



Exploring the effects of additive manufacturing technology adoption on the state of the supply chain: a resilience perspective

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Received: 16 March 2023 / Revised: 25 September 2024 / Accepted: 2 January 2025 / Published online: 13 February 2025
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Abstract

As a digital technology, the adoption of additive manufacturing (AM), otherwise known as 3D printing, affects the *state* of the supply chain, consequently affecting supply chain resilience. To investigate the subject matter from the industry’s viewpoint, an exploratory survey was conducted to collect quantitative and qualitative empirical data from a heterogeneous sample of experts in various companies with hands-on experience in AM technology adoption. The quantitative data analysis indicates that adopting AM technology affects the supply chain’s *state* to a moderate extent overall, which in turn is likely to moderately affect supply chain resilience. The qualitative data analysis elucidates how different adoption features of AM technology affect the supply chain’s *state* and identifies the barriers inhibiting these effects. Generic propositions are put forward to reflect the theoretical implications of the study. Moreover, an empirical framework is conceived that outlines the managerial implications of the study. This framework can be used by practitioners and academics seeking to understand to what extent and how AM adoption affects the supply chain’s *state*, a fundamental prerequisite for assessing the supply chain resilience outcomes of adopting this digital technology.

Keywords 3D printing · Additive manufacturing · Digital technology adoption · Supply chain state · Supply chain resilience · Empirical framework

1 Introduction

In recent years, there has been an ongoing stream of research regarding the effects of adopting Industry 4.0 technologies on enhancing supply chain resilience. Among these technologies, additive manufacturing (AM) has received remarkable attention, especially in response to the worldwide supply chain vulnerabilities and disruptions triggered by the COVID-19 outbreak (Ardolino et al. 2022; Kunovjanek and Wankmüller 2020; Pansare and Yadav 2022), which is mainly due to its versatility in promoting different applications that improve supply chain resilience (Belhadi et al. 2022). AM technology adoption, i.e., “act or process of using AM in the production processes” (Patil

et al. 2023), changes the supply chain’s structure (Dolgui and Ivanov 2020; Durach et al. 2017), therefore affecting the underlying supply chain capabilities and vulnerabilities that define supply chain resilience (Pettit et al. 2019; Naghshineh and Carvalho 2022a). To better comprehend these structural changes (i.e., supply chain structural dynamics), which consequently affect supply chain resilience (Dolgui and Ivanov 2020), it is essential to first comprehend to what extent and how adopting AM technology affects the *state* of the supply chain (Naghshineh and Carvalho 2022a). The “state of the SC [supply chain] is a specific arrangement of SC entities and relational links between them and others SCs, material and information flows, management policies and lead times” (Carvalho et al. 2012), indicated by different supply chain state variables (Carvalho et al. 2022). This definition expands on the definition of “supply chain macro-state”, which is “a general supply chain state in which one or more supply chain objects can operate and fulfill jobs and processes” (Ivanov 2018, p.5). Supply chain structural dynamics take place when the supply chain transitions from one general state to another (Ivanov 2018, p.6). Given these explanations, along with the widely cited definition

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of supply chain resilience—i.e., “the ability of a system to return to its original state or move to a new, more desirable state after being disturbed” (Christopher and Peck 2004)—we concur with Carvalho et al. (2012) that a “fundamental pre-requisite for assessing SC resilience is an understanding of current and future system states”. This highlights the significance of comprehending to what extent and how the supply chain’s state is affected by AM adoption in order to assess its implications for supply chain resilience (Naghshineh and Carvalho 2022a).

Nonetheless, after reviewing the existing literature, we found no empirical research that addresses this knowledge gap in detail. Although there are dispersed pieces of information throughout the literature that imply how AM affects different supply chain state variables, no empirical study has holistically examined the effects of adopting this technology on the state of the supply chain while taking on a resilience perspective. Naghshineh and Carvalho (2022a) conducted a systematic literature review to propose how adopting AM technology affects the supply chain’s state, thereby influencing the supply chain capabilities and vulnerabilities that underpin the notion of supply chain resilience. Subsequently, they called for empirical research to expand their study and validate their findings using empirical insights. Given these considerations, the objective of our research is to empirically examine the adoption effects of AM technology on the supply chain’s state while employing a resilience perspective. Hence, we address the following research questions (RQs) using empirical data:

RQ1. To what extent does AM technology adoption affect the state of the supply chain?

RQ2. How does AM technology adoption affect the state of the supply chain?

To address these RQs from the viewpoint of the industry, we conducted an exploratory survey targeting experts who worked for companies involved in different industries and supply chains, which had already adopted one or more AM processes for different applications. Thereafter, we identified to what extent AM adoption affects the supply chain’s state by drawing on the collected quantitative data (i.e., Likert scale responses), thus addressing RQ1. We also gathered qualitative data (i.e., texts) from the experts aimed at explaining their quantitative answers and compared them with the existing evidence in the literature to elucidate how AM adoption affects the supply chain’s state, thereby addressing RQ2.

The motivation behind this research stems from the increasing importance of resilience in dealing with supply chain vulnerabilities and disruptions. Despite the growing attention AM has received for enhancing supply chain resilience, there is a considerable gap in empirical research

that specifically explores to what extent and how adopting this technology affects the supply chain’s state, which is a critical factor influencing supply chain resilience. Therefore, the main objective of this exploratory research is to investigate the extent and manner in which AM technology adoption affects the supply chain’s state, offering practical relevance for practitioners by providing a framework to help assess and enhance supply chain resilience through informed decision-making.

The originality of this research is attributable to its comprehensive exploration of AM’s adoption effects on the supply chain’s state. Unlike previous studies that have only touched on isolated adoption effects of AM on a limited number of supply chain state variables, this study provides a holistic examination of these effects, considering a broad range of supply chain state variables. Although conceptual work, such as Naghshineh and Carvalho (2022a), exists, this study is the first to investigate the subject matter using both quantitative and qualitative empirical data. The exploratory survey targets experts from diverse industries, making the findings directly applicable to real-world scenarios. This practical relevance distinguishes the research from more theoretical studies and underscores its potential impact on industry practices related to AM adoption and supply chain resilience. The study introduces a new empirical framework that outlines AM’s adoption effects on the supply chain’s state, providing a practical tool for managers and practitioners to assess the impact of adopting this technology on their supply chains and make informed decisions to enhance supply chain resilience.

This paper continues as follows. The theoretical background and the research methodology are described in sections two and three respectively. In section four, the research results are presented and discussed in detail. In section five, propositions and a novel empirical framework are put forward that reflect the research implications. Lastly, in section six, conclusions are drawn, and future research directions are suggested.

2 Theoretical background

AM is an advanced digital technology that uses specific raw materials, computer-aided design (CAD) models, and specialized computer devices known as 3D printers to create objects layer by layer (ISO/ASTM 52900 2021). As noted in section one, the adoption of this digital technology gives rise to supply chain structural dynamics, signifying a transition in the general *state* of the supply chain (Dolgui and Ivanov 2020; Ivanov 2018). This transition entails changes occurring in the main supply chain dimensions (also known as mapping dimensions), i.e., supply chain entities (nodes), relational links (between the supply chain entities/nodes), information flow,

material flow, lead times, and management policies (Carvalho et al. 2012). Supply chain state variables are defined and used to project these changes and their implications for supply chain resilience (Carvalho et al. 2012, 2022). For example, as shown in Table 1, “Production lead time” and “Delivery lead time” are two supply chain state variables that reflect the changes in the supply chain dimension “Lead times”. These supply chain state variables and their metrics were primarily defined by Carvalho et al. (2012) and later developed and used in an empirical investigation by Carvalho et al. (2022) to assess supply chain resilience. Moreover, Naghshineh and Carvalho (2022a) used these supply chain state variables to propose how AM technology adoption affects supply chain resilience; hence, they serve the objective of this research. Besides, after reviewing the literature, we found no other sources that put forward a comprehensive list of variables and metrics aimed at assessing the state of the supply chain while taking on a resilience perspective.

From a resilience perspective, understanding the changes that occur in the supply chain’s state because of AM technology adoption is important (Dolgui and Ivanov 2020) since they, in turn, affect the underlying supply chain capabilities that are necessary to mitigate supply chain vulnerabilities (Naghshineh and Carvalho 2022a; Pettit et al. 2019). For instance, based on the following piece of evidence from the literature: “The distributed manufacturing of spare parts in locations closer to the final user may have several advantages, such as reduced delivery lead times and reduced logistics costs” (Durão et al. 2017), AM adoption positively affects the supply chain state variable “Delivery lead time”, which can

be measured by its designated metric “Ease (in terms of cost) of reducing delivery lead time”. This improvement in delivery lead time will consequently affect the supply chain’s capability to swiftly adapt (i.e., supply chain adaptability) to vulnerabilities such as unpredictability in customer demand (Naghshineh and Carvalho 2022a). Given these considerations, we concur with Carvalho et al. (2012) who state that the “definition of SC resilience implies that the identification of the state of the system is an essential part of resilience analysis.”

Within the last decade, there has been a fair share of empirical research investigating the supply chain effects of AM technology. However, to date, no empirical research has attempted to comprehensively explore to what extent and how AM adoption affects the supply chain’s state to establish a strong basis for future research to investigate the supply chain resilience outcomes of adopting this technology. That is, the empirical evidence concerning AM’s adoption effects on the supply chain’s state is fragmented throughout the literature, especially when considering the subject matter from a resilience perspective. To highlight this research gap, as shown in Table 2, we have analyzed several empirical works at the interface of AM and supply chain management that investigate the supply chain effects of this technology. Moreover, in Table 3, we have critically reviewed the existing empirical research that implies how AM affects different supply chain state variables, further illustrating the lack of an empirical study that holistically examines the adoption effects of this technology on the state of the supply chain. As outlined in these tables, no empirical research has comprehensively explored the RQs under study.

Table 1 Supply chain dimensions, supply chain state variables, and metrics. (source Carvalho et al. 2012, 2022)

Supply chain dimensions	Supply chain state variables	Metrics
Management policies	Available alternatives for production processes	Possibility to outsource production processes Operations versatility* Redundancy in production processes
	Production capacity slack	Ease (in terms of time and cost) of adjusting the production capacity
	Production schedule adaptability	Ease (in terms of time and cost) of changing the production schedules
Supply chain entities	Available alternatives for production sites	Number of available alternatives for production sites
Lead times	Available alternatives for sources of supply	Number of available alternatives for sources of supply
	Production lead time	Ease (in terms of cost) of reducing production lead time
Material flow	Delivery lead time	Ease (in terms of cost) of reducing delivery lead time
	Distribution channels	Ease (in terms of time and cost) of switching between distribution channels
Information flow	Transport mode	Number of available alternatives for transporting goods and material
	Information sharing	Ease (in terms of time and cost) of exchanging reliable and timely information with supply chain partners
Relational links	Relationship type	The degree of cooperation with other firms in the supply chain

*“Operations versatility” refers to a production system’s ability to perform diverse operations (Tsourveloudis and Valavanis 2002)

Naghshineh and Carvalho (2022a) highlighted this empirical research gap by performing a systematic literature review. They proposed that several AM adoption features positively affect the supply chain's state, while certain barriers inhibit this effect. In line with extant literature (e.g., Durach et al. 2017; Naghshineh et al. 2023), they proposed that such barriers, otherwise known as limitations or bottlenecks, considerably influence the extent to which and how AM technology adoption affects the state of the supply chain. Thereafter, they called for empirical research to validate their findings. Therefore, our objective in this exploratory study is to address this empirical research gap. Hence, we adapted part of their conceptual research model that fits the scope of this study, and represents the main research variables (Fig. 1).

As indicated in Fig. 1, “Additive manufacturing adoption” is represented by two main variables, i.e., “Additive manufacturing adoption features” and “Additive manufacturing adoption barriers”. From a resilience perspective, AM adoption features tend to motivate the “State of the supply chain” to transition to a more favorable state, i.e., positive triggers of supply chain structural dynamics (Dolgui and Ivanov 2020), whereas AM adoption barriers tend to inhibit this effect (Naghshineh and Carvalho 2022a). For instance, as noted in Table 3, while distributed manufacturing (i.e., AM adoption feature) reduces the delivery lead time (i.e., supply chain state variable), the excessive need for post-processing (i.e., AM adoption barrier) inhibits this enhancing effect. Subsequently, AM adoption's overall impact on delivery lead time affects the adaptability of the supply chain (i.e., supply chain capability) to the unpredictability in customer demand (i.e., supply chain vulnerability), therefore influencing supply chain resilience (Naghshineh and Carvalho 2022a). The latter statement is used to explain one of the potential supply chain resilience outcomes of AM technology adoption. However, it is beyond the scope of this study, and therefore, the variables that represent “Supply

chain resilience” in Fig. 1 (i.e., “Supply chain capabilities” and “Supply chain vulnerabilities”) are grayed out. We only drew on these variables to highlight the implications that adopting AM technology bears for supply chain resilience due to its effects on the state of the supply chain.

3 Research methodology

3.1 Research design

Given the lack of empirical research on the subject matter, we conducted an exploratory survey to investigate to what extent and how AM technology adoption affects the supply chain's state. As Forza (2002) states, “Descriptive and exploratory survey research are important and widely used in OM [Operations Management].” This method is particularly useful at “the early stages of research into a phenomenon, when the objective is to gain preliminary insight on a topic” (Forza 2002), laying out the foundation for in-depth future research. Unlike case studies and time-intensive interviews, exploratory surveys enable the targeting of a larger sample, providing a greater likelihood of involving field experts who are otherwise difficult to engage with (Babbie 1990). Moreover, survey-based studies that involve multiple respondents from various industry sectors and supply chain tiers tend to provide a general view of the implications of Industry 4.0 technologies, including AM, for supply chain resilience (Tortorella et al. 2022). Hence, we opted to perform an exploratory survey using a heterogeneous sample with a rather large size (compared to case studies and interviews) to acquire a general comprehension of the subject matter and support the development of propositions and transferable theory for future research (Forza 2002).

Exploratory surveys have already been used in supply chain and operations management research similar to the context of the present study, e.g., Hübner et al. (2016) and Kembro and

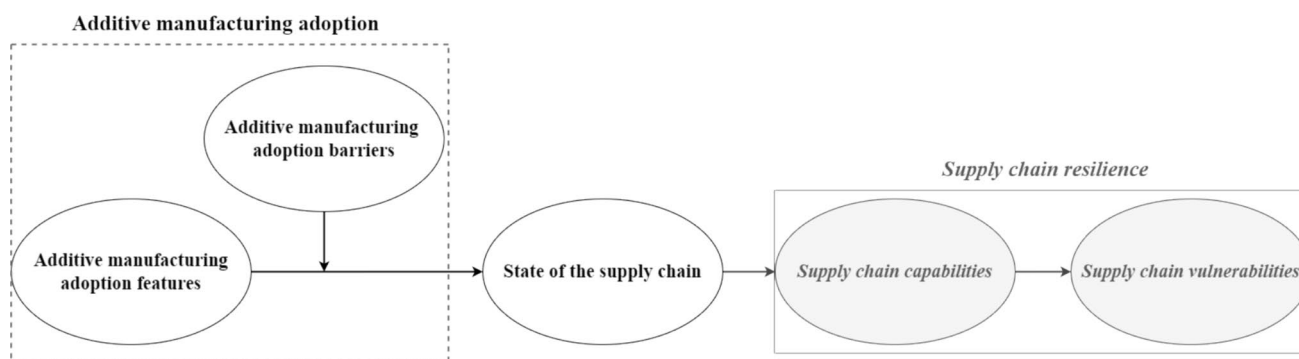


Fig. 1 Conceptual research model

Table 2 Empirical studies investigating the supply chain effects of AM technology

Source	Research purpose	Method	Main findings
Khajavi et al. (2014)	Assess how improvements in AM technology could impact the spare parts supply chain configuration.	Scenario modeling	Distributed manufacturing becomes increasingly feasible as AM machines advance to require less investment, operate with greater independence, and achieve faster production cycles. AM improves supply chain performance by decreasing lead times and total costs.
Chiu and Lin (2016)	Develop a decision aid for optimizing supply chain configuration for additively manufactured products under various demand uncertainties.	Simulation	Adopting AM significantly influences supply chain management processes associated with supply and demand.
Oettmeier and Hofmann (2016)	Examine AM's adoption impacts on supply chain management processes.	Case study	The AM's effects concerning changes in the supply chain's structure, logistics, and customer centrality are proposed.
Durach et al. (2017)	Explore emerging AM processes, their adoption barriers, and anticipated effects on the supply chain.	Survey	Compatibility issues and the benefits related to the demand side of the supply chain are the primary factors determining the implementation of AM among firms.
Oettmeier and Hofmann (2017)	Investigate the multifaceted factors influencing the implementation of AM for part production, with a special emphasis on the supply chain issues.	Survey	Supply chain integration and intellectual property issues need to be tackled to unlock AM's full potential. In particular, licensing platforms need to be implemented to address legal complications.
Chan et al. (2018)	Uncover the obstacles hindering AM's mass-scale adoption.	Semi-structured interviews	Adopting AM affects supply chain and firm performance positively. Moreover, by enabling supply chain integration, AM generates a positive indirect effect on supply chain and firm performance.
Delic et al. (2019)	Examine AM's impacts on supply chain and firm performance while considering supply chain integration.	Survey	The inherent flexibility of AM systems in centralized/decentralized production settings potentially offers novel solutions for supply chain issues and enables on-demand production closer to usage points.
Zanoni et al. (2019)	Analyze the implications of AM technologies across different supply chain stages.	Case study	Adopting AM positively affects flexibility, which subsequently enhances the overall supply chain performance.
Delic and Eysers (2020)	Develop a framework to examine the connections between adopting AM, flexibility, and supply chain performance.	Survey	AM can decrease the raw materials inventory by about 4% and its diffusion rate is influenced by the utility of the technology.
Kunovjanek and Reiner (2020)	Investigate AM's potential impacts on established manufacturing and supply chain processes, particularly to provide insights into material inventory reduction and diffusion rates of the technology.	Simulation (system dynamics)	AM adoption has the potential to save up costs by 31.46% in the production and supply chain operations of highly customized products, highlighting the impact of critical parameters on supply chain costs.
Cui et al. (2021)	Explore the cost-saving potentials of AM technology and critical parameters impacting supply chain costs.	Case study	AM has the potential to cultivate ambidextrous dynamic capabilities, balancing both resilience and efficiency, with critical determinants including data-driven systems and supply chain collaboration.
Belhadi et al. (2022)	Explore whether AM technology can reconcile the conflicting goals of supply chain efficiency and resilience, using an ambidextrous perspective.	Focus group and case study	

Table 2 (continued)

Source	Research purpose	Method	Main findings
Jimo et al. (2022)	Investigate AM's adoption impact on supply chain complexities and dependencies to understand its implications for competitiveness.	Case study	AM's ability to decrease supply chain complexities and dependencies varies based on, industry, geographical, organizational, technological, and economic factors, highlighting the importance of understanding these dynamics for achieving competitiveness.
Naghshineh and Carvalho (2022b)	Explore how barriers to adopting AM can cause vulnerabilities in the supply chain, which consequently diminish supply chain resilience.	Case study	Adoption barriers are identified that cause different supply chain vulnerabilities such as production capacity, supplier capacity, and reliance on specialty sources.
Patil et al. (2023)	Examine AM adoption contingencies and devise a framework for appraising adoption viability.	Semi-structured interviews	Contingent factors affecting AM adoption are identified and categorized as strategic, organizational, and technological factors, proposing a framework to examine the viability of adopting this technology.
Naghshineh and Carvalho (2024)	Develop a practice-based framework to delineate the pathways to enhancing supply chain resilience via AM technology adoption.	Survey	The developed framework outlines how AM adoption affects different resilience practices that are necessary for addressing supply chain vulnerabilities and enhancing supply chain resilience.
Priyadarshini et al. (2024)	Explore the conflicting priorities that emerge when adopting AM technology in the healthcare sector aimed at augmenting the circular economy.	Focus group and semi-structured interviews	The study identifies four competing priorities when adopting AM in the healthcare sector to improve the circular economy and suggests ways to manage arising tensions using a pluralistic perspective.

Norrman (2022). As evidenced in these studies, exploratory surveys are particularly useful for answering open-ended “how” questions that focus on unexplored areas. Addressing such RQs is a valid reason for performing exploratory surveys, which can help develop propositions for future research grounded in empirical evidence (Forza 2002). Furthermore, as Edmondson and McManus (2007) state, “The combination of qualitative data to help elaborate a phenomenon and quantitative data to provide preliminary tests of relationships can promote both insight and rigor.” Therefore, we gathered both quantitative and qualitative survey data to address the RQs using a heterogeneous sample of AM experts from different industries and supply chain tiers (see Table 4). We used the collected quantitative data (i.e., Likert scale responses) to estimate to what extent AM adoption affects the supply chain's state (RQ1) while concurrently analyzing the qualitative data (i.e., texts containing the experts' explanations) to understand how adopting this technology affects the supply chain's state (RQ2). Hence, this mixed-methods exploratory survey research design enabled us to gather qualitative data to explain and lend support to the credibility of the quantitative data, thereby establishing methodological triangulation (Jack and Raturi 2006).

3.2 Sampling and data collection

To prompt alternative explanations and integrate a variety of viewpoints from different industries that use AM, we required a heterogeneous sample (Patil et al. 2023). According to Wohlers (2021), AM is mainly used by companies involved in the aerospace, automotive, medical, and energy, among other industries. Therefore, to survey experts involved in these industries, we used the LinkedIn professional network platform, which is commonly used for expert sampling and data collection in this research area, e.g., Kurpjuweit et al. (2021). We used different search strings composed of relevant keywords (e.g., “Managing director”, “Operations manager”, “Production manager”, “Supply chain manager”, etc., combined with either “Additive manufacturing” or “3D printing”) to find experts registered on the LinkedIn platform that potentially possessed the knowledge and managerial experience in the AM field. Our search resulted in 417 professional profiles. After reviewing each profile to ensure the accuracy of the search results, we sent out 400 invitations for participation in the survey over the course of December 2021. Each invitation included a concise description of the survey along with a weblink to an online questionnaire. We started receiving responses from mid-December 2021 through the end of January 2022. After sending follow-up reminders to late responders, we received 69 questionnaires, corresponding to a response rate of 17.3%. However, we discarded 9 questionnaires due to incomplete answers, which left us with 60 usable questionnaires. This sample size corresponds to the sample sizes in the exploratory surveys conducted by Hübner et al. (2016) and Kembro and Norrman (2022), which are 60 and 50 respectively.

Table 3 Potential effects of AM adoption on different supply chain state variables based on past empirical research

Supply chain state variables	AM adoption effects	Sources
Available alternatives for production processes	Increases the likelihood of outsourcing the production processes to AM bureaus, reducing the need for high upfront investment costs.	Ford and Despeisse (2016)
	Increases the possibility of outsourcing production processes via capacity pooling.	Khajavi et al. (2014)
	Reduces the possibility of outsourcing production processes due to an absence of well-defined legal frameworks for transferring liability in AM outsourcing agreements.	Friedrich et al. (2022)
	Reduces the possibility of outsourcing production processes due to intellectual property (IP) rights problems.	Chekurov et al. (2018)
	Reduces the possibility of outsourcing production processes due to performance and consistency issues, which can lead to quality problems.	Dwivedi et al. (2017)
	Increases operations versatility by manufacturing products directly in one manufacturing step.	Kunovjanek and Reiner (2020)
	Increases operations versatility via fast turnaround time and no tooling, i.e., the time to produce a part is relatively fast and no production tools are needed.	Chan et al. (2018)
	Increases operations versatility by eliminating the pre-assembly activities.	Oettmeier and Hofmann (2017)
	Increases operations versatility by simplifying the manufacturing process.	Chiu and Lin (2016)
	Reduces operations versatility due to slow printing speed.	Shukla et al. (2018)
	Reduces operations versatility as most printers only function with one material/color.	Rayna et al. (2015)
	Increases redundancy in production processes via a hybrid approach by combining AM with traditional tool-based manufacturing.	Khajavi et al. (2015)
	Reduces redundancy owing to the considerable cost of AM equipment.	Chekurov et al. (2018)
	Production capacity slack	Increases the time and costs required to adjust production capacity due to small production platforms and limited build volumes.
Reduces the time and costs to adjust production capacity by enhancing capacity flexibility mainly through design innovations.		Belhadi et al. (2022)
Reduces the time and costs to adjust production capacity through small batch orientation.		Luomaranta and Martinsuo (2020)
Reduces the capacity to process multiple materials (i.e., lack of multi-material printing), requiring more cost and time to adjust production capacity due to frequent material changeovers.		Eyers et al. (2018)
Reduces the costs of adjusting production capacity via economies of technology, e.g., managing several AM devices via a single operator.		Tuck et al. (2007)
Production schedule adaptability	Increases the costs and time needed to alter the production plans due to low throughput rate and slow production speed.	Dwivedi et al. (2017)
	Increases the costs and time needed to alter the production plans due to excessive post-processing requirements.	Achillas et al. (2017)
	Reduces the costs and time needed to alter the production plans by eliminating the necessity to keep various materials in stock.	Chan et al. (2018)
	Reduces the costs and time needed to alter the production plans by eliminating laborious machine setups.	Shukla et al. (2018)

Table 3 (continued)

Supply chain state variables	AM adoption effects	Sources
	Reduces the costs and time needed to alter the production plans by eliminating the need for expensive production tools. e.g., molds or jigs.	Steenhuis and Pretorius (2017)
Available alternatives for production sites	Increases the number of potential production sites via distributed manufacturing, since any supply chain node outfitted with AM apparatus can act as a production site.	Zanoni et al. (2019)
	Increases the number of potential production sites via capacity sharing (i.e., capacity pooling).	Jiang et al. (2017)
Available alternatives for sources of supply	Reduces the number of potential production sites due to the expensive nature of the machine infrastructure.	Eyers et al. (2018)
	Reduces the number of potential supply sources due to a lack of suppliers for specialized post-processing and finish machining.	Jimo et al. (2022)
	Reduces the number of potential supply sources as AM materials are limited and expensive.	Thomas-Seale et al. (2018)
	Reduces the number of potential supply sources because of the limited range of materials and supplier shortage.	Niaki and Nonino (2017)
	Reduces the number of qualified supply sources due to a shortage of verification/certification processes for AM machines and materials.	Wagner and Walton (2016)
Production lead time	Increases the production costs and lead time due to the excessive need for post-processing.	Chekurov et al. (2018)
	Increases the production costs and lead time as there is unreliability and instability in AM processes.	Durach et al. (2017)
	Increases the production cost due to longer manufacturing time.	Chen et al. (2015)
	Reduces production lead time and costs by eliminating subassemblies for products with a large number of components.	Patil et al. (2023)
	Reduces the production costs and lead time by enabling the just-in-time approach.	Belhadi et al. (2022)
	Reduces the production costs and lead time by reducing subparts/components needed for production, procurement, or assembly.	Priyadarshini et al. (2022)
	Reduces the production time and cost since the entire part can be manufactured in one build.	Cui et al. (2021)
	Reduces the production lead time and costs by rapid prototyping and testing designs.	Candi and Beltaoui (2019)
	Reduces the production costs and lead time by eliminating molds and auxiliary tools, as well as rapid prototyping of models and prototypes.	Zanoni et al. (2019)
	Reduces the production costs and lead time by reducing the parts/components needed for a final part.	Chan et al. (2018)
	Reduces the production costs and lead time by reducing tooling and setup time.	Rylands et al. (2016)
Delivery lead time	Increases the delivery costs and lead time due to excessive post-processing requirements.	Naghshineh and Carvalho (2022b)
	Increases the delivery costs and lead time due to excessive post-processing requirements.	Chekurov et al. (2018)
	Reduces the time of delivery by decreasing the transportation lead times via AM-enabled decentralized configurations.	Friedrich et al. (2022)
	Reduces the delivery costs and lead time by enabling the just-in-time approach.	Belhadi et al. (2022)

Table 3 (continued)

Supply chain state variables	AM adoption effects	Sources
Distribution channels	Reduces the delivery costs and lead time since parts can be manufactured near the customer on demand.	Delic and Eyers (2020)
	Reduces the delivery lead time and costs by minimizing parts/components needed for a final part.	Chan et al. (2018)
	Reduces the delivery time and logistics costs via distributed manufacturing of parts near the point of consumption.	Durão et al. (2017)
	Reduces the delivery time and costs via the localization of manufacturing.	Schniederjans (2017)
	Reduces the delivery time and costs via decentralized production close to the target market.	Bogers et al. (2016)
	Reduces the time and cost of switching distribution channels by eliminating the necessity to keep various materials in stock.	Chan et al. (2018)
	Reduces the time and cost of switching distribution channels due to simplified logistics as fewer and more basic material inputs are used.	Ford and Despeisse (2016)
Transport mode	Reduces the time and cost of switching distribution channels due to the capability to manufacture economic low volumes (small batch sizes).	Mellor et al. (2014)
	Increases the number of available alternatives for transport due to fewer types of materials and inventory.	Chan et al. (2018)
	Increases the transport options for goods and materials by using basic materials and digital files.	Ford and Despeisse (2016)
Information sharing	Increases the number of available alternatives for transport because of the possibility of using digital inventory.	Dwivedi et al. (2017)
	Increases the risk and cost of sharing accurate and timely information due to a lack of digital infrastructure.	Friedrich et al. (2022)
	Increases the risk and cost of sharing accurate and timely information due to lack of cyber security.	Zanoni et al. (2019)
	Increases the risk and cost of sharing accurate and timely information due to intellectual property rights.	Chan et al. (2018)
	Increases the cost of sharing accurate and timely information due to ICT inadequacies.	Chekurov et al. (2018)
	Reduces the time and cost of exchanging information because of AM's compatibility with sensors and data analytics methods.	Belhadi et al. (2022)
	Reduces the time and cost of exchanging information through sharing digital design files.	Beltagui et al. (2020)
Relationship type	Reduces the time and cost of exchanging information using 3D model data and stored digital representations of objects.	Oettmeier and Hofmann (2016)
	Reduces the time and cost of exchanging information via the electronic transfer of design files.	Eyers and Potter (2015)
	Increases cooperation among supply chain partners by boosting the levels of visibility, innovation, and information exchange.	Belhadi et al. (2022)
	Increases cooperation in the supply chain due to increased customer interaction and new partnerships.	Hannibal (2020)
	Increases cooperation in the supply chain via open and cooperative relationships.	Luomaranta and Martinsuo (2020)
	Increases cooperation in the supply chain by involving the consumer as a co-creator of the products.	Delic et al. (2019)

Table 3 (continued)

Supply chain state variables	AM adoption effects	Sources
	Increases cooperation in the supply chain by allowing direct co-creation with users.	Bogers et al. (2016)
	Increases supply chain cooperation by allowing the customers to be part of the product design phase.	Chiu and Lin (2016)
	Increases cooperation in the supply chain due to strong working relationships among material and machine suppliers.	Oettmeier and Hofmann (2016)
	Increases cooperation in the supply chain by allowing the customers to co-design their own customized products.	Eyers and Potter (2015)
	Increases cooperation in the supply chain via collaboration with customers and suppliers.	Mellor et al. (2014)
	Reduces cooperation in the supply chain because of insufficient consumer awareness and acceptance.	Durach et al. (2017)
	Reduces cooperation in the supply chain due to a lack of trust in technology vendors.	Dwivedi et al. (2017)

3.3 Survey instrument

The survey instrument was designed to gather both quantitative and qualitative data concurrently. Five-point Likert scale questions were used to collect quantitative data reflecting the experts' perceptions of the extent to which AM adoption affects the supply chain's state (where 1 indicated "Very low effect" and 5 indicated "Very high effect"). To this end, the metrics representing the supply chain state variables in Table 1 were used to develop the questions. After each question, an open text field was provided for the experts to explain and support their quantitative answers. These explanations allowed us to understand how different AM adoption features and barriers affect each supply chain state variable. The questionnaire also contained general questions regarding the company size, the country, the industry sector, the supply chain tier, and the expert's position in the company, as well as the adopted AM processes and their applications. To ensure anonymity, questions inquiring about the names of experts/companies were presented as optional. Prior to dispatch, the questionnaire was first reviewed by an academic and an expert in the field and then pilot tested in several companies that had adopted different AM processes. Based on the feedback we received in the pilot testing phase, the questionnaire was first fine-tuned and then administered online via Google Forms (Appendix).

3.4 Data analysis

The descriptive analysis of the sample is available in Table 4. The experts had an average of approximately 9 years of experience in the AM field, mainly in managerial positions, indicating an ideal level of experience and knowledge for answering the survey questions. The derived sample includes a "diverse range of participants and companies,

which could lead to more robust findings and a more in-depth understanding of the subject." (Belhadi et al. 2022). Additionally, the descriptive analysis of the AM processes and their applications adopted by the companies in the sample are presented in Table 4. Comparatively, these descriptive analyses are in line with the report by Wohlers (2021) regarding the "3D Printing and Additive Manufacturing Global State of the Industry", corroborating that the derived sample is representative of the targeted industries.

Before proceeding with the statistical analysis of the quantitative data to estimate to what extent AM adoption affects the state of the supply chain (RQ1), we checked scale reliability using Cronbach's α (Cronbach 1951). The Cronbach's α is 0.86, which exceeds the commonly accepted value of 0.70, confirming the reliability of the scales. Thereafter, similar to Durach et al. (2017), among others, we drew on the importance of mean scores to interpret the results of the Likert scale responses while paying attention to the frequency and dispersion of the responses. Since this type of statistical analysis is often used in exploratory survey research and is descriptive in nature, a priori analysis for determining the minimum sample size was not necessary. As Israel (1992) states, "If descriptive statistics are to be used, e.g., mean, frequencies, then nearly any sample size will suffice." Nevertheless, as our study is exploratory in nature, we put forward generic propositions based on our findings that are open to further investigation by future research.

In conjunction with the statistical analysis of the quantitative data, we analyzed the experts' explanations throughout the open text fields to understand how adopting AM technology affects the state of the supply chain (RQ2). To do this, we used the exhaustive list of AM adoption features and barriers by Naghshineh and Carvalho (2022a) as our coding scheme/criteria (research dimensions). In this way, we ensured that the explanations were analyzed and summarized based on

Table 4 Descriptive analysis of the sample

	Frequency	Percent		Frequency	Percent
Country			Industry sector		
Austria	2	3%	Aerospace	12	20%
Canada	4	7%	Automotive	14	23%
Denmark	1	2%	Engineering services	10	17%
China	4	7%	Energy (equipment and spare parts)	11	18%
France	2	3%	Medical	13	22%
Finland	1	2%	<i>Total</i>	60	100%
Germany	11	18%	Supply chain tier		
Italy	2	3%	2nd tier supplier	18	30%
Netherlands	3	5%	1st tier supplier	32	53%
Portugal	1	2%	Focal company	10	17%
Spain	2	3%	<i>Total</i>	60	100%
Sweden	1	2%	Experts' positions		
Switzerland	1	2%	AM engineer	12	20%
United Kingdom	10	16%	AM manager	14	24%
United States	15	25%	Managing director	10	17%
<i>Total</i>	60	100%	Operations manager	11	18%
Company size			Production manager	8	13%
< 50 employees	20	33%	Supply chain manager	5	8%
50–250 employees	12	20%	<i>Total</i>	60	100%
> 250 employees	28	47%			
<i>Total</i>	60	100%	AM applications		
AM processes			Direct part manufacturing	56	39%
Powder bed fusion	50	32%	Rapid prototyping	52	36%
Sheet lamination	4	3%	Rapid tooling	24	17%
Directed energy deposition	12	8%	Maintenance, repair, and overhaul	12	8%
Vat photopolymerization	24	16%	<i>Total</i>	144	100%
Material extrusion	34	23%			
Material jetting	10	7%			
Binder jetting	16	11%			
<i>Total</i>	150	100%			

the same underlying research dimensions (Miles and Huberman 1994). For instance, regarding “Delivery lead time”, the expert explanation “*Producing on site and on demand means no transportation costs and shorter delivery lead times*” was coded as “On-demand manufacturing”, whereas the expert explanation “*There is a lot of post additive work involved, therefore it is not very easy to reduce delivery lead time*” was coded as “Excessive post-processing requirements”. Hence, we managed to summarize the experts’ explanations into manageable units (Miles and Huberman 1994), thereby identifying the AM adoption features and barriers that affect each supply chain state variable. Subsequently, we compared the insights extracted from the experts’ explanations with the existing evidence in the literature to further triangulate our findings (Jack and Raturi 2006).

4 Results and discussion

Table 5 presents the derived scores for the mean and standard deviation (SD) of the Likert scale responses, which are ranked from the highest to the lowest mean score. The extent to which AM adoption affects each supply chain state variable is approximated based on the derived mean scores, which were rounded up/down to the nearest whole number. In the following subsections, the findings for each supply chain state variable are discussed. As noted in Table 5, “Available alternatives for production processes” is measured by three metrics, i.e., “Possibility to outsource production processes”, “Operations versatility”, and “Redundancy in production processes”; hence, for brevity, from this point forward we will mention these metrics when referring to this supply chain state variable.

4.1 Production schedule adaptability

The Likert scale responses yielded the highest mean score for production schedule adaptability. Additionally, the dispersion in the answers was the lowest, indicating the highest level of consensus among the experts. In terms of frequency, this supply chain state variable received the maximum number of “Very high effect” answers. This result confirms the proposition by Naghshineh and Carvalho (2022a) that production schedule adaptability is highly affected by AM adoption.

An expert noted that in AM, “BOM [bill of materials] is first level (raw materials only)”, leading to fewer materials and inventory in the supply chain. This facilitates the adaptability of production schedules due to reduced material handling and packaging, storage and warehousing, and transportation. Moreover, different explanations by the experts, such as “Few changes are required to redeploy the production plans” or “Setup is the same for a variety of parts, especially if AM build designs are already approved”, suggest fast production setup. This AM adoption feature makes production planning easier, especially when considering time and cost factors. The use of digital files (e.g., digital inventory) was also associated with ease in changing production schedules. As one expert explained, “AM is flexible in this respect since you’re working with digital files.” Furthermore, due to tool-less manufacturing in AM, “the ability to change to a new part type can be done quicker than traditional methods” (industry expert). This AM feature mitigates the need for laborious setups and specific production tools, increasing the flexibility of changing production schedules. Overall, the explanations were on par with each other, stating that production planning is relatively easy with AM, especially compared to conventional manufacturing methods.

Nevertheless, one expert explained that “Production planning is relatively easy with 3d printing compared to injection molding or CNC [Computer Numerical Control], but unsteady processes may cause problems.” This finding supports the proposition put forward by Naghshineh and Carvalho (2022a) that “unstable AM processes inhibit the enhancing effect of AM adoption on production schedule adaptability”, mainly due to consequential quality issues, as well as scrap and rework. Production volume is another determining factor. According to one expert, it “Depends on the volumes”. In other words, due to AM’s low throughput rate (i.e., the rate at which parts can be printed traversing the production process from start to finish), adjusting production plans with ease in cases where AM is not used for low production volumes may not be feasible. Moreover, slow production speed exacerbates this situation. As one expert stated, “Builds can take multiple days to finish, so it is not easy to change once the plan is in place.” Excessive post-processing in many AM parts was noted to reduce AM’s agility in changing or modifying the production schedules. Another interesting explanation was that although AM is compatible with Manufacturing Execution Systems (MES), “There is no good MES solution quite yet in the market” (industry expert). This, as an information and communication technology (ICT) inadequacy (Chekurov et al. 2018), inhibits AM’s capability in terms of production planning.

4.2 Delivery lead time

With the third lowest level of dispersion in the Likert scale responses, most experts agreed that delivery lead time is highly affected by adopting AM. According to the explanation, “Producing on site and on demand means no transportation costs and shorter delivery lead times” (industry

Table 5 Quantitative data analysis results

Supply chain state variables	Mean	SD	Extent of AM effect	Rank
Production schedule adaptability	4.04	1.01	High	1st
Delivery lead time	3.78	1.18	High	2nd
Operations versatility*	3.62	1.29	High	3rd
Production capacity slack	3.56	1.21	High	4th
Production lead time	3.52	1.28	High	5th
Relationship type	3.38	1.22	Moderate	6th
Redundancy in production processes*	3.28	1.29	Moderate	7th
Information sharing	3.25	1.47	Moderate	8th
Possibility to outsource production processes*	3.03	1.41	Moderate	9th
Available alternatives for sources of supply	2.69	1.28	Moderate	10th
Available alternatives for production sites	2.48	1.34	Low	11th
Transport mode	2.18	1.63	Low	12th
Distribution channels	1.91	1.07	Low	13th

Cronbach’s $\alpha = 0.86$

*Metrics representing “Available alternatives for production processes”

expert), two important features of AM adoption are the on-demand manufacturing and distributed manufacturing of parts. Through these AM adoption features, production can be relocated closer to customers, which contributes to reducing delivery lead times and transportation costs considerably. As one expert noted, *“Lead times can be a matter of hours.”* Additionally, rapid prototyping via AM reduces the product development cycle time as part of the whole manufacturing process, thereby reducing the delivery lead time of products. *“If we look at the whole process from product development, prototyping and production, AM can significantly reduce delivery lead time”* (industry expert). Apart from rapid prototyping, some experts mentioned the importance of high design freedom in AM. For instance, the explanation *“Some highly complex and time-consuming parts can be produced with AM”* (industry expert) highlights this feature of AM adoption. This feature also facilitates consolidating multiple parts into a single elaborate unit, which in turn expedites delivery lead time. This is evident in the following explanation: *“With AM lead times for products can be reduced due to fewer parts and elimination of many assembly processes”* (industry expert).

However, excessive post-processing was considered a barrier that can prolong the delivery lead time of additively manufactured products. *“There is a lot of post additive work involved, therefore it is not very easy to reduce delivery lead time”* (industry expert).

4.3 Operations versatility

Most answers were marked as “High effect”, with the distribution of answers being slightly dispersed. The flexibility in AM design was regarded as an enhancer of operations versatility by multiple experts, who commonly referred to the high flexibility in altering part designs for improving functionality and performance (e.g., design/part optimization). *“High flexibility and freedom in design provided by AM production”*; *“the flexibility to alter designs and processes to achieve best possible results is very important”*; and *“We are taking advantage of AM design and getting higher functionality of the parts”* are illustrative explanations provided by some experts. Automated manufacturing, as well as tool-less manufacturing, were also mentioned as two interrelated AM features that boost the versatility of operations. *“Increased automation and reduced downtime”* and *“Not having to make a large investment for each product cycle to retool a factory and retrain employees is a very important versatility aspect that an AM factory has”* were two explanations by different experts in this regard. Furthermore, AM presents the opportunity to quickly produce the necessary tools on-site (i.e., rapid tooling), adding to the versatility of operations. *“We are also able to rapidly produce variable tools on site”* (industry expert). Some experts also explained that through rapid prototyping and manufacturing

of parts, temporary solutions can be improvised that allow the production system to reduce downtimes. *“In some cases, it [AM] allows us to create temporary solutions whilst finalizing manufacture using other methods”*; *“The technology provides the flexibility to get prototypes in a fast way and do quick checks”*; or *“AM allows for a lot of versatility: starting with prototyping, product development and going all the way to direct manufacturing of parts”* are illustrative explanations provided by different experts in this respect.

Several explanations highlighted AM's capability of producing different products directly in a single manufacturing step (Holmström et al. 2016). For instance, one expert explained that *“various types of parts can be produced with one process (e.g., we build frames and also axles with MJF [Multi Jet Fusion]. With conventional methods you need sheet bending processes, welding, milling and drilling to produce the same parts)”*. This explanation indicates the possibility of integrating many production processes into a single process using AM. In this case, the number of production steps for most parts is reduced to one, thereby reducing the complexity of operations and making production planning much easier. Along the same lines, part consolidation was also noted, in the sense that with *“direct manufacturing of parts”* (industry expert), it is practicable to decrease the number of components needed to build a final part. According to an expert, *“there is some interest from clients in reducing the number of parts of certain components using AM.”* Another implication raised by some experts was that only few types of raw materials and inventory are needed to produce an additively manufactured part, which in turn increases the versatility of operations. As one expert stated, *“several AM parts are based on the same raw material, so an SLM [Selective Laser Melting] machine could be used for various parts.”*

Regarding barriers, it was noted that it is *“not easy to change materials”* (industry expert). This issue is primarily caused by the lack of multi-material printing (Rayna et al. 2015; Eyers et al. 2018), which in turn requires thorough cleaning of the printer before starting a new build with different materials. This barrier is also mentioned by Eyers et al. (2018), who found material changeovers to be a “labor-intensive task” across all the cases in their study. Moreover, unstable AM processes and slow production speed were noted to inhibit the positive impact of AM adoption on operations versatility. *“Quality measurement systems, several comfort features and fast production updates (e.g., multi laser) are implemented within newer systems, but the investment costs for those machines are too high for small enterprises”* (industry expert). According to this explanation, *“Quality measurement systems”* can mitigate unstable AM processes while *“fast production updates”* can address slow production speed, which are available in newer systems, however, their high acquisition cost may prevent many firms from (re)investing in them.

4.4 Production capacity slack

For this supply chain state variable, most answers were marked as “High effect”, followed by “Very high effect” and “Moderate effect”. Some experts explained that AM can be used to better respond to unpredictable customer demand. “*We change based on customer demands with ease*” and “*Adjusting production capacity can be easily accomplished*” were among such explanations by the experts. These explanations lend support to the statement by Weller et al. (2015) that AM “facilitates the adjustment of production output to meet fluctuating customer demand.” However, it was noted that this can only be done for small batches of products. “*From prototype to small series: Yes; From small series to series: No*” (industry expert). Some explanations referred to the reduced number of operators due to automated manufacturing, implying more flexibility in terms of labor when adjusting production capacity. AM-enabled automation promotes the notion of economies of technology, whereby it is possible to significantly reduce labor (Tuck et al. 2007). Two experts explained that there is a “*Good ratio of machines to operators – 1 operator can service 6–10 machines depending on the duration of the build and production cadence*” and that it is “*Quick and easy to change schedules on a daily basis - small manpower issue*”.

In reference to barriers, one expert noted that it “*Depends on whether changing materials is involved or not*”, implying difficulty in cleaning machines and switching materials before starting a new job. This difficulty is mainly caused by the lack of multi-material printing in AM, which may be why many manufacturers prefer to dedicate a 3D printer to building a specific set of parts that do not require different types of materials and frequent material changeovers. “*Dedicated machines for dedicated products*” (industry expert). Another relevant AM adoption barrier is the limited capacity of the build volumes, which limits the number of parts that can be printed before having to proceed with material recycling and restarting the job, resulting in a low throughput rate. “*Scalability depends on the number of machines installed*” (industry expert). This explanation implies the limited capacity of the build volumes, which requires increasing the number of installed 3D printers to compensate for the low throughput rate. Alternatively, another solution is to increase the utilization rate of 3D printers by adding extra work shifts, which may lead to faster depreciation of the machines and increase maintenance costs. “*Capacity is slow to change, but utilization rate can be changed readily with night/weekend working shifts*” (industry expert). One way or another, these barriers will inhibit the possibility of easily adjusting the production capacity for batch production, which can be elucidated based on the following explanations by the experts: “*Until we reach the maximum capacity of the machines. After that, we may have problems*

with the capacity”; “*Production capacity of AM is limited compared to other high-volume processes*”; and “*As far as I know, 3D printing is not used at the moment for serial production in our sites.*” Lastly, it was mentioned that AM is an expensive production method (especially metal AM), which makes it difficult to increase the production capacity. One reason for this economic infeasibility is the high cost of industrial-grade AM machines, especially when manufacturers are forced to upgrade to newer systems. This was pointed out by an expert who noted that “*New machines allow for a linear growth but are expensive*”.

4.5 Production lead time

The literature emphasizes the significant impact of AM adoption on production lead time (Naghshineh and Carvalho 2022a). Comparably, the experts’ answers indicated that adopting AM highly impacts production lead time. Some experts believed that tool-less manufacturing considerably contributes to reducing production lead time. One expert even attributed AM’s fast production turnaround (i.e., the time to print and post-process a part) to tool-less manufacturing. Along the same lines, fast production setup was mentioned multiple times, which is facilitated by AM’s tool-less nature. Two illustrative explanations by different experts are as follows: “*Quick machine relocation, installation and production startup*” and “*If you have the right AM technologies and proper part design, production startup is fast.*” Moreover, rapid design iterations via AM were noted to decrease production lead time, especially for parts that possess complex geometries. “*Rapid design iteration with additive gets to functional components faster*” (industry expert). This was mainly attributed to rapid prototyping and rapid manufacturing, as these AM features considerably reduce the time required for the design and manufacture of a functional part. “*The big benefit for prototypes, however, is mainly the lower production time*” (industry expert). Additionally, the reduction in the number of required components to produce a final part (i.e., part consolidation) streamlines the whole production process, resulting in faster production lead times. “*Simplified and faster production process due to reduction of parts in subassemblies*” (industry expert). This AM adoption feature, in turn, simplifies the supply chain, especially for parts that possess intricate geometries and are burdensome to manufacture via conventional methods.

However, several experts also explained that reducing the production lead time via AM is dependent on different variables, e.g., the AM process, part complexity, 3D printer model, and post-processing load. For instance, the AM processes used for printing plastic parts entail shorter production lead times than those used for printing metal parts, which need to undergo more stringent post-processing steps such as machining and thermal treatment. “*In plastics it’s*

easy to reduce the production time. But in metals if the end components need surface finishing, e.g., machining, then the production time can be much longer and the machining can be a bottleneck” (industry expert). AM is generally criticized because of its slow production speed. This issue is likely to improve in newer 3D printer models; however, according to some experts, the high cost of frequent upgrades to faster industrial-grade AM machines is a problem. Finally, the present instability in AM processes was considered by several experts to be a determining factor as to whether AM can reduce the production lead time efficiently. This lends empirical support to the proposition by Naghshineh and Carvalho (2022a) that unstable AM processes “can offset the contributions of AM towards reducing production lead times.”

4.6 Relationship type

The Likert scale responses for this supply chain state variable were dispersed rather evenly among different choices, with “Moderate effect” being the most frequent response. Some experts explained that AM enables customer involvement and cooperation in the design and manufacturing stages of products (i.e., co-creation/co-design, consumer-centric production), which is particularly useful for manufacturing complex parts to avoid potential project failures. “High-level cooperation is necessary due to the complexity of the parts we are producing. Each project leads to usually several meetings (kick off, quality review, ...)” (industry expert). Furthermore, close collaboration with suppliers and customers was mentioned multiple times, corroborating the findings of Oettmeier and Hofmann (2016), who state that a cooperative approach among the members of an AM supply chain is necessary for success. “I would note that generally AM companies seem to be more collaborative than many traditional manufacturers” and “In AM you need to understand the whole value chain in more detail and you need to have a good network” were among the explanations provided by different experts, highlighting the importance of close collaboration. Another explanation referred to the high level of competition in the AM markets, which requires a high degree of cooperation between supply chain members to avoid failure. “There’s a lot of competition in the AM market. In order to survive, cooperation is needed” (industry expert). This was further explained by several experts who stated that AM is still young and that many still have doubts about this technology, highlighting the lack of trust as well as consumer awareness and acceptance as important adoption barriers (Durach et al. 2017; Dwivedi et al. 2017). “There are still some doubts regarding AM in many industries that require more cooperation” and “As AM Technology is still young, there is a need for partnership along the supply chain” were among such explanations by the experts. Apart from these barriers, another inhibiting factor is intellectual

property (IP) rights complications, which may arise due to issues concerning proprietary knowledge, licensing, copyrights, patents, or counterfeiting. According to two experts, AM’s adoption effect on the level of cooperation between firms can be “Low due to IP/technology”, and “Proprietary techniques and knowledge reduce some communication within the supply chain”.

4.7 Redundancy in production processes

Most answers were marked as “Moderate effect”, resulting in minor dispersion. Many experts believed that AM adoption is a suitable method for low-volume production (i.e., small batch production) since it does not require various production tools. “We often produce small series of parts that would otherwise require tooling” (industry expert). Hence, AM can be used alongside conventional methods in a hybrid setting, providing extra capacity (Khajavi et al. 2015; Holmström and Partanen 2014). “Allows us to utilize additive for extra capacity” (industry expert). In this way, it would be possible to provide the necessary redundancy in production processes to deal with the variability in demand, particularly for parts with low and sporadic demand, and therefore reduce forecasting efforts. Another option for providing redundancy is to use the extra AM capacity available at external sources (i.e., capacity pooling). As an expert stated, “High flexibility to increase/decrease production by external suppliers.”

However, concerns were expressed regarding the financial viability of AM as an asset for providing redundancy in production processes. Several experts stated that AM machines need to work at full capacity to justify the financial investment made in them. Moreover, some experts explained that investing in AM requires a large amount of capital, mainly due to the substantial cost of industrial-grade AM machines. “Sure, but when owning AM systems, you will have to keep them full to avoid making financial losses” and “scaling capacity would require capital investments which makes it more expensive than equivalent subtractive options” are relevant explanations by two experts illustrating this adoption barrier. Apart from cost implications, technological barriers were also mentioned. AM’s low throughput rate was raised by multiple experts. “AM can be capacity constrained because most of AM processes are designed for small batch production”; “Volume scaling is actually limited with the existing AM equipment”; and “Only possible for low volume production” are explanations by different experts that imply the limited rate at which parts can be printed. This barrier restricts the availability of adequate redundancy in production processes when necessary. Other interrelated barriers were mentioned that exacerbate this situation. For example, one expert noted that “AM is still too slow to produce at high numbers”, indicating that it may

not be a suitable option for providing redundancy in a mass production setting. Currently, few discrepant cases exist that have overcome the slow production speed of AM for mass production (Huang et al. 2021). Besides, it was stated that “switching between materials can be time consuming, especially in metal processes” (industry expert), implying the lack of multi-material printing as a barrier (Eyers et al. 2018; Rayna et al. 2015), which further inhibits AM’s throughput rate. Nevertheless, multiple experts explained that in the foreseeable future, many of these barriers will be overcome as AM technology advances.

4.8 Information sharing

The experts expressed rather different opinions about the impact of adopting AM technology on information sharing. Some explanations corroborated the notion that the easy and inexpensive transmission of designs as digital files (i.e., digital file distribution) empowers real-time distributed manufacturing. It was also noted that the need to store many parts in the form of finished goods inventory is vastly overcome by the ability to store them as digital files instead (i.e., digital inventory). “It’s easy and inexpensive to exchange information to get the parts manufactured. There is no need for physical samples from the clients, unless they require reverse engineering services” (industry expert). Furthermore, it was noted that as a digital technology, AM is compatible with different types of information systems, including MES, Material Requirement Planning (MRP), and Enterprise Resource Planning (ERP), which facilitates information sharing. Additionally, close collaboration and networking between supply chain partners were considered important for information sharing. “Partner network and support is really important in AM” and “Communication between partners is also very important, and good networking is essential in this respect” are two illustrative explanations provided by the experts on this matter.

On the other hand, some experts noted that improvements are necessary to streamline the information flow between different production sites, drawing attention to the importance of establishing adequate means of ICT in AM settings (Chekurov et al. 2018; Priyadarshini et al. 2022). Moreover, potential IP rights complications were mentioned multiple times, referring to the concerns that many companies have over exchanging data with other supply chain entities via unreliable ICT infrastructure. For instance, an expert noted that “Too much is at stake in terms of IP”.

4.9 Possibility to outsource production processes

The dispersion in the answers was relatively high due to contrasting opinions between the experts. Some experts explained that AM grants their companies the opportunity

to outsource production and gain access to extra production capacity via capacity pooling, hence avoiding the high costs of procuring AM machinery and learning how to use them. “Allows us access to extra AM capacity and allows us to grow product applications without needing to have an installed machine base”; “For the last year we have setup a precise plan on how to externalize some production processes in order to save lead time and increase production volume”; and “Easy to increase production capacity via external partners but at a higher cost” are explanations by different experts that illustrate the AM-enabled possibilities for outsourcing production and capacity pooling. In this way, it is possible to focus on activities (other than production) that bring more value to the company.

Despite these advantages, several experts stated that the considerable cost of AM processes can make the outsourcing of production economically unviable. As one expert explained, “On one hand, by outsourcing production, you have the agility to focus on other tasks and staff. Easier to start up and not have a large factory investment. On the other hand, now you are paying someone more money to make your product so that eats away from your profit margin.” Moreover, some experts stated that outsourcing production is not an easy task because it can lead to quality issues, while some others stated that to avoid quality issues and preserve consistency, they would rather produce parts in-house under their own supervision (i.e., insourcing). “Yes, it is very handy to be able to switch to another AM contract manufacturer, but they mostly deliver different quality – even when owning the same machinery type”; “We can outsource our AM printing as long as quality approaches are understood”; and “We are producing all our tooling internally due to the high-quality needs” are some illustrative explanations by the experts in this regard. These explanations correspond to the findings of Dwivedi et al. (2017) regarding the lack of consistency in AM processes, which, according to Naghshineh and Carvalho (2022a, b), is more likely to occur when production is outsourced. This issue is exacerbated by the lack of standardization in AM processes and materials, suggesting why multiple experts mentioned that they would rather keep the AM processes in-house than outsource them, e.g., “Additive is a core in-house process for us, rarely outsourced to maintain consistency and quality” and “We keep our core manufacturing processes in-house”. Also, it was noted that by insourcing AM processes, potential complications regarding IP rights can be avoided since sharing sensitive information (e.g., proprietary designs) with external sources is no longer a requirement.

4.10 Available alternatives for sources of supply

Overall, the effect of AM adoption on this supply chain state variable was perceived as moderate. Many experts explained

that there are still not a lot of AM materials and machine suppliers on the market, which forces them to single-source their materials and equipment. *“There is only a couple of sources of raw material and a few for additive equipment”* (industry expert). However, it was also noted that this issue differs between the AM processes. One expert explained that in plastics, there are more material suppliers, whereas in metal AM, there are fewer qualified suppliers. *“In plastics it’s quite easy to have lots of suppliers. In metals the quality is a defining factor and thus you need to audit and validate the suppliers in more detail”* (industry expert). Along the same lines, some experts commented that there is currently a lack of proven machine suppliers in the AM industry. *“It is hard to qualify more machine suppliers because of the industry space”* and *“Fewer proven equipment manufacturers and support services not yet fully mature for production”* are explanations provided by two different experts regarding this matter. According to the explanations, another relevant barrier that forces manufacturers to single-source (rather than multi-source) is the need for rigorous supplier checks and qualifications to ensure quality standards before proceeding with material/machine acquisition. This is mainly caused by the present lack of regulations and standards governing AM processes and materials (Thomas-Seale et al. 2018; Chekurov et al. 2018). *“Each new supplier/machine/raw material needs to be qualified extensively before starting the manufacturing of parts”* (industry expert). However, according to some experts, this problem is expected to improve over time as the AM market matures. Last but not least, the high cost of AM materials and industrial-grade AM machines were mentioned as two other adoption barriers that limit the number of potential supply sources.

4.11 Available alternatives for production sites

Most answers were either “Low effect” or “Very low effect”, averaging to “Low effect”. Some experts believed that distributed AM is groundbreaking as it grants manufacturers access to backup production sites and facilities at different locations, especially near the point of consumption, corroborating the findings of Durão et al. (2017) and Zanoni et al. (2019). *“Having a backup plant for additional capacity is fairly easy to setup”* (industry expert). Along the same lines, the notion of mobile manufacturing was implied. Mobility in the context of manufacturing is “the ability to change between geographically different places with little penalty in time, effort, cost, or performance” (Stillström and Jackson 2007). *“At the cost of a printer and few other ancillary equipment, production can be set up almost anywhere”* (industry expert). Moreover, emphasis was placed on the possibility of outsourcing production, as well as pooling the available AM capacity at other production sites. Accordingly, one expert explained that *“AM is becoming more*

mainstream and there is a good chance a company can have alternative production options.”

In contrast, some experts stated that having access to specialized infrastructure is important for establishing alternative production sites through AM. They particularly noted that the availability of a reliable utility infrastructure is necessary because AM is an energy-intensive technology.

4.12 Transport mode

The mean score for transport mode was low, with the maximum dispersion in the answers, indicating contrasting opinions among the experts. Several experts commented that in AM supply chains, the transportation of parts normally takes place last mile, hinting at close distances between the distribution centers and customers. This was mainly attributed to the distributed manufacturing configurations where production takes place near the point of consumption, e.g., at the distribution centers, therefore reducing the need for long-haul transportation. In addition, an expert noted that *“The supply chain is digital”*, making it possible to store and distribute files digitally for on-site manufacturing instead of warehousing and transporting physical inventory. It was further explained that these AM features will lead to fewer materials and inventory in the supply chain. This would, in turn, make it easier to use “different transportation modalities” (Verboeket and Krikke 2019). *“Easy to use multiple transportation methods”* (industry expert). Moreover, it was noted that by equipping vehicles with 3D printers, parts can be manufactured en route to the point of consumption, corroborating the notion of mobile manufacturing via AM. Another interesting explanation was that since AM is normally used for low-volume production (i.e., small batch production), many manufactured parts can be shipped via normal courier services. *“Because of the low volumes, AM products can be dispatched with typical services like FedEx”* (industry expert). This ease in terms of transport mode may explain why some answers were marked as “Very high effect”, accompanied by explanations such as *“Many alternatives for transportation are available”* (industry expert). At the same time, multiple explanations did not concur with the idea that AM is any different from conventional methods in terms of transportation. Only in one case, it was noted that the transportation of hazardous powders may be slower. As for potential barriers, no specific explanations were provided by the experts.

4.13 Distribution channels

This supply chain state variable received the largest number of “Very low effect” and the fewest number of “Very high effect” responses. Some experts explained that in AM, parts are normally produced in small batches, leading to fewer materials

and inventory in the supply chain, which facilitates distribution. In contrast, some experts mentioned that it is rather expensive and difficult to switch between distribution channels. This was mainly attributed to the considerable cost of AM processes and the lack of AM process standards. One expert explained that “*It is very expensive to setup a new process; therefore, it is very difficult to move production to a new distribution channel*”, whereas another expert explained that “*Approvals, audits and qualification for additive parts are much slower than subtractive so switching industries e.g., defense to civil aerospace or medical is highly difficult.*” Overall, AM technology adoption was not considered to have a considerable effect on the ease of switching between distribution channels, and even some experts believed that the same distribution principles that apply to other manufacturing methods apply to AM as well.

5 Research implications

Drawing on the survey results, a comprehensive framework is put forward that indicates to what extent and how AM technology adoption affects the state of the supply chain (see Fig. 2). The AM adoption features and barriers outlined in this framework and their effects on the supply chain’s state have already been discussed thoroughly in Sect. 4. Since this framework is based on empirical insights derived from industries that use various AM processes for different applications (see Table 4), it provides a holistic view of the subject matter. Based on these findings, we put forward the following propositions that reflect the theoretical implications of this exploratory research.

Proposition 1 *AM technology adoption highly affects the lead times and management policies in the supply chain, mainly due to features that help reduce the time and cost of adjusting production schedule and capacity, as well as providing alternatives for production processes via enhanced operations versatility, redundancy in production processes, and the possibility to outsource production processes. However, various adoption barriers still inhibit this effect.*

Proposition 2 *AM technology adoption moderately affects the relational links and information flow in the supply chain, mainly due to features that promote the degree of cooperation and information sharing among supply chain members. However, some adoption barriers, such as IP rights complications and ICT inadequacies, inhibit this effect.*

Proposition 3 *AM technology adoption moderately affects the supply chain entities, mainly due to features that contribute to increasing the number of alternative production sites. However, several existing barriers limit the number of alternative supply sources, thereby inhibiting this effect.*

Proposition 4 *AM technology adoption affects the material flow in the supply chain to a lesser extent, mainly because of features that facilitate the use of alternative transport modes and distribution channels. However, some adoption barriers currently inhibit this effect.*

In these propositions, the estimations concerning the extent to which AM technology adoption affects the main supply chain dimensions are derived based on the average score of their related supply chain state variables (see Table 5). Given these estimations, the overall effect of AM technology adoption on the supply chain’s state is moderate, which would in turn moderately affect supply chain resilience. This is in line with the findings of Durach et al. (2017), who stated that some of the expected supply chain impacts of AM adoption are unlikely to fully materialize and that “AM is therefore better understood as a groundbreaking technology rather than a disruptive technology that changes supply chains as we know them.” However, as AM advances over time, the inhibiting effects of the identified adoption barriers are expected to decrease, thereby increasing AM’s adoption effect on the supply chain’s state and resilience.

Proposition 5 *Overall, AM technology adoption is expected to have a moderate effect on the state of the supply chain and its resilience. This effect tends to intensify over time as adoption barriers gradually dissipate.*

Considering practical implications, the proposed framework can be used by practitioners as well as academics who aim to further analyze the supply chain effects of AM technology adoption. This framework is particularly useful for investigating the potential supply chain resilience outcomes of AM technology adoption, as it utilizes supply chain state variables that are primarily defined for assessing supply chain resilience (Carvalho et al. 2012, 2022). The most frequently noted AM adoption features in the framework are distributed manufacturing (empowered by digital inventory and digital file distribution), small batch production, tool-less manufacturing, and fewer materials and inventory, followed by part consolidation, rapid prototyping, and capacity pooling. In other words, when considering the significant changes that take place in the supply chain’s state (and consequently resilience), these AM adoption features are likely to be more influential than others. Likewise, the most frequently mentioned AM adoption barriers in the framework are slow production speed and high cost of industrial-grade AM machines, followed by excessive post-processing requirements, unstable AM processes, lack of multi-material printing, low throughput rate, lack of AM process standards, and IP rights complications. Furthermore, as noted throughout Sect. 4, interrelations exist between these adoption features/barriers that can considerably increase/decrease the extent of AM’s impact on the supply chain’s state. For instance, AM’s design freedom enables

Additive Manufacturing Technology Adoption			State of the Supply Chain		
Adoption features	Inhibited by	Adoption barriers	Metrics	Supply chain state variables	Supply chain dimensions
On-demand manufacturing Distributed manufacturing Rapid prototyping Design freedom Part consolidation	Inhibited by	Excessive post-processing requirements	→ Ease (in terms of cost) of reducing delivery lead time	Delivery lead time	Lead times
Tool-less manufacturing Fast production setup Rapid prototyping Rapid manufacturing Part consolidation	Inhibited by	Excessive post-processing requirements Slow production speed High cost of industrial-grade AM machines Unstable AM processes	→ Ease (in terms of cost) of reducing production lead time	Production lead time	
Fewer materials and inventory Fast production setup Digital inventory Tool-less manufacturing	Inhibited by	Unstable AM processes Low throughput rate Slow production speed Excessive post-processing requirements ICT inadequacies	→ Ease (in terms of cost and time) of changing the production schedules	Production schedule adaptability	Management policies
On-demand manufacturing Small batch production Automated manufacturing Economies of technology	Inhibited by	Lack of multi-material printing Limited build volumes Low throughput rate High cost of AM processes High cost of industrial-grade AM machines	→ Ease (in terms of cost and time) of adjusting the production capacity	Production capacity slack	
Design freedom Automated manufacturing Tool-less manufacturing Rapid tooling Rapid prototyping Temporary solutions Process integration Part consolidation Fewer materials and inventory	Inhibited by	Lack of multi-material printing Unstable AM processes Slow production speed	→ Operations versatility	Available alternatives for production processes	
Small batch production Tool-less manufacturing Hybrid manufacturing Capacity pooling	Inhibited by	High cost of industrial-grade AM machines Low throughput rate Slow production speed Lack of multi-material printing	→ Redundancy in production processes		
Capacity pooling Outsourcing production	Inhibited by	High cost of AM processes Lack of AM process standards Lack of AM materials standardization IP rights complications	→ Possibility to outsource production processes		
Consumer-centric production Co-creation/co-design Close collaboration	Inhibited by	Lack of trust in AM Lack of consumer awareness and acceptance IP rights complications	→ The degree of cooperation with other firms in the supply chain	Relationship type	Relational links
Digital file distribution Distributed manufacturing Digital inventory Close collaboration	Inhibited by	ICT inadequacies IP rights complications	→ Ease (in terms of cost and time) of exchanging reliable and timely information with SC partners	Information sharing	Information flow
(No specific features were found)	Inhibited by	Limited variety and supply of AM materials Limited supply of industrial-grade AM machines Lack of AM materials standardization Lack of AM process standards High cost of AM materials High cost of industrial-grade AM machines	→ Number of available alternatives for sources of supply	Available alternatives for sources of supply	Supply chain entities
Distributed manufacturing Mobile manufacturing Outsourcing production Capacity pooling	Inhibited by	Lack of specialized production infrastructure	→ Number of available alternatives for production sites	Available alternatives for production sites	
Distributed manufacturing Digital file distribution Digital inventory Fewer materials and inventory Mobile manufacturing Small batch production	Inhibited by	(No specific barriers were found)	→ Number of available alternatives for transporting goods and material	Transport mode	Material flow
Small batch production Fewer materials and inventory	Inhibited by	High cost of AM processes Lack of AM process standards	→ Ease (in terms of cost and time) of switching between distribution channels	Distribution channels	
Note:		Yellow cells = Slightly affected		Green cells = Moderately affected	Blue cells = Highly affected

Fig. 2 Empirical framework (see the online version for colors)

part consolidation, leading to fewer materials and inventory across the supply chain. This will, in turn, decrease the supply chain's complexity by decreasing supply chain layers (Ivanov et al. 2019), hence simplifying its state and structural dynamics (i.e., a positive trigger of supply chain structural dynamics (Dolgui and Ivanov 2020)). As a consequence, this change in the supply chain's state would positively affect supply chain resilience. As for AM adoption barriers, an illustrative example is the lack of multi-material printing, which necessitates material changeovers to manufacture different parts, thereby reducing the throughput rate. This will negatively affect the ease with which production capacity can be adjusted (i.e., reduced production capacity slack), making it more difficult to meet customer demands on time (i.e., increased supply chain vulnerability to unpredictability in customer demand), which as a result negatively affects supply chain resilience (Naghshineh and Carvalho 2022a, b). Therefore, gaining thorough knowledge about the AM adoption features and barriers in the proposed framework can help managers and practitioners make informed decisions about adopting this technology and its ensuing effects on the supply chain's state, which, in turn, will influence supply chain resilience.

This study was specifically designed to close the gap between theoretical insights and practical applications in the context of AM technology adoption and its effects on the state of the supply chain. The exploratory nature of the research enabled the collection of quantitative and qualitative empirical data directly from experts with knowledge of AM technology adoption across various industry sectors. This approach was deliberately chosen to capture a wide range of real-world perspectives and experiences, ensuring the findings are grounded in actual industry practices. Moreover, the developed empirical framework serves as a practical tool for managers and industry practitioners, outlining the key AM adoption features and barriers and their effects on the state of the supply chain. This framework is not only theoretically robust but also designed to be actionable, helping managers and decision-makers to assess and optimize their supply chains with a focus on enhancing resilience through informed AM adoption. By incorporating insights from industry experts, this research offers valuable guidance for practitioners on navigating the complexities of AM adoption, highlighting specific areas where attention is needed to mitigate potential barriers and leverage the technology's full potential to enhance supply chain resilience.

6 Conclusion and future work

In this exploratory research, we aimed to investigate AM's adoption effects on the supply chain's state while taking on a resilience perspective. To this end, we conducted an exploratory survey among experts working for companies in various industries that use a diverse range of AM processes for

different applications (see Table 4). Using Likert scale questions, we assessed the experts' perceptions of the extent to which AM adoption affects different supply chain state variables, which are primarily used for assessing supply chain resilience (Carvalho et al. 2012, 2022), thus addressing RQ1. Moreover, we asked the experts to provide an explanation for each question, thereby enhancing the credibility of the Likert scale responses. We extracted meaningful insights from the explanations to clarify how AM adoption affects each supply chain state variable. More specifically, we identified and explained the adoption features and barriers that collectively define how AM technology affects the supply chain's state, thereby addressing RQ2. Subsequently, we discussed our findings and put forward propositions, which highlight the theoretical implications of this exploratory research. Given the scarcity of empirical research, these propositions provide an agenda for future research to further investigate the subject matter. Additionally, we put forward an empirical framework (Fig. 2), partly validating the conceptual framework by Naghshineh and Carvalho (2022a). This empirical framework may serve as a point of reference for practitioners and academics who intend to further look into AM's adoption effects on the supply chain's state and its consequences for supply chain resilience.

In summary, in this study, we overcame an important empirical research gap, contributing to a more profound understanding of AM's adoption implications for supply chain resilience. While a handful of empirical studies, such as Belhadi et al. (2022), have examined the effects of AM on supply chain resilience, none have delineated to what extent and how adopting this technology affects the supply chain's state, which is essential for a thorough assessment of supply chain resilience outcomes (Carvalho et al. 2012, 2022). Although, Naghshineh and Carvalho (2022a) drew attention to this empirical research gap, no study provided comprehensive results aimed at overcoming it.

In terms of limitations, this study aimed to identify experts with first-hand experience in the AM field across various industries, including aerospace, automotive, medical, and energy. Our motive for doing this was to address the RQs using empirical data derived from a heterogeneous sample of experts working in these industries, as they are at the forefront of AM technology adoption (Wohlers 2021). Hence, to obtain a research sample composed of such experts, who are difficult to find through probability sampling techniques, we resorted to expert sampling via the LinkedIn professional network platform, which may have compromised the representativeness of the sample. To ensure the sample was representative of the aforementioned industries, we benchmarked its descriptive analyses against the Wohlers (2021) report, which revealed a high level of similarity. It is worth noting that the "diverse range of participants and companies" in the sample may have contributed to yielding "more robust findings and

a more in-depth understanding of the subject” (Belhadi et al. 2022). Moreover, as the companies in the sample belong to developed countries, this study addresses the call for research by Belhadi et al. (2022) regarding the “exploration of AM technology adoption in developed nations”, particularly when considering the subject matter from a resilience perspective. Nevertheless, the propositions put forward in this exploratory study are open to further investigation. Hence, to validate their generalizability, we recommend that future research conduct large-scale surveys and employ different quantitative/qualitative methods to analyze the data. Alternatively, case studies could be carried out that focus on industry-specific AM processes and applications to compare their results with this study and refine the propositions contextually. While we drew on the supply chain state variables employed by Naghshineh and Carvalho (2022a), future research can expand upon our findings by incorporating a broader range of supply chain state variables. Additionally, future research can examine the relative importance of supply chain state variables within specific contexts and assign weights to each variable accordingly. This may result in different estimations of the AM’s adoption effects on the supply chain’s state. Last but not least, longitudinal research can examine the veracity of the findings over time, especially as AM technology advances and the barriers to its adoption gradually diminish.

Appendix

The questionnaire can be found at the Open Science Forum (OSF) using the following web link: https://osf.io/gyx25/?view_only=2e6c56227f1f4b4e9c527a093c0dcd78.

Acknowledgements The first author acknowledges the Portuguese Foundation for Science and Technology (FCT–MCTES) for its financial support via the Doctoral grant PRT/BD/152828/2021 under the MIT Portugal Program. The second author acknowledges FCT–MCTES for its financial support via the project UID/00667 (UNIDEMI).

Funding Open access funding provided by FCTIFCCN (b-on).

Data availability The participants of this study did not give written consent for their data to be shared publicly, so due to the sensitive nature of the research supporting data is not available.

Declarations

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

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