would bear: *'We don't have in-house printers for the production of metal parts. This is because the technology today is capital intensive, requiring a large investment'*. Indeed, this company uses AM to produce metal tooling and a few components, making a printer purchase inconvenient. The consequence in terms of supply network is a slight increase in the number of suppliers because the company did not replace traditional manufacturing with AM but simply added a few other suppliers for new or redesigned components. These new suppliers are printing service providers, and the company states that the Italian landscape sees few players that can provide high-quality industrial metal printing, with only around 10 companies that have the necessary structure to be able to produce industrial metal AM components. This implies a high concentration in the supply market that, in turn, creates a lock-in effect for the buyer company, which cannot easily switch suppliers. To deal with this issue, the company decided on a long-term relationship with service providers, making this choice a *collaborative buy*.

Make is the choice of five companies (A, B, D, I and J). It emerged that this choice does not depend on the material (plastic or metal) or on the AM technique. Interviewees indicated that it depends on the general commitment of the company to invest in this technology, in line with the level of experience with AM. Indeed, most of these companies adopted AM by first purchasing the printing service and then purchasing plastic or metal printers. For instance, P1 reported, *'Initially we relied on an Italian service provider [. . .] When we saw that the mechanical and hydraulic world reacted very well and with great interest to the first 3D printed components, we decided to make the leap and buy our first metal printer'*. All companies that made the decision to *make* have seen a slight increase in the number of suppliers, which can be classified into two clusters: (1) suppliers of printers that also supply raw materials and (2) suppliers of AM-related services, such as post-processing services, certificatory bodies, etc. Regarding this increase in suppliers, P12 stated, *'New suppliers are needed for the post-processing stages (e.g. dyeing). [. . .] if you decide to bring the technology in-house, you should then have whoever supplies the material, the machine, the finishing . . . so in this case the number of suppliers increases'*. Common among cases is the type of relationship these companies have with their AM suppliers: they all establish a long-term collaboration because whoever supplies the machine will then also supply raw materials and assist the client with other services (e.g. design).

Make and buy is the common choice of companies adopting AM with both plastic and metal materials. Companies E, G and H decided to purchase plastic printers since they recognized the value of AM, but they have not committed to extending in-house production to metal components because of the high initial investments. P6 explained, *'Unfortunately, we are not able to afford sintering machines or stereolithography equipment, which are quite expensive investments [. . .], so we have our own network of suppliers'*. Company H's case differs slightly since they produce plastic components in-house to have greater control of the production process. By contrast, AM is too expensive for metal components since the number of products does not justify the investment and costs of additive production. All three companies reported an increase in the number of suppliers because AM has not replaced traditional manufacturing and metal components are outsourced to external AM service providers. Moreover, even if production of plastic components is in-house, some products still need to be refined by other suppliers. Thus, equipment producers, raw material suppliers and AM-related service providers have entered the new supply base. Also in this case, the buyer–supplier relationship is based on long-term collaboration.

Finally, there is one case of *vertical integration*: Company F decided to directly purchase suppliers to make them part of the same business. This choice is certainly strategic as this company works in the aerospace sector, where there are strict rules and regulatory constraints involved in using any new component in aircraft. Hence, the company decided to purchase the suppliers to gain maximum control of production processes. Components still need to be reworked and subjected to heat treatments, but these processes are done not only for additively produced parts but also for those produced with traditional technologies. Thus, the company turned to traditional suppliers to take advantage of their expertise.

Figure 2 depicts the revised framework enriched with the empirical evidence described above.

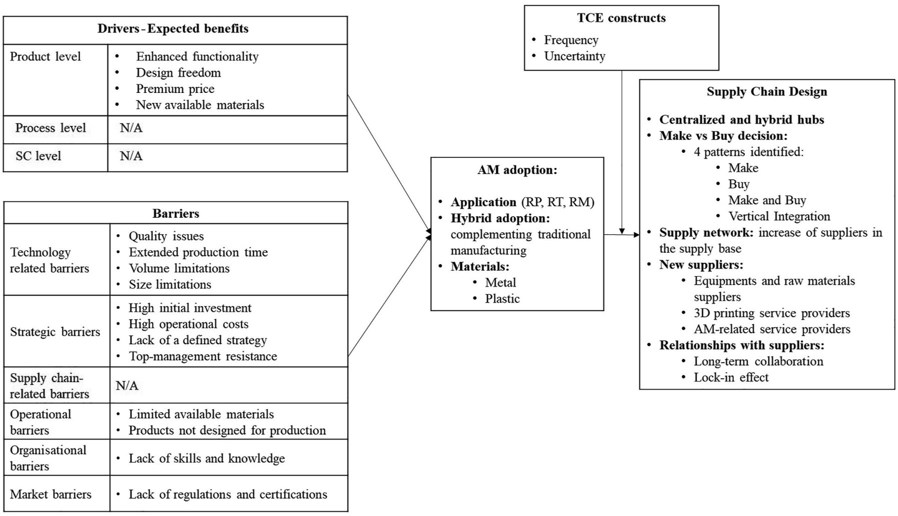
5. Discussion

5.1 Impacts of drivers and barriers on AM adoption

In line with the literature (Oettmeier and Hofmann, 2017), companies see AM as a tool to enhance actual products or to enlarge their business models (Bogers *et al.*, 2016). The main drivers are design freedom and the enhanced functionalities of products, both focused on innovation. Therefore, AM is adopted first with plastic material as a prototype, and when advantages are experienced, the use of the technology is enlarged to produce components, often internalizing production. Indeed, AM starts with a product-innovation focus and ends with innovating the manufacturing process as well.

Nevertheless, several barriers hinder the adoption process, especially in certain industries and for metal materials. Extended production time and size and volume limitations were indicated mainly by companies in the aerospace and automotive sectors, which report that AM is not yet able to replace traditional manufacturing, especially considering some AM techniques and materials (metal). These results align with academic literature (Attaran, 2017; Shukla *et al.*, 2018), but we have identified a relationship with the industry variable and provided further empirical evidence supporting the literature.

Two other barriers—*high initial investments and operational costs* and *lack of skills and knowledge about AM*—have significant impacts on AM adoption, a finding that echoes most studies in the literature (Martinsuo and Luomaranta, 2018; Thomas-Seale *et al.*, 2018).



Source(s): Created by author

Figure 2. Revised research framework

These two barriers have driven several companies to outsource AM production, thus determining the make or buy decision (cases C and G). Again, these barriers appear to be associated with the material used as they are perceived with metals more than with plastics.

5.2 Impact of AM adoption on upstream SCs

The abovementioned results are discussed here through the lens of TCE and summarized below in Table 3

As shown in Table 3, the variable that is impacted the most by the constructs of TCE is the make or buy decision. This is surprising—most of the literature that uses TCE in purchasing has found the same result (Ellram *et al.*, 2008; Williamson, 2008)—but with this research, we enlarge that stream by focusing on and providing evidence of the specific AM technology. Nevertheless, in this realm, we see that frequency and uncertainty play a relevant role, while asset specificity is not crucial for SC design when AM is adopted.

Starting from *asset specificity,* results show that AM does not require relationship-specific investments since the technology is inherently flexible; the specificity is confined to the digital model of the product. Adopting AM, therefore, does not require specific investments by the supplier. Hence, for all the variables we have considered, we identified a low asset specificity, making this construct non-discriminant in its impact on SC design, confirming what Friedrich *et al.* (2022) found with the make or buy decision.

Frequency, meanwhile, is represented in our model mainly in AM application (RP, RT and RM). This, in turn, influences the experience with the technology and affects investments in it and in skilled human resources, as depicted in Table 3. In our case studies, frequency is not important for the centralization decision: all companies were found to have adopted AM with a centralized and hybrid approach either to produce new components or to complement traditional manufacturing, in agreement with the study by Braziotis *et al.* (2019) that proposed a combinational configuration, regardless of the technology usage frequency. Despite this, frequency may have an impact on the supply network: almost all companies have seen a slight increase in the number of suppliers. Our results show that, contrary to what the literature reports, SCs are not simplified but, instead, the supply base is enlarged with new suppliers. When passing from RP to RM, firms' supply base is more impacted as more suppliers are involved, namely equipment producers, printing services and AM-related service providers. Specifically, if the frequency is low, firms onboard only printing service providers, opting for a buy choice; when moving toward an additive production in series, the firm also involves equipment producers and AM-related service providers, addressing the need for higher requirements in quality. Hence, this research partially contradicts what academic literature has reported about the reduction of SC complexity and the number of tiers (Holmström *et al.*, 2016; Ivanov *et al.*, 2019). The reason may be that these studies assumed that AM is adopted to replace traditional manufacturing.

Moreover, frequency is decisive in the make or buy decision: the only company in our sample to adopt the *buy* pattern expressed its motivation by noting that the investment was unjustified because of the infrequent use of AM. Instead, companies that chose to *make* reported that this decision was reached after a process of acquiring knowledge and experience with the technology (see the results section). Indeed, companies lack the competencies to install and use additive manufacturing, so the skills and knowledge barrier makes outsourcing more convenient. Prahalad and Hamel (1990) and Arnold (2000) highlighted the importance of having experience and competencies in the make or buy choice; when competencies are lacking, firms tend to outsource. By contrast, as in this case, if the frequency of technology usage increases, making it a core process, firms may be willing to invest in both the technology and skilled labour force. Only after necessary skills were acquired and benefits were recognized did these companies opt to purchase machines. When

Variables		TCE constructs Asset specificity	Frequency	Uncertainty
Definition		- Relationship specific investments (RSIs): investments specific to the buyer-supplier relationship	- Experience level with the technology: the higher the experience, the more frequent the usage of AM - Investments in technology and skilled human resources: the more frequent the usage of the technology, the higher the need to purchase printers and hire skilled and competent human resources	- Control over production: the higher the need for certifications and qualified products, the higher the need to reduce the uncertainty
Make and buy	Buy (collaborative)	Not relevant-AM does not require relationship-specific investments since the technology is inherently flexible, while the specificity is confined to the digital model of the product	Low- the investment in AM is not justified when there is an infrequent use of the technology	Low- AM mainly used for rapid prototyping, there is not a high uncertainty due to the low-quality requirements on production and consequent low need to have control over production
	Make (plastic) and buy (metal)		Medium (plastic) - investment in AM is justified by a frequent use of the technology either for rapid prototyping or for rapid manufacturing Low (metal) - the investment in AM is not justified for metal additive production as this usage is occasional and there is a consequent lack of competence that makes more convenient to outsource	Medium (plastic) - more frequent usage of the technology brings more control over production, that leads to the decision to internalize additive manufacturing Medium (metal) - the requirements are high when printing components in metal for rapid manufacturing. Not being able to internalize production, close long-term relationships with suppliers are set
	Make		High- after a process of acquisition of knowledge and experience with the technology (from RP to RM), companies opt to purchase machines since AM usage increased	High- the more frequent use of AM for rapid manufacturing rather than for rapid prototyping brings the company to have a higher need to control production to satisfy quality requirements

(*continued*)

Table 3.
Impact of AM adoption on upstream SC-TCE constructs applied to the four patterns of AM adoption

Variables		TCE constructs Asset specificity	Frequency	Uncertainty
	Vertical integration		Very high- experience and frequency of usage high enough to internalize the production choosing the integration of the supplier	Very high- the uncertainty on the technology brings the need to have a total control over production, that in turn leads to internalize additive manufacturing by acquiring suppliers
SC design	Centralization	Not relevant-AM does not require relationship-specific investments since the technology is inherently flexible, while the specificity is confined to the digital model of the product	Not relevant- frequency does not have an impact on centralization choice in our cases: Both in cases of rapid prototyping, and in those of rapid tooling or manufacturing, the choice falls on a centralized approach	Uncertainty may induce companies in centralizing the production internally to guarantee a higher control over production. Despite not having cases of distributed manufacturing, outsourcing production towards an external distributed network may imply losing control. Thus, high uncertainty will lead firms to opt for a centralized approach
Impact on supply network	Increase in the number of suppliers New actors in the supply network New roles and relationship	AM does not require relationship-specific investments since the technology is inherently flexible, while the specificity is confined to the digital model of the product	High frequency (from RP to RM) implies a higher number of new actors and vendors involved in the supply base (certificatory body, AM-related service providers, etc.)	Higher uncertainty means higher need to control production and assure quality. It implies having stronger relationships with suppliers that, in some cases, may lead to a lock-in effect in the buyer-supplier relationship

Table 3.

Source(s): Created by author

the frequency was sufficiently high to justify the investment, the companies opted to *make*. This is in line with the literature since transaction costs increase with frequency (Williamson, 2008), leading to the *make* choice being more convenient than *buying*. One example is provided by Company F, which has decided to vertically integrate: it uses more than 50 printers to produce components, justifying the large investment for acquiring not only the technology, but the supplier itself. Hence, the higher the frequency, the higher the tendency to adopt a *make* strategy. Our results agree with those of Friedrich *et al.* (2022), who showed that companies with an established maturity level apply AM to produce new parts and spare parts and tend to choose an in-house strategy. By contrast, firms with a low maturity level use AM for prototyping and for education and research, implying an outsourcing strategy.

Uncertainty also plays a distinctive role in SC design, with the exception of the centralization decision, which in our case studies was not dependent on any of the TCE constructs. First, uncertainty is discriminant in the make or buy decision as it activates the *vertical integration* pattern. In particular, the company that vertically integrated the printing service by acquiring its supplier needed to have strong *control over the production* performance and, consequently, had a significant need to reduce the technology uncertainty. Indeed, this company adopted AM in the aerospace sector for a series production of components that must be certified to be installed in aircraft. Thus, Company F aimed to reduce the bounded rationality to which it is subject and any opportunistic behaviour by the supplier that could reduce quality to obtain a greater margin, a finding that is in line with the literature (Walker and Weber, 1984; Ellram *et al.*, 2008).

Uncertainty is also important when considering the impact on supply network, specifically in the relationships with suppliers. As previously stated, the number of suppliers increases in direct proportional to the frequency. Still, uncertainty determines the degree of the buyer-suppliers relationship. Specifically, when the control over production is high, given the high bounded rationality and lack of internal competencies, the buyer company tends to forge a strict and long-term relationship with the supplier, regardless of the make or buy choice. To assure high quality and the satisfaction of product requirements, and due to the high complexity and concentration of the market, firms want to establish long-term collaborations with equipment producers and service providers. This also affects buyer-suppliers relationships as companies report that changing suppliers is not easy since raw materials offered by other players have poorer quality, causing waste, breakdowns and inefficiencies. In fact, several companies reported being locked into a relationship with suppliers; whoever supplies the machine will also supply raw materials and related services.

6. Contributions

6.1 Theoretical contributions

This research contributes to academic literature in understanding the role of drivers and barriers in AM adoption and the impacts on upstream SCs related to make or buy decisions and changes in the supply network. Based on 10 case studies, this paper is among the few studies presenting results based on multiple explanatory case studies; most of the literature remains theoretical and lacks empirical evidence.

We have adopted TCE, which helps explaining the impact of AM on SC design, especially on the upstream side. We found that AM technology is generally adopted with a centralized SC configuration, using a combinational approach (traditional and additive manufacturing together). This leads to a supply base enlargement, a finding that contrasts with the main results of extant academic literature. Our results show that the centralization decision is not affected by transaction costs. Instead, the make or buy decision and the supply network are highly affected by frequency and uncertainty. Specifically, as the frequency increases, transaction costs increase. Thus, companies tend to internalize the production as it is more convenient and easier to justify the high investments that AM adoption implies. Moreover, due to the lack of internal competencies and experience with the technology, especially at the beginning of the process, there is a high degree of uncertainty due to a high level of bounded rationality. To reduce this uncertainty, firms tend to establish long-term relationships with new suppliers to have more control over production, making their SCs even more complex. Asset specificity, by contrast, seems not to affect SC design as there are not relationship-specific investments borne by the supplier when AM is adopted. The make or buy decision emerged as the most impacted variable by transaction costs, despite the fact that only a few authors have addressed this dynamic (Sasson and Johnson, 2016; Kunovjanek *et al.*, 2022; Friedrich *et al.*, 2022). We identified four patterns of governance structures (make, buy, make and buy, vertical integration) when adopting AM, driven essentially by the TCE constructs of frequency and uncertainty. In particular, the higher the frequency and uncertainty, the more likely firms are to use the technology and require strong control over production, opting to insource production. In this choice, we have also shown how strategic barriers can have an influence, as high investments and the lack of skills and knowledge may drive companies towards outsourcing.

6.2 Managerial contributions

This research sheds light on the key variables to consider for the adoption of AM manufacturing, which is a critical decision for managers. Companies that are willing to adopt AM may understand with this research how different variables impact the adoption process and how adoption implies changes to the SC design. Specifically, the framework is a guideline that, based on the company's level of AM experience and uncertainty, can provide indications to managers in choosing the right combination regarding AM adoption. With this research, we have identified several key factors that guide companies in the make or buy decision, as well as showing the consequent effects in terms of supply base enlargement and changes in the buyer–supplier relationship. Indeed, this paper offers a clear view of the effects of AM adoption. We identified an increase in the number of suppliers and a consequent increase in the supply complexity given the lock-in relationships buyers have with equipment producers and AM service providers. This informs buyers about selecting the right contracting terms to avoid being locked in, thus preserving control over production.

7. Conclusions

Industrial AM is becoming increasingly adopted by companies willing to digitise their production processes. Despite this, companies still do not know very much about how AM can impact their SCs' linkages and processes. In academia, some models have been conceptualized to propose new SC configurations. For instance, Holmström *et al.* (2010) proposed two potential SC designs: a centralized approach in which AM printers are deployed in a central hub, or a distributed manufacturing approach that requires a manufacturing network with local hubs in which printers are deployed close to the end customer. These hubs can also be standalone entities, where only AM is deployed, or hybrid hubs, where AM is complemented with traditional manufacturing (Braziotis *et al.*, 2019). Recently, another research stream has been opened, aiming to study the make or buy decision for industrial AM (Friedrich *et al.*, 2022) and the consequent impacts of this decision on the upstream SC. Our research fits in this research stream, proposing 10 case studies in which we have analysed the drivers and barriers of AM adoption, as well as the effects of this adoption on SC design. We have proposed four adoption patterns for AM, studied the effects on the supply network and on relationships with suppliers, contributed to current understanding and expanded the current knowledge base.

7.1 Limitations and future research directions

This research is constrained to 10 cases. Although the sample is quite heterogeneous, we have collected data mainly from large companies (only three SMEs) operating in just a few industries. Drivers—and especially barriers—can differ according to size and industry, as we have highlighted in the paper. Thus, future research might adopt our framework to study different industries and companies in terms of size to better understand if and how contingency factors matter in the influence of drivers and barriers on AM adoption. In addition, this research is qualitative by nature, so to understand the effects of other factors such as contingencies and to quantify actual benefits, quantitative studies are needed to complement these results. Furthermore, this paper demonstrates that the impact of AM adoption on upstream SCs is relevant yet underexplored, and this research contrasts with conceptual papers in the literature, finding that suppliers increase rather than decrease when AM is adopted. Hence, further studies are needed to understand how companies adapt the supply base when adopting AM. The make or buy decision is key for firms, implying changes in terms of both SC design and SC performance. Hence, further studies should consider this variable when investigating the effects of AM adoption on SC.

References

Ashour Pour, M., Zanoni, S., Bacchetti, A., Zanardini, M. and Perona, M. (2019), "Additive manufacturing impacts on a two-level supply chain", *International Journal of Systems Science: Operations and Logistics*, Vol. 6 No. 1, pp. 1-14.

Afshari, H., Searcy, C. and Jaber, M.Y. (2020), "The role of eco-innovation drivers in promoting additive manufacturing in supply chains", *International Journal of Production Economics*, Vol. 223, 107538.

Arnold, U. (2000), "New dimensions of outsourcing: a combination of transaction cost economics and the core competencies concept", *European Journal of Purchasing and Supply Management*, Vol. 6 No. 1, pp. 23-29.

Attaran, M. (2017), "The rise of 3-D printing: the advantages of additive manufacturing over traditional manufacturing", *Business Horizons*, Vol. 60 No. 5, pp. 677-688.

Beltagui, A., Kunz, N. and Gold, S. (2020), "The role of 3D printing and open design on adoption of socially sustainable supply chain innovation", *International Journal of Production Economics*, Vol. 221 No. 107462, doi: 10.1016/j.ijpe.2019.07.035.

Bogers, M., Hadar, R. and Bilberg, A. (2016), "Additive manufacturing for consumer-centric business models: implications for supply chains in consumer goods manufacturing", *Technological Forecasting and Social Change*, Vol. 102, pp. 225-239.

Braziotis, C., Rogers, H. and Jimo, A. (2019), "3D printing strategic deployment: the supply chain perspective", *Supply Chain Management: An International Journal*.

Chaudhuri, A., Rogers, H., Soberg, P. and Pawar, K.S. (2019), "The role of service providers in 3D printing adoption", *Industrial Management and Data Systems*, Vol. 119 No. 6, pp. 1189-1205, doi: 10.1108/IMDS-08-2018-0339.

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I. and Jussila, A. (2018), "The perceived value of additively manufactured digital spare parts in industry: an empirical investigation", *International Journal of Production Economics*, Vol. 205, pp. 87-97.

Coase, R.H. (1937), "The nature of the firm", *Economica*, Vol. 4 No. 16, pp. 386-405.

Colosimo, B.M., Huang, Q., Dasgupta, T. and Tsung, F. (2018), "Opportunities and challenges of quality engineering for additive manufacturing", *Journal of Quality Technology*, Vol. 50 No. 3, pp. 233-252.

den Boer, J., Lambrechts, W. and Krikke, H. (2020), "Additive manufacturing in military and humanitarian missions: advantages and challenges in the spare parts supply chain", *Journal of Cleaner Production*, Vol. 257 No. 120301, doi: 10.1016/j.jclepro.2020.120301.

Ellram, L.M., Tate, W.L. and Billington, C. (2008), "Offshore outsourcing of professional services: a transaction cost economics perspective", *Journal of Operations Management*, Vol. 26 No. 2, pp. 148-163.

Eyers, D.R. and Potter, A.T. (2015), "E-commerce channels for additive manufacturing: an exploratory study", *Journal of Manufacturing Technology Management*.

Friedrich, A., Lange, A. and Elbert, R. (2022), "Make-or-buy decisions for industrial additive manufacturing", *Journal of Business Logistics*. doi: 10.1111/jbl.12302.

Ghadge, A., Karantoni, G., Chaudhuri, A. and Srinivasan, A. (2018), "Impact of additive manufacturing on aircraft supply chain performance", *Journal of Manufacturing Technology Management*.

Halassi, S., Semeijn, J. and Kiratli, N. (2019), "From consumer to prosumer: a supply chain revolution in 3D printing", *International Journal of Physical Distribution and Logistics Management*.

Hedenstierna, C.P., Disney, S.M., Eyers, D.R., Holmström, J., Syntetos, A.A. and Wang, X. (2019), "Economies of collaboration in build-to-model operations", *Journal of Operations Management*, Vol. 65 No. 8, pp. 753-773.

Holmström, J., Partanen, J., Tuomi, J. and Walter, M. (2010), "Rapid manufacturing in the spare parts supply chain", *Journal of Manufacturing Technology Management*.

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 No. 1, pp. 1-10.

Hopkinson, N., Hague, R. and Dickens, E. (2006), *Rapid Manufacturing: an Industrial Revolution for the Digital Age*, John Wiley & Sons, Hoboken, NJ.

Ivanov, D., Dolgui, A. and Sokolov, B. (2019), "The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics", *International Journal of Production Research*, Vol. 57 No. 3, pp. 829-846.

Khajavi, S.H., Partanen, J. and Holmström, J. (2014), "Additive manufacturing in the spare parts supply chain", *Computers in Industry*, Vol. 65 No. 1, pp. 50-63.

Kunovjanek, M., Knofius, N. and Reiner, G. (2022), "Additive manufacturing and supply chains – a systematic review", *Production Planning and Control*, Vol. 33 No. 13, pp. 1231-1251.

Liu, P., Huang, S.H., Mokasdar, A., Zhou, H. and Hou, L. (2014), "The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis", *Production Planning and Control*, Vol. 25 Nos 13-14, pp. 1169-1181.

Luomaranta, T. and Martinsuo, M. (2020), "Supply chain innovations for additive manufacturing", *International Journal of Physical Distribution and Logistics Management*, Vol. 50 No. 1, pp. 54-79, doi: 10.1108/IJPDLM-10-2018-0337.

Maresch, D. and Gartner, J. (2020), "Make disruptive technological change happen-The case of additive manufacturing", *Technological Forecasting and Social Change*, Vol. 155, 119216.

Martinelli, E.M. and Christopher, M. (2019), "3D printing: enabling customer-centricity in the supply chain", *International Journal of Value Chain Management*, Vol. 10 No. 2, pp. 87-106.

Martinsuo, M. and Luomaranta, T. (2018), "Adopting additive manufacturing in SMEs: exploring the challenges and solutions", *Journal of Manufacturing Technology Management*.

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

Melo, M.T., Nickel, S. and Saldanha-Da-Gama, F. (2009), "Facility location and supply chain management–A review", *European Journal of Operational Research*, Vol. 196 No. 2, pp. 401-412.

Meyer, M.M., Glas, A.H. and Eßig, M. (2021), "Systematic review of sourcing and 3D printing: make-or-buy decisions in industrial buyer–supplier relationships", *Management Review Quarterly*, Vol. 71, pp. 723-752.

Muir, M. and Haddud, A. (2018), "Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain", *Journal of Manufacturing Technology Management*, Vol. 29 No. 2, pp. 372-397.

Nascimento, D.L., Alencastro, V., Quelhas, O.L., Caiado, R.G., Garza-Reyes, J.A., Rocha-Lona, L. and Tortorella, G. (2019), "Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context", *Journal of Manufacturing Technology Management*.

Öberg, C. and Shams, T. (2019), "On the verge of disruption: rethinking position and role–the case of additive manufacturing", *Journal of Business and Industrial Marketing*.

Oettmeier, K. and Hofmann, E. (2016), "Impact of additive manufacturing technology adoption on supply chain management processes and components", *Journal of Manufacturing Technology Management*.

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 No. 1, pp. 97-124.

Pfohl, H.C., Yahsi, B. and Kurnaz, T. (2015), "The impact of Industry 4.0 on the supply chain", *In Innovations and Strategies for Logistics and Supply Chains: Technologies, Business Models and Risk Management*, *Proceedings of the Hamburg International Conference of Logistics (HICL)*, Berlin: Epubli GmbH, Vol. 20, pp. 31-58.

Prahalad, C. and Hamel, G. (1990), "The core competence of the corporation", *Harvard Business Review*.

Ruffo, M., Tuck, C. and Hague, R. (2007), "Make or buy analysis for rapid manufacturing", *Rapid Prototyping Journal*, Vol. 13 No. 1, pp. 23-29.

Ryan, M.J., Eyers, D.R., Potter, A.T., Purvis, L. and Gosling, J. (2017), "3D printing the future: scenarios for supply chains reviewed", *International Journal of Physical Distribution and Logistics Management*.

Sasson, A. and Johnson, J.C. (2016), "The 3D printing order: variability, supercenters and supply chain reconfigurations", *International Journal of Physical Distribution and Logistics Management*.

Savastano, M., Amendola, C., Fabrizio, D. and Massaroni, E. (2016), "3-D printing in the spare parts supply chain: an explorative study in the automotive industry", *Digitally Supported Innovation*, Vol. 18, pp. 153-170.

Shukla, M., Todorov, I. and Kapletia, D. (2018), "Application of additive manufacturing for mass customisation: understanding the interaction of critical barriers", *Production Planning and Control*, Vol. 29 No. 10, pp. 814-825.

Song, G., Sun, L. and Wang, Y. (2018), "A decision-making model to support the design of a strategic supply chain configuration", *Journal of Manufacturing Technology Management*.

Sun, L. and Zhao, L. (2017), "Envisioning the era of 3D printing: a conceptual model for the fashion industry", *Fashion and Textiles*, Vol. 4 No. 1, p. 25.

Thomas-Seale, L.E., Kirkman-Brown, J.C., Attallah, M.M., Espino, D.M. and Shepherd, D.E. (2018), "The barriers to the progression of additive manufacture: perspectives from UK industry", *International Journal of Production Economics*, Vol. 198, pp. 104-118.

Tziantopoulos, K., Tsolakis, N., Vlachos, D. and Tsironis, L. (2019), "Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era", *Production Planning and Control*, Vol. 30 No. 7, pp. 510-521.

Wagner, S.M. and Walton, R.O. (2016), "Additive manufacturing's impact and future in the aviation industry", *Production Planning and Control*, Vol. 27 No. 13, pp. 1124-1130.

Walker, G. and Weber, D. (1984), "A transaction cost approach to make-or-buy decisions", *Administrative Science Quarterly*, Vol. 29 No. 3, pp. 373-391.

Williamson, O.E. (1979), "Transaction-cost economics: the governance of contractual relations", *The Journal of Law and Economics*, Vol. 22 No. 2, pp. 233-261.

Williamson, O.E. (1981), "The economics of organization: the transaction cost approach", *American Journal of Sociology*, Vol. 87 No. 3, pp. 548-577.

Williamson, O.E. (2008), "Outsourcing: transaction cost economics and supply chain management", *Journal of Supply Chain Management*, Vol. 44 No. 2, pp. 5-16.

Yampolskiy, M., King, W.E., Gatlin, J., Belikovetsky, S., Brown, A., Skjellum, A. and Elovici, Y. (2018), "Security of additive manufacturing: attack taxonomy and survey", *Additive Manufacturing*, Vol. 21, pp. 431-457.

Yin, R. (1984), *Case Study Research: Design and Methods*, Sage Publications, London.

(The Appendix follows overleaf)

Annex A

Variables		Code	Quotes	Company
Impact on upstream SC	Make or buy	Make	*Initially we relied on an Italian service provider, as we did not yet have our own 3D printer. When we saw that the mechanical and hydraulic world reacted very well and with great interest to the first 3D printed components, we decided to make the leap and buy our first metal printer*	Company A
		Buy	*We don't have in-house printers for the production of metal parts. This is because the technology today is capital intensive, requiring a large investment*	Company C
		Make and buy	*Unfortunately, we are not able to afford sintering machines or stereolithography equipment, which are quite expensive investments [. . .], so we have our own network of suppliers*	Company E
		Vertical Integration	*There is a tendency to apply additive to new components instead of replacing existing ones. So, the company tends to buy the key suppliers of the technology (machinery and powders) and make them part of the same business'*	Company F
	Centralized vs decentralized	Centralized	*Geographically, there is only one production plant where all the printers are located*	Company G
		Decentralized	-	-
	Supply network	Increase in number of suppliers	*New suppliers are needed for the post-processing stages (e.g. dyeing). [. . .] if you decide to bring the technology in-house, you should then have whoever supplies the material, the machine, the finishing . . . so in this case the number of suppliers increases*	Company J
		Decrease in number of suppliers	-	-
	New suppliers	Equipment and raw materials suppliers	*Unfortunately, we are not able to afford sintering machines or stereolithography equipment, which are quite expensive investments [. . .], so we have our own network of suppliers*	Company E
		AM-related service providers	*New suppliers are needed for the post-processing stages (e.g. dyeing). [. . .] if you decide to bring the technology in-house, you should then have whoever supplies the material, the machine, the finishing . . . so in this case the number of suppliers increases*	Company J

Table A1.
quotations from interviews and codes for data analyses

(*continued*)

Variables		Code	Quotes	Company
	Relationship with suppliers	Long-term collaboration	*We have created a sort of partnership with the suppliers [. . .] they provide us with a series of information, that the powder is certified with practical tests, the fact that the machine has used certain parameters and that if tomorrow I want to do the same piece, I have to do it the same way. They gave us a lot of information, it is such a new topic that the more we share this information, the more we are able to achieve the common goal*	Company H
		Lock-in effect	*We started at the beginning using the raw material recommended by the manufacturer of the machine [. . .] We tried then to purchase it on Amazon, which was much cheaper but with very different results. So, I have to say a very first impact on the SC was "Ok, let's go back to the supplier that has an agreement with the machine, which although more expensive, however, guarantees us not to have much waste"*	Company A

Source(s): Created by author

Table A1.

Corresponding author
Alessio Ronchini can be contacted at: alessio.ronchini@polimi.it