Management Review Quarterly
https://doi.org/10.1007/s11301-023-00376-y

Mapping the enhancing effects of additive manufacturing technology adoption on supply chain agility

Bardia Naghshineh[1]

Received: 20 March 2023 / Accepted: 22 September 2023

Abstract
Given the proclaimed importance of additive manufacturing (AM) for generating agile supply chains, this study draws on the dynamic capabilities view to investigate the enhancing effects of adopting this digital technology on supply chain agility (SCA). To this end, relevant pieces of evidence are systematically gathered from a sample of 101 high-quality peer-reviewed journal articles at the intersection of AM technology and supply chain management.This information is then analyzed and synthesized to holistically map the features of AM technology adoption that enhance SCA. As a result, 42 features of AM technology adoption are identified that enhance thirteen different dimensions of SCA. The derived map explicitly indicates which features of AM technology adoption enhance which dimensions of SCA. Hence, this map can be used as a strategic tool by managers and policymakers who wish to explore different ways of enhancing SCA via AM technology adoption. This would, in turn, enable the adopting firm to deal with erratic business environments and dynamic supply chains in an agile manner, and therefore gain a competitive advantage. Moreover, based on the identified "white space" in the derived map, multiple questions are put forward that form a research agenda for future research.

Keywords Additive manufacturing · 3D printing · Digital technology adoption · Supply chain agility · Systematic literature review · Research agenda

Communicated by Stefan Lier.

✉ Bardia Naghshineh
b.naghshineh@fct.unl.pt

[1] UNIDEMI, Department of Mechanical and Industrial Engineering, NOVA School of Science and Technology, NOVA University Lisbon, Caparica 2829-516, Portugal

Published online: 23 May 2024

1 Introduction

Additive manufacturing (AM) technology, otherwise known as three-dimensional (3D) printing, has received remarkable attention from many industrial firms in recent years. This is mainly due to the different adoption features of this digital technology that empower the agile manufacture of customized and innovative products to respond to erratic customer demands (Candi and Beltagui 2019), especially when time is a crucial factor. This digital technology uses 3D model data to additively (i.e., layer by layer) join materials on a build platform and create a final part/product (ISO/ASTM 52,900 2021). AM technology is said to bring about "more agility and responsiveness" in many firms that operate in uncertain market environments and dynamic supply chains (Waller and Fawcett 2014). Oftentimes, such firms are forced to cope with supply chain disruptions caused by unforeseen events, and AM technology can grant them the speed and agility they need for business continuity. This assertion is endorsed by Kunovjanek and Wankmüller (2020), who analyzed the global AM response to the COVID-19 pandemic, stating that the speed and agility of the firms that used AM technology "to supply novel products was astonishing."

Durach et al. (2017) propose that "supply chain agility, as a fundamental supply chain capability, is likely to increase as a result of AM introduction." However, their study does not present detailed results regarding the enhancing effects of AM technology adoption on supply chain agility (SCA). Moreover, neither Verboeket and Krikke (2019) nor Kunovjanek et al. (2020) in their literature reviews explicitly explain the effects of AM technology on SCA. They only note that AM technology adoption leads to increased responsiveness as a supply chain performance outcome. In this sense, SCA is regarded as a fundamental supply chain capability that increases the responsiveness of the supply chain and subsequently improves its performance. Nevertheless, these reviews do not clearly explain the role of AM technology adoption in enhancing SCA as a precursor to increased supply chain responsiveness and performance. More recently, Khan and Manzoor (2021) reported that AM technology played an important role in enabling many supply chains to quickly respond to the COVID-19 pandemic, while Meng et al. (2022) briefly noted that AM adoption contributes to SCA. Similarly, none of these reviews comprehensively looks into the ways AM technology adoption can enhance SCA. While there are dispersed pieces of evidence in some studies that claim AM adoption improves SCA, to date, no study has taken a holistic approach to map the enhancing effects of adopting this digital technology on SCA. This knowledge shortfall is also highlighted in the systematic search and review performed by Naghshineh and Carvalho (2022a).

From a strategic point of view, overcoming this gap is important because it assists managers and policymakers in appraising the dimensions of SCA that tend to be affected by AM technology adoption, as well as the ensuing implications for their firms' supply chain management processes. Therefore, this study aims to systematically gather, analyze, and synthesize the dispersed pieces of evidence in the literature to holistically map the enhancing effects of AM technology adoption on SCA. To do this, this study identifies different features of AM technology adoption that tend to enhance certain dimensions of SCA. Generally, this has proven to be a reasonable approach in different studies at the intersection of AM technology adoption and supply chain management, e.g., Kunovjanek et al. (2020), Patil et al. (2022), Naghshineh et al. (2023), among others. This holds true since different features of AM technology adoption define its positive effects on fundamental supply chain capabilities such as agility and resilience (Durach et al. 2017; Naghshineh and Carvalho 2022a). Hence, by developing a comprehensive outlook on which AM adoption features enhance which dimensions of SCA, it would be possible to fill this gap in the body of literature.

In the conceptualization process of this study, the dynamic capabilities view was employed as the theoretical lens, which is an extension of the resource-based view of the firm (Teece et al. 1997). According to the resource-based view, the main focus of the firm is on accumulating different resources, including technology, to gain a competitive advantage (Wernerfelt 1984), failing to consciously consider the dynamic market environment in which the firm operates. However, based on the dynamic capabilities view, a firm may use technology as a resource to purposefully develop the necessary capabilities (e.g., agility) to adapt to the dynamic market environment, and therefore gain a competitive advantage (Teece et al. 1997). Moreover, in the dynamic capabilities view, the notion of agility as a dynamic supply chain capability becomes quite relevant (Aslam et al. 2018), which indicates a firm's capability to quickly respond to changes in the supply chain and market environment (Dubey et al. 2018). This is especially true in the context of digital supply chain transformation via AM adoption, as various features of this digital technology tend to enable the adopting firm to enhance its agility, and thus quickly respond to changing market needs (Shashi et al. 2020; Belhadi et al. 2022). In other words, viewing the subject matter through this theoretical lens helps explain the importance of AM technology adoption for developing agility as a dynamic supply chain capability that enables the adopting firm to deal with "rapidly changing environments" (Teece et al. 1997). Therefore, in line with the dynamic capabilities view of the firm toward technology adoption, the main objective of this study is to comprehensively identify the features of AM technology adoption that enhance different dimensions of SCA, and in doing so, also explore the understudied areas ("white space") that would benefit from further research (Frankel et al. 2005).

The remainder of this paper is organized as follows. In Sect. 2, the methodological approach and findings are explained. In Sect. 3, the implications of this research are presented. Finally, in Sect. 4, concluding remarks are noted.

2 Methodological approach

In this study, a systematic review was performed to extensively look for relevant information in the extant literature following a transparent and replicable process (Tranfield et al. 2003). More specifically, given that the existing studies do not comprehensively outline the enhancing effects of AM technology adoption on SCA, a systemtaic review was conducted to rigorously gather, analyze, and synthesize relevant pieces of evidence to address this gap, and subsequently come up with a research agenda. This systematic review was performed in line with the established procedures set forth by Tranfield et al. (2003). Figure 1 presents an overview of the methodological approach taken in this study.

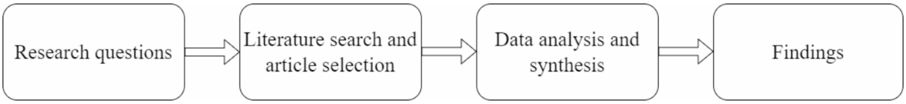

Fig. 1 Overview of the methodological approach

2.1 Research questions

As elaborated in the introduction section, the objective of this study is to comprehensively map the enhancing effects of AM technology adoption on SCA by identifying the AM adoption features that tend to enhance certain dimensions of SCA, and subsequently highlight the understudied areas ("white space") that would help devise a detailed research agenda. Therefore, given this research objective, the following research questions (RQs) will be answered:

RQ1 What features of AM technology adoption tend to enhance SCA?

RQ2 What dimensions of SCA are enhanced by AM technology adoption?

2.2 Literature search and article selection

In the first step of this procedure, a comprehensive search string was formulated and applied to the Scopus and Web of Science databases (see Table 1). These databases were chosen because they include a wide range of peer-reviewed articles (Mongeon and Paul-Hus 2016). The terms "leagile" and "leagility" were also included in the search string since they are based on the notions of agility and leanness; therefore, articles concerning supply chain leagility normally discuss SCA as an antecedent (Humdan et al. 2020). The search was performed in December 2022, with no time span restrictions for maximum exposure. After discarding duplicate articles, the titles, abstracts, and keywords of the remaining articles were screened to ensure that they were relevant. Articles that contained information regarding the effects of AM technology adoption on different dimensions of SCA were considered relevant. In cases where it was not possible to ensure the relevance of the articles by screening their titles, abstracts, and keywords, the articles were screened in their entirety instead. Subsequently, irrelevant articles were discarded. Moreover, to ensure data quality, only peer-reviewed articles were selected (Light and Pillemer 1984), which were written in English and were mainly published in journals with an AJG (aka ABS) ranking by the Chartered Association of Business Schools (2021). In the last step, the search results were complemented by a backward search. This was done by examining the references of the resultant articles to identify additional sources that contained relevant information about the subject matter while abiding by the mentioned inclusion criteria (Thomé et al. 2016). These steps led to deriving the necessary sample for the review (Table S1 - online supplementary material).

Table 1 presents the details about the search string as well as the article selection procedure. Table 2 presents the journal details and the number of selected articles per journal. Figure 2 depicts the year-wise distribution of the articles.

2.3 Data analysis and synthesis

2.3.1 Research dimensions

To ensure that all the selected articles were assessed against the same underlying criteria in the review process (Tranfield et al. 2003), this study made use of established research dimensions (aka coding criteria) available in the literature. To code the gathered evidence in the review sample concerning AM features that enhance SCA, the comprehensive list of AM adoption features proposed by Naghshineh and Carvalho (2022a) was used. In some cases where this list did not contain an appropriate AM adoption feature that would properly summarize the text segment under study, new codes were generated. For instance, the text segment "The system downtime can also be reduced by using a temporary fix for broken spare parts" (Boer et al. 2020) was coded as "Temporary solutions". It is worth noting that some text segments were coded more than once because they were indicative of different AM adoption features. The complete list of codes and their definitions is provided in Table 3.

Since the extant literature falls short of an exclusive definition for SCA that would comprehensively characterize this concept and specify its different dimensions, this study adapted the most commonly used measures of SCA instead. To do this, the proposed SCA measures in studies by Swafford et al. (2006, 2008), Whitten et al. (2012), Blome et al. (2013), Yang (2014), and Gligor et al. (2015) were meticulously analyzed and selected to derive a comprehensive list of SCA dimensions (Table 4). According to Gligor et al. (2022), these studies include the most commonly applied SCA measures in the operations and supply chain management literature today. To validate its comprehensiveness, the derived list was then benchmarked against the

Table 1 Literature search and article selection

Search string				
"additive manufacturing" OR "3D printing" OR "layer manufacturing" OR "direct digital manufacturing" OR "freeform fabrication" OR "digital fabrication" OR "rapid manufacturing" OR "rapid prototyping" OR "rapid tooling"	AND	"supply chain" OR "supply network" OR "value chain" OR "logistics"	AND	"agility" OR "agile" OR "leagility" OR "leagile"
Databases	**No. of articles**			
Scopus	335			
Web of Science	162			
Total	497			
Total (after removing the duplicates)	383			
Total (after applying the inclusion criteria*)	89			
Backward search	12			
Total articles selected (i.e., review sample)	101			

Note: *inclusion criteria = relevant articles + written in English + with AJG ranking

Table 2 Number of papers per journal

Journal name	Journal AJG/ABS ranking	No. of papers
International Journal of Production Economics	3	20
Journal of Manufacturing Technology Management	1	14
Production Planning and Control	3	8
International Journal of Production Research	3	6
International Journal of Physical Distribution and Logistics Management	2	6
International Journal of Operations and Production Management	4	6
International Journal of Advanced Manufacturing Technology		6
Technological Forecasting and Social Change	3	5
Journal of Cleaner Production	2	5
Supply Chain Management: An International Journal	3	4
Computers in Industry	3	4
Journal of Business Logistics	3	3
Research Technology Management	2	2
Business Horizons	2	2
Technovation	3	1
Socio-Economic Planning Sciences	2	1
Operations Management Research	1	1
Journal of Public Procurement	1	1
Journal of Engineering and Technology Management	2	1
Journal of Business Economics	2	1
International Journal of Services and Operations Management	1	1
International Journal of Agile Systems and Management	1	1
Industrial Management and Data Systems	2	1
Energy Policy	2	1
Total		101

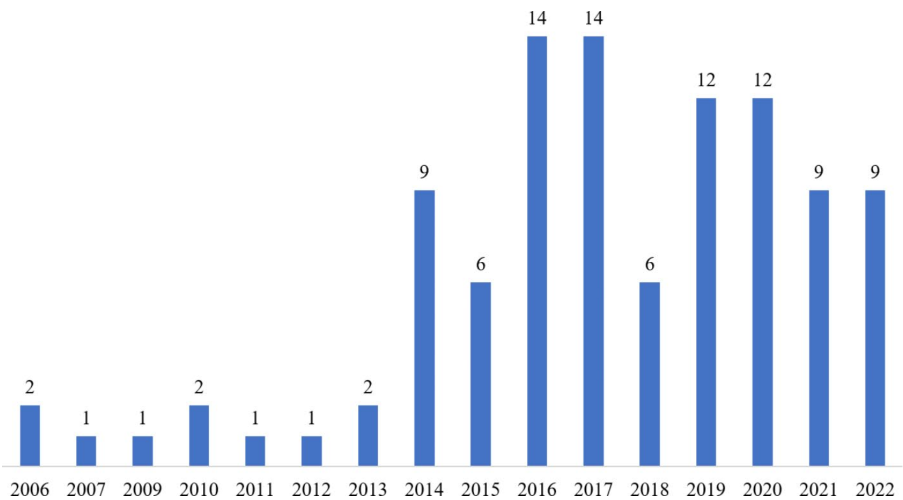

Fig. 2 Distribution of the articles by year

Table 3 Codes for AM adoption features and their definitions adapted from Naghshineh and Carvalho (2022a)

Codes for AM adoption features	Definitions
Automated manufacturing	Using automated (vs. manual) production processes.
Capacity pooling	Making use of the available capacity in different facilities.
Close collaboration	Cooperating closely with other supply chain members toward the same goal.
Co-creation/co-design	The possibility to involve customers in the design and production phases.
Customer-centric production	User-oriented manufacturing.
Design freedom	High levels of design flexibility.
Digital file distribution	The capability to transfer digital files throughout the supply chain.
Digital inventory	The capability to keep inventory in the form of digital files instead of finished goods inventory.
Direct digital manufacturing*	The direct manufacturing of products using raw materials and design data retrieved from digital files.
Distributed manufacturing	The capability to manufacture close to the point of consumption.
Economies of one*	The possibility to manufacture one-off products with economic feasibility.
Economies of scope*	The possibility to produce distinct products (normally in low quantities) with economic feasibility.
Economies of technology	The possibility to minimize the required resources/input (e.g., labor) for production via technology.
Engineer/make-to-order production	The possibility to manufacture products based on the specifications defined by customers.
Fast setup*	The capability to quickly set up the production equipment/line.
Fewer raw materials	The need for fewer types of raw materials.
Hybrid manufacturing model	The use of two (or more) different manufacturing methods (e.g., 3D printing and machining).
Import/export substitution	The possibility to substitute an imported/exported product by manufacturing it locally/remotely.
Just-in-time production	Manufacturing products exactly when and in the amount they are needed.
Manufacturing flexibility*	High levels of versatility and ease in production operations.
Market entry	The possibility to enter a new market rather easily.
Mass customization	The possibility to manufacture customized products in high numbers.
Mass production*	The possibility to manufacture in high numbers/volumes.
Medium production runs	The possibility to bridge the time span between the product design phase and the mass production phase by producing medium-sized batches.
Mobile manufacturing	The capability to manufacture while in transit.
New business models	The inception of new business ideas and ways of doing business, mainly through innovative means of production and technologies such as AM.
On-demand manufacturing	The capability to manufacture when demand materializes.
Outsourcing production	The possibility to outsource production to external suppliers (e.g., AM service providers).
Part consolidation*	The possibility to integrate multiple parts/components into one functional part/product.
Process integration	The possibility to integrate multiple production processes into one process.
Product life cycle extension	The ability to extend the life of a product through repair, refurbishment, or remanufacture.

Table 3 (continued)

Codes for AM adoption features	Definitions
Production postponement	The capability to postpone the production phase of a product to later stages.
Rapid manufacturing	The capability to quickly manufacture a part.
Rapid prototyping	The capability to quickly fabricate a model (mock-up/prototype) of a part, normally by using computer-aided design (CAD) software.
Rapid tooling	The capability to quickly create production tools such as jigs, fixtures, and molds on-site.
Remote work	The possibility to remotely control the machines and manufacturing equipment.
Supply chain innovation	The capability to devise and implement innovative ideas/solutions throughout the supply chain.
Simplified operations*	The possibility to reduce the complexity of production processes and supply chain operations.
Small production runs	The possibility to schedule small production runs, normally aimed at manufacturing small batches of products.
Sustainable production	The capability to reduce waste as well as the required input materials/resources in the production process.
Temporary solutions*	The ability to come up with temporary fixes (e.g., provisional spare parts) to avoid system downtime until a definitive solution is available.
Tool-less manufacturing	The capability to manufacture without elaborate production tools in place.

Note: *New codes generated in this study

Table 4 SCA dimensions adapted from the extant literature

SCA dimensions	Definition	Sources
Collaborative relationships	Ability to develop collaborative relationships with suppliers and customers	Whitten et al. (2012)
Customer service	Speed in improving customer service level	Swafford et al. (2006, 2008)
Delivery capability	Speed in adjusting delivery capacity	Swafford et al. (2006, 2008)
Delivery reliability	Speed in reducing delivery lead time	Swafford et al. (2006, 2008)
Development cycle time	Speed in reducing product development cycle time	Swafford et al. (2006, 2008)
Information sharing	Ability to promote information exchange with suppliers and customers	Whitten et al. (2012)
Manufacturing lead time	Speed in reducing manufacturing lead time	Swafford et al. (2006, 2008)
Market responsiveness	Speed in improving responsiveness to changing market needs	Swafford et al. (2006, 2008)
New product introductions	Speed in increasing the frequency of new product introductions	Swafford et al. (2006, 2008)
Product customization	Speed in increasing levels of product customization	Swafford et al. (2006, 2008)
Production volumes	Speed in adjusting production volumes	Yang (2014)
Range of products	Speed in producing a range of products	Yang (2014)
Supply-side changes	Speed in reacting to supply-side changes*	Blome et al. (2013)

Note: *Examples of supply-side changes are sudden supplier outages, delivery failures, or market shortages (Blome et al. 2013) twenty-five definitions of SCA compiled in the literature review by Humdan et al. (2020).

2.3.2 Analysis and synthesis method

The aforementioned research dimensions were used to analyze and synthesize the evidence in the review sample. More specifically, the codes in Table 3 were used to summarize the text segments that contained relevant information regarding features of AM technology adoption, which were subsequently associated with the SCA dimensions in Table 4 based on their contextual relevance. For instance, the text segment "No tooling is needed significantly reducing production ramp-up time and expense" (Holmström et al. 2010) was coded as "Tool-less manufacturing". In this instance, as there is no need to have various production tools in place when using AM technology, the adopting firm can quickly ramp up (adjust) its production volumes to satisfy the erratic customer demand, thereby enhancing SCA. Hence, "Tool-less manufacturing" was associated with "Production volumes" given its contextual relevance inferred from the aforementioned text segment. More illustrative examples can be found in Table S2 (online supplementary material), where these codes and associations are displayed.

Following this structured process helped to reduce the gathered evidence into manageable units for data display, analysis, and synthesis, thus improving the validity of the findings (Miles and HuBerman 1994). Moreover, this process was reviewed multiple times to ensure the soundness and rigor of the inferred associations (Tranfield et al. 2003). Completing this structured process led to mapping the enhancing effects of different AM adoption features on the identified SCA dimensions. These findings are discussed in the following subsection.

2.4 Findings

Figure 3 represents the derived map that comprehensively illustrates the enhancing effects of the identified AM adoption features on different SCA dimensions. The indicated numbers in the map represent the pieces of evidence that were found in the review sample concerning the AM adoption features that tend to enhance the SCA dimensions under study. More specifically, the numbers at the intersection of AM adoption features and SCA dimensions are derived based on the number of times each identified AM adoption feature was associated with an SCA dimension. Hence, these numbers roughly represent the proportional amount of existing evidence in the literature regarding the subject matter. This type of descriptive analysis is also employed in reviews by Ryan et al. (2017) and Kunovjanek et al. (2020), among others, to highlight the relative importance of the findings and to identify the understudied areas ("white space") that would benefit from further research.

As shown in Fig. 3, 42 identified features of AM technology adoption enhance 13 different dimensions of SCA. The map indicates that "Mass customization", "Distributed manufacturing", and "Design freedom" are the top three features of AM adoption that alone account for 22% of the identified enhancing effects on almost all the SCA dimensions. The next set of features is "Small production runs", "Tool-

SCA dimensions / AM adoption features	Market responsiveness	Product customization	Customer service	Delivery capability	Production volumes	Delivery reliability	Manufacturing lead time	Collaborative relationship	Range of products	Development cycle time	New product introduction	Information sharing	Supply-side changes	Total	Percentage
Mass customization	12	44	13			1			5		1			76	*7.8%*
Distributed manufacturing	12	2	10	21	2	22		1					1	71	*7.3%*
Design freedom	10	19	1	3	3	4	3	1	6	8	8		1	67	*6.9%*
Small production runs	6	8	4	1	28	1	2		4	1				55	*5.7%*
Tool-less manufacturing	6	7		2	7		16		6	1	2			47	*4.8%*
On-demand manufacturing	13		6	12	1	9	4						1	46	*4.7%*
Rapid prototyping	4	4	1	2	2	2	3	1	1	18	7			45	*4.6%*
Customer-centric production	4	9	16	2		3		8						42	*4.3%*
Digital file distribution	3		3	5	1	3		2				22		39	*4.0%*
Co-creation/co-design	5	7	8					17			1			38	*3.9%*
Direct digital manufacturing	5	2	4	7	3	4	3	2	1	1		1	1	34	*3.5%*
Hybrid manufacturing model	7	1	3		7	2	1		3		1		1	26	*2.7%*
Manufacturing flexibility	2	7		1	3	1	5		4	1			1	25	*2.6%*
Simplified operations	2			10	1	8	3		1					25	*2.6%*
Close collaboration	1		2					17				2	1	23	*2.4%*
Economies of scope	1	6	1		10				3		2			23	*2.4%*
Digital inventory	1		5	7		1		1	1			6		22	*2.3%*
Outsourcing production	2		5	1	3	1					1	1	7	21	*2.2%*
Engineer/make-to-order production	3	4	5	2	1	3		1						19	*2.0%*
SC innovation	6	1	2					1	2	1	6			19	*2.0%*
Economies of one	3	4	1	1	6	1			1	1				18	*1.9%*
Market entry	18													18	*1.9%*
New business models	6	2	6	1		1					2			18	*1.9%*
Capacity pooling	2			1	7	2							3	15	*1.5%*
Rapid manufacturing	3	2	3			4	3							15	*1.5%*
Part consolidation	1			2		3	5				1		1	13	*1.3%*
Product life cycle extension			11					1					1	13	*1.3%*
Fast setup							12							12	*1.2%*
Fewer raw materials	2			5		1			2				1	11	*1.1%*
Mobile manufacturing	2		1	3	1	4								11	*1.1%*
Production postponement	4	2	1			1							1	9	*0.9%*
Medium production runs	1				4				1	1	1			8	*0.8%*
Automated manufacturing		1	1			3	1		1					7	*0.7%*
Import/export substitution	2			2		1							1	6	*0.6%*
Just-in-time production	1			2		2			1					6	*0.6%*
Process integration				1	1		4							6	*0.6%*
Rapid tooling	1		1			1	2		1					6	*0.6%*
Temporary solutions							4						2	6	*0.6%*
Economies of technology					2	1								3	*0.3%*
Remote work	1			2										3	*0.3%*
Sustainable production				2										2	*0.2%*
Mass production							1							1	*0.1%*
Total	152	132	114	98	93	90	72	53	44	33	33	32	24	**970**	*100%*
Percentage	*15.7%*	*13.6%*	*11.8%*	*10.1%*	*9.6%*	*9.3%*	*7.4%*	*5.5%*	*4.5%*	*3.4%*	*3.4%*	*3.3%*	*2.5%*	*100%*	

Fig. 3 Map of the enhancing effects of AM adoption features on SCA dimensions

less manufacturing", "On-demand manufacturing", and "Rapid prototyping", which together account for almost 20% of the enhancing effects of AM adoption on different SCA dimensions. In the same vein, the third set of identified features is "Customer-centric production", "Digital file distribution", "Co-creation/co-design", "Direct digital manufacturing", "Hybrid manufacturing model", "Manufacturing flexibility", and "Simplified operations" that account for almost 24% of the enhancing effects. In summary, these 14 features account for almost 66% (roughly two-thirds) of the total enhancing effects of AM adoption on different SCA dimensions, while the remaining 28 features only account for 34% (roughly one-third) of the enhancing effects.

Based on these observations, the following proposition is put forward:

Proposition 1: While many features of AM technology adoption tend to enhance SCA, a major share of this enhancing effect is caused by AM-enabled *mass customization*, *distributed manufacturing*, *design freedom*, *small production runs*, *tool-less manufacturing*, *on-demand manufacturing*, *rapid prototyping*, *customer-centric production*, *digital file distribution*, *co-creation/co-design*, *direct digital manufacturing*, *hybrid manufacturing model*, *manufacturing flexibility*, and *simplified operations*.

Regarding SCA, "Market responsiveness", "Product customization", and "Customer service" are the top three SCA dimensions that alone receive more than 40% of the identified enhancing effects of AM adoption. The next three SCA dimensions are "Delivery capability", "Delivery reliability", and "Production volumes" which receive almost 30% of the enhancing effects. While these six SCA dimensions together receive roughly 70% (more than two-thirds) of the enhancing effects, the other seven SCA dimensions only receive the remaining 30% (less than one-third) of the enhancing effects.

Proposition 2: While a major share of the enhancing effects of AM technology adoption on SCA is due to potential improvements in *market responsiveness*, *product customization*, *customer service*, *delivery capability*, *delivery reliability*, and *production volumes*, the remainder is due to potential improvements in the *manufacturing lead time*, *collaborative relationships*, *range of products*, *development cycle time*, *new product introductions*, *information sharing*, and *supply-side changes*.

3 Research implications

3.1 Theoretical implications

The contributions of this study are manyfold. Given the scarcity of comprehensive studies at the intersection of Industry 4.0 and SCA (Seyedghorban et al. 2020), particularly studies investigating the effects of AM technology adoption on SCA (Naghshineh and Carvalho 2022a), this study puts forward a holistic map that helps overcome this knowledge shortfall. There have been some studies in the extant literature that examine the effects of AM technology adoption on supply chains. However, to date, no study has comprehensively investigated the ways in which adopting this digital technology enhances SCA. To this end, this study extensively identified the features of AM technology adoption that tend to enhance SCA. Furthermore, this study explicitly identified which dimensions of SCA are enhanced by which features of AM technology adoption. The derived map would allow academics and practitioners to navigate these variables and extrapolate the existing relationships between them. In addition, the identified "white space" in the map presents opportunities for investigating the understudied areas concerning the subject matter.

In their study, Durach et al. (2017) proposed that **"**It is likely that AM will change supply chains in such a way that we see increased supply chain agility in the next ten years." They mainly attributed this increase in SCA to AM-enabled distributed manufacturing, as well as the ability to adjust production capacity based on demand, allowing the adopting firm to be more responsive to changing market needs. For the most part, their projections are in accord with the findings of this study, since “Distributed manufacturing” and “On-demand manufacturing” are among the most influential AM adoption features that enhance SCA (see Fig. 3). To complement their findings, however, this study explicitly identifies the SCA dimensions that are enhanced by these AM adoption features. “Delivery capability” and “Delivery reliability” are largely enhanced by these AM adoption features, allowing the adopting firm to quickly adjust its delivery capacity based on the existing demand and reduce delivery lead time using a distributed manufacturing setting. Subsequently, “Market responsiveness” and “Customer service” are notably improved as well. This extrapolated relationship corroborates the findings of Akmal et al. (2022), who state that a switchover to AM technology for the on-demand manufacture of problematic parts enhances the delivery performance of the adopting firm, which, in turn, will result in improved customer service and market responsiveness. This is an example of how the derived map allows the extrapolation and understanding of such relationships between different AM adoption features and SCA dimensions.

In their literature reviews, both Verboeket and Krikke (2019) and Kunovjanek et al. (2020) note that AM technology increases supply chain responsiveness, but they do not explicitly mention the effects of AM technology adoption on SCA. In these reviews, responsiveness is regarded as a supply chain performance outcome, which is mainly induced by SCA as a dynamic supply chain capability (Blome et al. 2013; Aslam et al. 2018). Therefore, by employing the dynamic capabilities view as the theoretical lens and thoroughly identifying the AM adoption features that enhance different dimensions of SCA, this study bridges the gap in understanding why AM technology adoption leads to increased supply chain responsiveness and performance.

Given that there are still unexplored areas concerning the enhancing effects of different AM adoption features on SCA dimensions, this study draws on the identified “white space” in the derived map (Fig. 3) to propose several thought-provoking questions (see Table 5) that present avenues for future research. This research agenda proposes rather nuanced questions, in the sense that they are formulated based on the identified AM adoption features and their potential enhancing effects on relevant SCA dimensions. By putting forward these questions, this study seeks to stimulate further research aimed at building and testing theory at the intersection of AM technology adoption and SCA, hence generating new knowledge to fill the identified “white space”. It is worth noting that more questions may be formulated by drawing on the “white space” in the derived map, and that this study merely proposes the questions it speculates would benefit from further research, thereby contributing to theory and practice.

3.2 Managerial implications

Using the derived map (Fig. 3), some of the important enhancing effects of AM technology adoption on SCA are delineated in this subsection. For brevity and legibility, this subsection is not populated with a multitude of references. Nonetheless, inter-

Table 5 Research agenda

Collaborative relationships
Just-in-time production
How/To what extent would the use of a Just-in-time production model via AM affect the firm's ability to develop collaborative relationships with suppliers and customers?
Customer service
Temporary solutions
How/To what extent would temporary solutions/fixes via AM enable the firm to maintain customer service levels?
Delivery capability
Hybrid manufacturing model
To what extent would employing a hybrid manufacturing model via AM enable the firm to quickly adjust its delivery capacity?
Delivery reliability
Remote work
To what extent would operating AM machines remotely improve the firm's on-time delivery performance?
Development cycle time
Part consolidation
To what extent would part consolidation via AM reduce the development cycle time of complex products?
Information sharing
Just-in-time production
How/To what extent would the use of a Just-in-time production model via AM affect the ability of the firm to maintain a timely information flow with suppliers and customers?
Remote work
How/To what extent would operating AM machines remotely affect the ability of the firm to maintain a timely information flow throughout the supply chain?
Manufacturing lead time
Capacity pooling
How fast/To what extent would the firm be able to expedite its manufacturing lead times by pooling AM capacity?
Market responsiveness
Remote work
In what ways/To what extent would operating AM machines remotely improve the firm's responsiveness to changing market needs?
New product introductions
Customer-centric production
How/To what extent would customer-centric production via AM enable the firm to increase the frequency of new product introductions?
Product customization
Digital inventory
How/To what extent would the use of digital inventory in an AM setting enable the firm to quickly customize products?
Production volumes
Automated manufacturing
To what extent would the current level of automation in AM affect the firm's ability to quickly adjust its production capacity/volumes?
Fast setup
To what extent would AM's fast setup enhance the ability of the firm to quickly adjust its production capacity/volumes?

Table 5 (continued)

Production postponement
To what extent would production postponement via AM enable the firm to adjust its production capacity/volumes to cope with sudden changes in demand?
Range of products
Mass production
How/To what extent would mass production via AM affect the firm's ability to quickly produce a range of different products?
Rapid tooling
To what extent would rapid tooling via AM enable the firm to quickly produce a range of different products?
Supply-side changes
Digital inventory
To what extent would the use of digital inventory in an AM setting enable the firm to quickly react to supply-side changes (e.g., sudden supplier outages, delivery failures, or market shortages of certain spare parts)?
Just-in-time production
How/To what extent would utilizing a Just-in-time production model via AM affect the firm's ability to quickly react to supply-side changes (e.g., sudden supplier outages, delivery failures, or market shortages of raw materials)?
Mobile manufacturing
To what extent would mobile AM enable the firm to quickly react to supply-side changes (e.g., market shortage of certain products)?

ested readers can cross-check the identified implications against the supporting evidence and sources in Table S2 (online supplementary material).

The findings suggest that some AM adoption features tend to be more pronounced in enhancing certain dimensions of SCA. For instance, distributed manufacturing via AM would enhance the speed of the firm in adjusting its delivery capacity, as well as reducing its delivery lead times, mainly due to the possibility of manufacturing on demand in close proximity to the target market, thus reducing the need for many logistics activities such as warehousing and transportation (Durach et al. 2017; Zanoni et al. 2019). This would, in turn, enhance the capability of the firm to quickly respond to changing market needs and improve the level of customer service. Design freedom is another pronounced AM feature that enhances almost all the SCA dimensions under study. This is particularly noticeable in the case of product customization since AM allows the adopting firm to swiftly come up with new customized products to satisfy erratic customer demands, therefore increasing market responsiveness (Candi and Beltagui 2019; Belhadi et al. 2022). This feature reduces the development cycle time of new products. In fact, design freedom and rapid prototyping are the only two AM adoption features identified in the map that considerably reduce the development cycle time.

Another noteworthy feature is small production runs, which provides leeway in adjusting production volumes. This ability is augmented by the tool-less nature of AM technology, which allows the adopting firm to benefit from economies of scope as well as economies of one, especially when deploying a hybrid manufacturing model (Khajavi et al. 2015; Weller et al. 2015). In more specific terms, since AM does not require various tools or equipment to start production, it empowers the firm to manufacture an unlimited range of customized products in small quantities (or even one-off products) with economic viability, thus overcoming the constraints imposed by economies of scale. This can particularly become synergistic in a hybrid manufacturing setting, where slow-moving products with stochastic demand are assigned to AM, while fast-moving products with rather deterministic demand continue being manufactured via conventional methods (Khajavi et al. 2015; Verboeket and Krikke 2019). The required AM capacity in this hybrid approach can even be provided by pooling the available AM capacity in the market. This, in turn, will enhance the agility of the firm in adjusting its production volumes. Likewise, in the event of supplier outages, delivery failures, or sudden market shortages, production can be outsourced to AM service providers (Durach et al. 2017; Verboeket and Krikke 2019), allowing the firm to quickly react to such supply-side changes.

Along the same lines, tool-less manufacturing prompts a fast production setup, reducing the manufacturing lead time in AM settings. Integrating multiple production processes into one process is another AM feature that contributes to reducing the manufacturing lead time. This is further facilitated by the possibility of consolidating many parts into one enhanced functional part through AM (Knofius et al. 2019; Zanoni et al. 2019). Rapid tooling via AM technology may as well facilitate the production process by providing the opportunity to create necessary production tools (e.g., jigs, fixtures, and molds) on-site, hence contributing to reducing the manufacturing lead time. In the same vein, AM enables the quick provision of temporary solutions/fixes (Boer et al. 2020; Friedrich et al. 2022), allowing the firm to avoid costly system downtimes that prolong the manufacturing lead time. These features together turn AM into a flexible manufacturing method that grants the adopting firm the agility it needs to produce a wide range of customized products with short lead times.

Furthermore, simplified operations together with fewer raw materials and digital inventory in an AM setting facilitate logistics activities, allowing the firm to quickly adjust its delivery capacity and issue reliable delivery dates to customers. The AM-enabled possibility of postponing production based on an engineer/make-to-order model simplifies production planning since the production phase can begin after customer orders are received and processed (Zanoni et al. 2019; Delic and Eyers 2020). Just-in-time production can be facilitated using AM, as there will be fewer raw materials and finished goods inventory in the system to handle (Tuck et al. 2007; Patil et al. 2022). This feature is further enhanced by the ability to directly manufacture the required parts using raw materials and 3D models (i.e., direct digital manufacturing), which are normally kept in the form of digital inventory (vs. finished goods inventory). Additionally, mobile manufacturing can enhance the delivery capability and reliability of the firm. This can be done by equipping transport vehicles with AM machines, which then manufacture the requested parts in transit, thereby following the demand to its point of origin and reducing delivery lead time (Ryan et al. 2017; Basu et al. 2022). Moreover, in the case of sudden supply-side changes such as delayed deliveries due to import/export issues, the necessary parts can be produced locally/remotely via AM, thus maintaining the on-time delivery performance of the firm.

Given the digital nature of AM, adopting this technology will promote information sharing among supply chain partners. AM adoption gives rise to new business models through which it would be possible to involve the customer in the design and production phases, hence developing collaborative relationships and improving customer service levels (Bogers et al. 2016; Naghshineh and Carvalho 2022b). Another feature that can improve the level of customer service is the provision of legacy parts that no longer exist in the aftermarket. This can be accomplished through a customer-centric production model in which customers take over the production phase provided that they are supplied with the right 3D design data. In addition, customer service levels can be improved by extending the life cycle of products through AM-enabled repair and refurbishment (Boer et al. 2020; Patil et al. 2022). Altogether, such features of AM technology adoption lower the barriers to entering new markets.

Similar observations can be made by referring to the derived map, where the identified AM adoption features intersect with the SCA dimensions under study. Hence, this map can be of great use to managers and policymakers for strategic decision-making aimed at enhancing different dimensions of SCA via AM technology adoption. Overall, evidence suggests that by enhancing different dimensions of SCA, AM technology adoption prompts various opportunities for the adopting firm to gain a competitive advantage in erratic business environments.

4 Conclusion

Although dispersed pieces of evidence in the extant literature suggest that AM technology adoption tends to enhance SCA, to date, no study employed a holistic approach to investigate this topic. Grounded in the dynamic capabilities view, a systematic literature review was conducted to address this research gap in a rigorous manner. In doing so, this study managed to map the adoption features of AM technology that would augment the capability of the adopting firm to deal with erratic business environments in an agile manner, therefore gaining a competitive advantage. The derived map provides a strategic view for both academics and practitioners in the field who wish to look into the enhancing effects of AM technology adoption on SCA (see Fig. 3). More specifically, this map serves to highlight the AM adoption features that enable the adopting firm to enhance the SCA dimensions that it deems necessary. Considering the identified “white space” in the map, this study also proposes several questions to form a research agenda, presenting avenues for future research.

In an attempt to ensure data quality, this study only used peer-reviewed papers published in journals with an AJG (aka ABS) ranking. Therefore, some pieces of evidence in publications without this ranking may have been overlooked. Moreover, as this study drew on the scattered pieces of evidence in different studies to discover what features of AM technology adoption would enhance SCA, its findings are based on a wide range of AM processes and applications in various industries with different supply chain characteristics. While this provides an overall perspective, future research is required for a more nuanced understanding of the subject matter. Therefore, to put the derived map to the test, empirical research is recommended, especially case studies in specific industries and markets with distinct supply chain characteristics, where the effects of certain AM processes and their applications on enhancing the identified SCA dimensions can be examined. To further promote strategy analysis, future research can also analyze the evidence gathered in this review using different qualitative methods (e.g., critical review) to elaborate on how, and possibly to what extent, the identified AM adoption features enhance the SCA dimensions and speculate on the implications of such effects for supply chain management processes. While the focus of this review was on identifying the AM adoption features that enhance different dimensions of SCA, future research is required to identify the barriers that inhibit the enhancing effects of AM technology adoption in this regard. In the same vein, longitudinal research is recommended to examine how and to what extent the enhancing effects of AM technology adoption on different SCA dimensions change as the adoption barriers gradually disappear.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11301-023-00376-y.

Funding Open access funding provided by FCT|FCCN (b-on). The author acknowledges the financial support by the Doctoral Grant [PRT/BD/152828/2021] financed by the Portuguese Foundation for Science and Technology (FCT–MCTES) under the MIT Portugal Program.
Open access funding provided by FCT|FCCN (b-on).

Data Availability All data generated or analysed during this study are included in this published article [and its supplementary information files].

References

Akmal JS, Salmi M, Björkstrand R, Partanen J, Holmström J (2022) Switchover to industrial additive manufacturing: dynamic decision-making for problematic spare parts. Int J Oper Prod Manag 42(13):358–384. https://doi.org/10.1108/IJOPM-01-2022-0054

Aslam H, Blome C, Roscoe S, Azhar TM (2018) Dynamic supply chain capabilities: how market sensing, supply chain agility and adaptability affect supply chain ambidexterity. Int J Oper Prod Manag 38(12):2266–2285. https://doi.org/10.1108/IJOPM-09-2017-0555

Basu A, Yuvaraj MD M (2022) Improving agility and resilience of automotive spares supply chain: the additive manufacturing enabled truck model. Socio-Econ Plan Sci 85:101401. https://doi.org/10.1016/j.seps.2022.101401

Belhadi A, Kamble SS, Venkatesh M, Jabbour CJC, Benkhati I (2022) Building supply chain resilience and efficiency through additive manufacturing: an ambidextrous perspective on the dynamic capability view. Int J Prod Econ 249:108516. https://doi.org/10.1016/j.ijpe.2022.108516

Blome C, Schoenherr T, Rexhausen D (2013) Antecedents and enablers of supply chain agility and its effect on performance: a dynamic capabilities perspective. Int J Prod Res 51(4):1295–1318. https://doi.org/10.1080/00207543.2012.728011

Boer J, Lambrechts W, Krikke H (2020) Additive manufacturing in military and humanitarian missions: advantages and challenges in the spare parts supply chain. J Clean Prod 257:120301. https://doi.org/10.1016/j.jclepro.2020.120301

Bogers M, Hadar R, Bilberg A (2016) Additive manufacturing for consumer-centric business models: implications for supply chains in consumer goods manufacturing. Technol Forecast Soc Change 102:225–239. https://doi.org/10.1016/j.techfore.2015.07.024

Candi M, Beltagui A (2019) Effective use of 3D printing in the innovation process. Technovation 80:63–73. https://doi.org/10.1016/j.technovation.2018.05.002

Chartered Association of Business Schools (2021) The academic journal guide 2018. https://charteredabs.org/academic-journal-guide-2021-available-now/. Accessed 3 August 2021

Delic M, Eyers DR (2020) The effect of additive manufacturing adoption on supply chain flexibility and performance: an empirical analysis from the automotive industry. Int J Prod Econ 228:107689. https://doi.org/10.1016/j.ijpe.2020.107689

Dubey R, Altay N, Gunasekaran A, Blome C, Papadopoulos T, Childe SJ (2018) Supply chain agility, adaptability and alignment: empirical evidence from the Indian auto components industry. Int J Oper Prod Manag 38(1):129–148. https://doi.org/10.1108/IJOPM-04-2016-0173

Durach CF, Kurpjuweit S, Wagner SM (2017) The impact of additive manufacturing on supply chains. Int J Phys Distrib Logist Manag 47(10):954–971. https://doi.org/10.1108/IJPDLM-11-2016-0332

Frankel R, Naslund D, Bolumole Y (2005) The white space of logistics research: a look at the role of methods usage. J Bus Logist 26(2):185–209. https://doi.org/10.1002/j.2158-1592.2005.tb00211.x

Friedrich A, Lange A, Elbert R (2022) Supply chain design for industrial additive manufacturing. Int J Oper Prod Manag 42(11):1678–1710. https://doi.org/10.1108/IJOPM-12-2021-0802

Gligor DM, Esmark CL, Holcomb MC (2015) Performance outcomes of supply chain agility: when should you be agile? J Oper Manag 33:71–82. https://doi.org/10.1016/j.jom.2014.10.008

Gligor DM, Stank TP, Gligor N, Ogden JA, Nowicki DR, Farris T, Idug Y, Rana R, Porchia J, Kiran P (2022) Examining the rigor of SCM research: the case of supply chain agility. Supply Chain Manag J (ahead-of-print).

Holmström J, Partanen J, Tuomi J, Walter M (2010) Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment. J Manuf Technol Manag 21:687–697. https://doi.org/10.1108/17410381011063996

Humdan E, Shi Y, Behnia M, Najmaei A (2020) Supply chain agility: a systematic review of definitions, enablers and performance implications. Int J Phys Distrib Logist Manag 50(2):287–312. https://doi.org/10.1108/IJPDLM-06-2019-0192

ISO/ASTM 52900 (2021) Additive manufacturing — general principles —fundamentals and vocabulary. ASTM International, West Conshohocken

Khajavi SH, Partanen J, Holmström J, Tuomi J (2015) Risk reduction in new product launch: a hybrid approach combining direct digital and tool-based manufacturing. Comput Ind 74:29–42. https://doi.org/10.1016/j.compind.2015.08.008

Khan MR, Manzoor A (2021) Application and impact of new technologies in the supply chain management during COVID-19 pandemic: a systematic literature review. Int J Econ Bus Admin 9(2):277–292

Knofius N, van der Heijden MC, Zijm WH (2019) Consolidating spare parts for asset maintenance with additive manufacturing. Int J Prod Econ 208:269–280. https://doi.org/10.1016/j.ijpe.2018.11.007

Kunovjanek M, Wankmüller C (2020) An analysis of the global additive manufacturing response to the COVID-19 pandemic. J Manuf Technol Manag 32(9):75–100. https://doi.org/10.1108/JMTM-07-2020-0263

Kunovjanek M, Knofius N, Reiner G (2020) Additive manufacturing and supply chains–a systematic review. Prod Plan Control 33(13):1231–1251. https://doi.org/10.1080/09537287.2020.1857874

Light RJ, Pillemer DB (1984) Summing up: the science of reviewing research. Harvard University Press

Meng R, Yang Z, Sun J (2022), December Digital IT Innovation to Improve Supply Chain Resilience: A Systematic Literature Review. In 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) (0929–0933). IEEE

Miles MB, HuBerman AM (1994) Qualitative data analysis: an expanded sourcebook. Sage

Mongeon P, Paul-Hus A (2016) The journal coverage of web of Science and Scopus: a comparative analysis. Scientometrics 106(1):213–228. https://doi.org/10.1007/s11192-015-1765-5

Naghshineh B, Carvalho H (2022a) The implications of additive manufacturing technology adoption for supply chain resilience: a systematic search and review. Int J Prod Econ 247:108387. https://doi.org/10.1016/j.ijpe.2021.108387

Naghshineh B, Carvalho H (2022b) Exploring the interrelations between additive manufacturing adoption barriers and supply chain vulnerabilities: the case of an original equipment manufacturer. J Manuf Technol Manag 33(8):1473–1489. https://doi.org/10.1108/JMTM-04-2022-0148

Naghshineh B, Fragoso M, Carvalho H (2023) Rethinking Additive Manufacturing for spare parts Supply Chain Management. Res Technol Manag 66(4):38–47. https://doi.org/10.1080/08956308.2023.2207970

Patil H, Niranjan S, Narayanamurthy G, Narayanan A (2022) Investigating contingent adoption of additive manufacturing in supply chains. Int J Oper Prod Manag 43(3):489–519. https://doi.org/10.1108/IJOPM-05-2022-0286

Ryan MJ, Eyers DR, Potter AT, Purvis L, Gosling J (2017) 3D printing the future: scenarios for supply chains reviewed. Int J Phys Distrib Logist Manag 47(10):992–1014. https://doi.org/10.1108/IJPDLM-12-2016-0359

Seyedghorban Z, Tahernejad H, Meriton R, Graham G (2020) Supply chain digitalization: past, present and future. Prod Plan Control 31(2–3):96–114. https://doi.org/10.1080/09537287.2019.1631461

Shashi CP, Cerchione R, Ertz M (2020) Agile supply chain management: where did it come from and where will it go in the era of digital transformation? Ind Mark Manag 90:324–345. https://doi.org/10.1016/j.indmarman.2020.07.011

Swafford PM, Ghosh S, Murthy N (2006) The antecedents of supply chain agility of a firm: scale development and model testing. J Oper Manag 24(2):170–188. https://doi.org/10.1016/j.jom.2005.05.002

Swafford PM, Ghosh S, Murthy N (2008) Achieving supply chain agility through IT integration and flexibility. Int J Prod Econ 116(2):288–297. https://doi.org/10.1016/j.ijpe.2008.09.002

Teece DJ, Pisano G, Shuen A (1997) Dynamic capabilities and strategic management. Strateg Manag J 18(7): 509–533. https://doi.org/10.1002/(SICI)1097-0266 (199708)18:7 < 509::AID-SMJ882 > 3.0.CO;2-Z

Thomé AMT, Scavarda LF, Scavarda AJ (2016) Conducting systematic literature review in operations management. Prod Plan Control 27(5):408–420. https://doi.org/10.1080/09537287.2015.1129464

Tranfield D, Denyer D, Smart P (2003) Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br J Manag 14(3):207–222. https://doi.org/10.1111/1467-8551.00375

Tuck C, Hague R, Burns N (2007) Rapid manufacturing: impact on supply chain methodologies and practice. Int J Serv Oper Manag 3(1):1–22. https://doi.org/10.1504/IJSOM.2007.011459

Verboeket V, Krikke H (2019) The disruptive impact of additive manufacturing on supply chains: a literature study, conceptual framework and research agenda. Comput Ind 111:91–107. https://doi.org/10.1016/j.compind.2019.07.003

Waller MA, Fawcett SE (2014) Click here to print a maker movement supply chain: how invention and entrepreneurship will disrupt supply chain design. J Bus Logist 35:99–102. https://doi.org/10.1111/jbl.12045

Weller C, Kleer R, Piller FT (2015) Economic implications of 3D printing: market structure models in light of additive manufacturing revisited. Int J Prod Econ 164:43–56. https://doi.org/10.1016/j.ijpe.2015.02.020

Wernerfelt B (1984) A resource-based view of the firm. Strateg Manag J 5(2):171–180. https://doi.org/10.1002/smj.4250050207

Whitten GD, Green KW, Zelbst PJ (2012) Triple-A supply chain performance. Int J Oper Prod Manag 32(1):28–48. https://doi.org/10.1108/01443571211195727

Yang J (2014) Supply chain agility: securing performance for Chinese manufacturers. Int J Prod Econ 150:104–113. https://doi.org/10.1016/j.ijpe.2013.12.018

Zanoni S, Ashourpour M, Bacchetti A, Zanardini M, Perona M (2019) Supply chain implications of additive manufacturing: a holistic synopsis through a collection of case studies. Int J Adv Manuf Technol 102:3325–3340. https://doi.org/10.1007/s00170-019-03430-w