NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTAMENT OF MECHANICAL AND
INDUSTRIAL ENGINEERING

THE IMPLICATIONS OF ADDITIVE MANUFACTURING TECHNOLOGY ADOPTION FOR SUPPLY CHAIN RESILIENCE

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The Implications of Additive Manufacturing Technology Adoption for Supply Chain Resilience

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“Success is not final; failure is not fatal: It is the courage to continue that counts.”
(Winston S. Churchill).

ABSTRACT

As an emerging digital technology, the adoption of additive manufacturing is changing supply chains around the world, affecting their ability to cope with supply chain vulnerabilities. The ability of a supply chain to be resilient against vulnerabilities is crucial for business continuity. However, to date, no empirical study has extensively investigated how additive manufacturing technology adoption affects supply chain resilience by changing the state of the supply chain. Hence, the focus of this study is to investigate this knowledge gap by taking advantage of a multimethod research design while drawing on the dynamic capabilities view as its theoretical lens.

This research investigates how additive manufacturing technology adoption affects the state of the supply chain, consequently affecting the supply chain capabilities and vulnerabilities that underlie the concept of supply chain resilience. It also aims to explore resilience practices in the context of additive manufacturing technology adoption that help build the necessary supply chain capabilities for dealing with supply chain vulnerabilities, thus improving supply chain resilience. First a systematic literature search and critical review of 87 peer-reviewed journal articles was carried out, leading to the generation of propositions and subsequently the conception of a comprehensive conceptual framework that together illustrate the explicated relationships between the main research variables, i.e., additive manufacturing adoption, state of the supply chain, and supply chain capabilities and vulnerabilities that underlie supply chain resilience. Subsequently, empirical research comprised of an exploratory survey in different industries at the forefront of additive manufacturing technology adoption, as well as a case study of a leading Original Equipment Manufacturer that uses metal additive manufacturing, were carried out. Hence, relevant propositions and frameworks based on empirical data were put forward, identifying how and to what extent additive manufacturing adoption affects different supply chain state variables as well as resilience practices for building supply chain capabilities that are necessary to decrease supply chain vulnerabilities, consequently increasing supply chain resilience.

While the overall results suggest that adopting additive manufacturing adoption is expected to improve supply chain resilience by enhancing the state of the supply chain and positively affecting certain supply chain capabilities, it can also cause certain supply chain vulnerabilities to arise, which seem to be interrelated with some of the existing adoption barriers of this technology. In particular, the results suggest that production schedule adaptability is the supply chain state variable that tends to be affected the most and that additive manufacturing technology adoption greatly enhances the ability of the adopting firm to change its production schedules.

Keywords: Additive manufacturing technology adoption; Supply chain state; Supply chain capabilities; Supply chain vulnerabilities; Supply chain resilience; Resilience practices; Dynamic capabilities view; Exploratory research

RESUMO

A adoção da tecnologia digital de manufatura aditiva está a transformar a capacidade das cadeias de abastecimento serem resiliente face às vulnerabilidades. No entanto, até o momento, nenhum estudo empírico investigou extensivamente como a adoção da tecnologia de manufatura aditiva altera o estado da cadeia de abastecimento e, portanto, como afeta a sua resiliência. Este trabalho pretende abordar esta lacuna de conhecimento fazendo uso de uma abordagem de investigação que contempla múltiplos métodos e usa a teoria das capacidades dinâmicas como lente teórica.

Este trabalho investiga como a adoção da tecnologia de manufatura aditiva afeta o estado da cadeia de abastecimento, consequentemente afetando as suas capacidades e vulnerabilidades que suportam a sua resiliência. Também visa explorar as práticas de resiliência que no contexto da adoção de tecnologia de manufatura aditiva permitem desenvolver os recursos necessários para lidar com as vulnerabilidades da cadeia de abastecimento. Primeiro, foi realizada uma revisão sistemática da literatura, complementada por uma revisão crítica de uma amostra de 87 documentos. Este processo permitiu propor um conjunto de proposições e, posteriormente, desenvolver uma *framework* que contém as relações entre as principais variáveis de em estudo, ou seja, adoção da manufatura aditiva, variáveis de estado da cadeia de abastecimento, suas capacidades e vulnerabilidades. Posteriormente, foi realizado um estudo empírico composto por uma investigação exploratória em diferentes indústrias, assim como por um estudo de caso de um fabricante de equipamentos originais que utiliza a tecnologia de manufatura aditiva. Usando os dados empíricos, proposições e *frameworks* são propostas de modo a identificar como e em que medida a adoção da manufatura aditiva afeta as variáveis de estado da cadeia de abastecimento, bem como quais as práticas de resiliência que permitem desenvolver capacidades dinâmicas que diminuem as vulnerabilidades, consequentemente aumentam sua resiliência.

Os resultados sugerem que a adoção da manufatura aditiva permite melhorar a resiliência da cadeia de abastecimento, afetando positivamente algumas das suas capacidades. No entanto, a adoção desta tecnologia também pode causar vulnerabilidades na cadeia de abastecimento, que parecem estar inter-relacionadas com algumas das atuais barreiras à adoção da manufatura aditiva. Os resultados sugerem que a adaptabilidade na calendarização da produção é a variável de estado da cadeia de abastecimento mais afetada e, portanto, a adoção da tecnologia de manufatura aditiva suporta um conjunto de práticas de resiliência relacionadas com esta variável.

Palavas chave: Adoção da manufatura aditiva; Estado da cadeia de abastecimento; Capacidades da cadeia de abastecimento; vulnerabilidades da cadeia de abastecimento; Resiliência da cadeia de abastecimento; Práticas de resiliência; Teoria das capacidades dinâmicas; Investigação exploratória.

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ACRONYMS

3D	Three-dimensional
3PL	Third-party Logistics
AM	Additive Manufacturing
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
CM	Conventional Manufacturing
CNC	Computer Numerical Control
DCV	Dynamic Capabilities View
DMLS	Direct Metal Laser Sintering
ERP	Enterprise Resource Planning
FGI	Finished Goods Inventory
ICT	Information and Communications Technology
IP	Intellectual Property
MES	Manufacturing Execution Systems
MJF	Multi Jet Fusion
MRP	Material Requirement Planning
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PLS	Partial Least Squares
RQ	Research Question
RG	Research Goal
RVB	Resource-based View
SC	Supply Chain
SCM	Supply Chain Management
SCR	Supply Chain Resilience
SEM	Structural Equation Modeling
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

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INTRODUCTION

1. Motivation

As an emerging digital technology, additive manufacturing (AM), also known as 3D printing, rapid manufacturing or direct digital manufacturing among others, is changing the way firms manage their supply chains (SCs). AM is considered to be a manufacturing technology that digitizes SCs (Verboeket & Krikke, 2019). It uses data from three-dimensional (3D) computer-aided design (CAD) models to directly create objects via the incremental addition of materials, without the penalties inherent in conventional manufacturing, and thereby offers considerable opportunities for manufacturing as well as supply chain management (SCM) practices (Khajavi et al., 2014; Naghshineh et al., 2023; Torres et al., 2019). Hence, AM is believed to have the potential to cause significant changes in SCs (Holmström et al., 2010; Waller & Fawcett, 2014). For instance, AM can alter the focus of the SC from a push production strategy towards a pull strategy, making the SC more responsive to sudden changes and customer demands (Christopher & Ryals, 2014). That is why many firms around the world are currently utilizing AM to swiftly produce the essential parts on demand to mitigate the SC delays caused by the COVID-19 pandemic (Kunovjanek & Wankmüller, 2020). For instance, www.Formlabs.com has launched a support network by pooling multiple 3D printers to address the critical shortage of medical parts. An initiative like this will influence the resilience of the SC to vulnerabilities (Verboeket et al., 2021). This is just an example of how adopting AM technology stimulates new SC configurations, affecting and altering the state of the SC and its ability to cope with SC vulnerabilities and disruptions.

Resilience in SCs is vital for business continuity and preparing for unforeseen disruptions such as the recent COVID-19 pandemic, which has hindered the operations of many SCs around the world, causing them to sustain heavy financial losses (Ivanov, 2020). This instance proves that SCs need to be resilient against SC disruption vulnerabilities and be able to rapidly restore their operations with minimal loss. A concise definition for supply chain resilience (SCR) is the ability of an SC to cope with unexpected disruptions caused by SC vulnerabilities (Carvalho et al., 2012a). SCs are often vulnerable to numerous disruptions such as the aforementioned COVID-19 pandemic, and their effects are quite detrimental if compounded and not dealt with promptly. The frequent occurrence of such disruptions has created a notable interest in SCR (Pettit et al., 2013), as endeavors to deal with them via traditional risk management techniques have become inadequate (Jüttner & Maklan, 2011). SCR allows firms to maintain their normal operations even when disruptions take place (Carvalho et al., 2012a). Hence, it is sound to reason that SCR is of great importance to many firms to continue their business under such erratic conditions around the world (Ribeiro & Barbosa-Povoa, 2018). The latter statement explains why SCM has become vastly cognizant of SCR and has taken great interest in developing SC capabilities (Ponomarov & Holcomb, 2009; Pettit et al., 2010). This is the case as SC capabilities are the necessary antecedents of SCR, and are essential for mitigating SC vulnerabilities (Tang & Tomlin, 2008; Ponomarov & Holcomb, 2009; Pettit et al., 2010; 2013).

SCR is a multidimensional construct that is operationalized through different SC capabilities (Chowdhury & Quaddus, 2017; Carvalho et al., 2022). While, there is no consensus over a unique set of SC capabilities that constitute SCR, the majority of scholars consider flexibility, adaptability, redundancy, collaboration, visibility, capacity, and information sharing as the main antecedent SC capabilities that constitute SCR (Hohenstein et al., 2015). SC capabilities are considered to be essential elements of SCR that lead to enhancements in the performance of the firm when dealing with SC vulnerabilities and imminent disruptive events (Hosseini et al., 2019; Pettit et al., 2019). SC vulnerabilities are considered to be factors that make a firm vulnerable to disruptions, whereas, SC capabilities enable a firm to foresee and overcome disruptions (Pettit et al., 2010). Therefore, SC capabilities determine to what extent a SC is resilient to SC vulnerabilities (Han et al., 2020). In this sense, the existing set of capabilities and vulnerabilities in an SC projects its level of resilience (Pettit et al., 2019).

Relevantly, emerging Industry 4.0 technologies can be adopted to enhance SC capabilities (Ivanov et al., 2019). Among these technologies, the adoption of AM technology affects the state and structural dynamics of the SC (Dolgui & Ivanov, 2020), therefore influencing their ability to deal with vulnerabilities and disruptions, i.e., SCR (Ivanov et al., 2019). In their research, Durach et al. (2017) point out that the adoption of AM technology by various industries for different applications, namely prototyping, production tooling, parts production, and spare parts production, affects SCR. However, it is not yet evident how AM adoption affects the state of the SC, and how the subsequent changes in the state of the SC can affect the SC capabilities and SC vulnerabilities that underlie SCR (Pettit et al., 2010; 2013; Kochan & Nowicki, 2018). Durach et al. (2017) also emphasize the existing barriers that inhibit the widespread adoption of AM technology. The inhibiting effects of these barriers play an important role in determining the extent to which AM adoption affects the state of the SC (Durach et al., 2017; Verboeket & Krikke, 2019), consequently influencing SCR as well. Hence, it is important to understand their relevance in the context of AM technology adoption and SCR.

2. Research gap

Considering the potential implications that AM technology adoption can prompt for SCs, there is still a lack of empirical studies and most of the academic research regarding this knowledge area is conceptual and limited to predictions (Durach et al., 2017; Iftikhar 2022). More specifically, an important implication of AM technology adoption that has not been empirically investigated in the SC context is resilience (Ali & Gölgeci, 2019; Ivanov & Dolgui, 2020), which serves to be the underlying motivation of the present study.

The importance of AM adoption and its implications for SCR are explicitly highlighted in the works of Ali and Gölgeci (2019) as well as Ivanov and Dolgui (2020), who call for empirical research in this regard. Nevertheless, to date, the existing literature falls short of empirical research that can address this knowledge gap in a comprehensive manner. While works such as Verboeket and Krikke (2019) and Kunovjanek et al. (2020) identify the disruptive effects of AM adoption on SCs via literature reviews, or Durach et al. (2017) and Zanoni et al. (2019) take a step further and use empirical evidence to study the subject matter, none clearly specify how such effects can influence SCR. Also, there may be a limited number of empirical studies in extant literature such as Delic and Eyers (2020) who investigate the effects of AM adoption on a certain SC capability, e.g., SC flexibility, but not SCR.

To the best of our knowledge, no empirical research has yet comprehensively addressed the implications of AM adoption for SCR as a higher-order construct that is comprised of different SC capabilities and SC vulnerabilities. Just in a recent work, Naghshineh and Carvalho (2020) proposed a research model comprised of different SC capabilities for conducting empirical research. However, the proposed model in their work was only based on different SC capabilities that AM adoption would affect and did not consider different SC vulnerabilities as underlying variables that together with SC capabilities define SCR (Pettit et al., 2010, 2013). Thus, this study aims to fill this research gap.

3. Research questions

Given the mentioned considerations, we aim to investigate the implications of AM adoption for SCR based on the underlying postulate that AM adoption affects the state of the SC, which can be indicated by different SC state variables (Carvalho et al., 2012b; 2022). Considering the impacts (i.e., direct effects) of AM adoption on the state of the SC, as well as considering the adoption barriers that inhibit such impacts (Durach et al., 2017), we will analyze the implications (i.e., indirect effects) of AM adoption for SCR based on the notions of SC capabilities and SC vulnerabilities, which define SCR (Pettit et al., 2010; 2013; 2019; Kochan & Nowicki, 2018).

Furthermore, to contribute to SCM and outline the managerial implications of AM technology adoption for SCR, we also aim to examine resilience practices, particularly the ones that tend to be more effective in the context of AM technology adoption. More specifically, AM-enabled resilience practices aimed at enhancing SC capabilities and subsequently decreasing SC vulnerabilities will be explored. For instance, it is noted that AM enables the distributed manufacturing of products in locations closer to consumers (e.g., localized manufacturing/on-site manufacturing), thus allowing the adopting firm to reduce its delivery lead time (Durão et al., 2017). From an SCR perspective, reducing the delivery lead time is a resilience practice that improves SC responsiveness (Carvalho et al. 2022), which as an SC capability helps the adopting firm to deal with different SC vulnerabilities such as unpredictability in customer demands, therefore enhancing SCR (Naghshineh and Carvalho 2022a). In light of such opportunities, SCM would be willing to invest the firm's limited resources in AM-enabled resilience practices that help the firm to build the necessary SC capabilities against SC vulnerabilities, and therefore enhance SCR (Mellor et al. 2014; Pettit et al. 2019). This is supported by Balakrishnan and Ramanathan (2021) who posit that the use of digital technologies such as AM "influences the resilience practices in a firm's supply chain operations", as well as Zouari et al. (2020) who posit that adopting digital technologies such as AM improves the SC capabilities necessary to enhance SCR. However, to date, no empirical study has focused on comprehensively investigating the effects of AM technology adoption on SC capabilities as well as SC vulnerabilities that underlie SCR while considering the role of resilience practices.

Hence, we aim to overcome these knowledge gaps by addressing the following main RQs:

- **RQ1**. How does AM technology adoption affect the state of the SC?
- **RQ2**. Which barriers inhibit the effects of AM technology adoption on the state of the SC?
- **RQ3**. How does AM technology adoption influence different SC capabilities and SC vulnerabilities that underlie SCR?
- **RQ4**. What resilience practices enhance SCR in the context of AM technology adoption?

In light of these considerations, the main research goals (RG) of this PhD are as follows:

RG1. Contribute to the state of the art by understanding and conceptualizing how AM technology adoption affects the state of the SC and consequently the SC capabilities and vulnerabilities that underlie SCR.

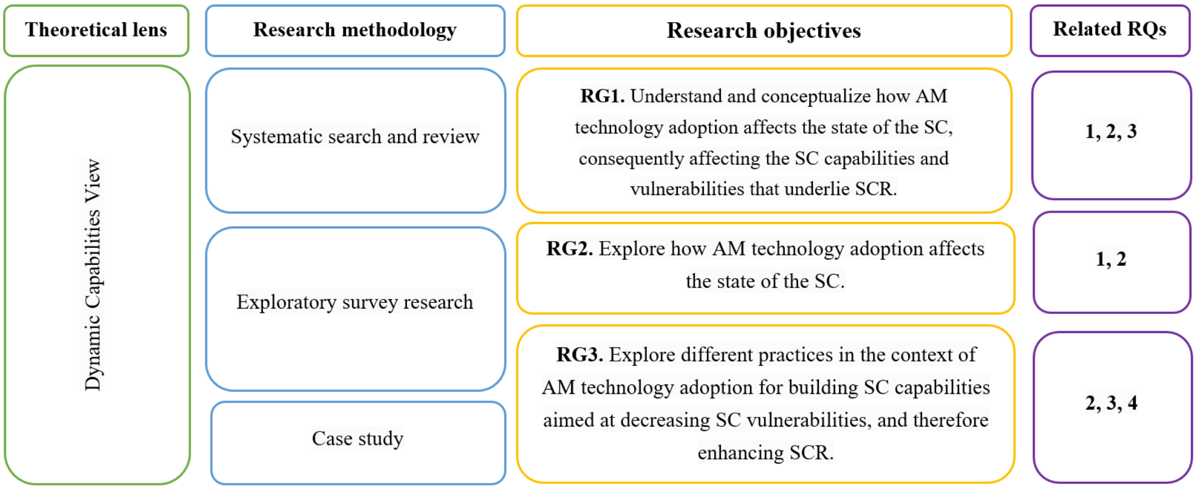
RG2. Conduct empirical research to explore how AM technology adoption affects the state of the SC.

RG3. Conduct empirical research to explore different practices in the context of AM technology adoption for building SC capabilities aimed at decreasing SC vulnerabilities, and therefore enhancing SCR.

4. Research approach

Considering the lack of empirical research and evidence in the existing literature regarding the subject matter, this research is exploratory in nature. Exploratory research is particularly useful at the early stages of research into nascent subject areas, e.g., SC digitalization and its ensuing implications for SCR (Iftikhar et al., 2022), whereby the main goal is to lay out the foundation for future research, mainly by putting forward testable propositions and frameworks (Flynn et al. 1990; Forza, 2002). This is in accord with Flynn et al. (1990) who stress the need for exploratory research in laying out the foundation for future explanatory research. Moreover, as currently at the intersection of digital technology adoption, particularly AM technology adoption, and SCR management, "many past studies are still conceptual and lack empirical corroboration" (Iftikhar et al. 2022), a multimethod exploratory research design was employed whereby different research methodologies (i.e., systematic search and critical review, exploratory survey, and case study) were used to address the RQs, thereby establishing methodological triangulation (Jack & Raturi, 2006).

The theoretical lens through which the subject matter is viewed is based on the Dynamic Capabilities View (DCV). In line with the aim of this study, we draw on DCV to identify the AM-enabled resilience practices that the adopting firm needs to exercise in order to build the SC capabilities required to deal with SC vulnerabilities, hence enhancing SCR. This theoretical lens becomes particularly relevant when dealing with studies at the intersection of technology adoption and SCR management (Ponomarov and Holcomb, 2009; Belhadi et al., 2022). More specifically, DCV emphasizes the capability of a firm to proactively acquire the necessary resources (e.g., technology) to deal with the dynamic nature of the markets and SCs in which it operates (Teece, 1997). In this view, concepts such as AM technology adoption and SCR become quite relevant as they are closely related to dealing with the constant changes that take place in the SCs that can cause disruption vulnerabilities (Belhadi et al., 2022). Hence, resilient companies tend to look for practices and knowledge that allow them to promote SCR in the face of imminent disruption vulnerabilities, and thus look beyond the so-called static resource-based view (RBV), whereby only accumulating resources without paying close attention to the existing volatility and turbulence in SCs would not necessarily lead to a sustainable competitive advantage over time (Eisenhardt and Martin, 2000; Christopher and Peck, 2004). Given these considerations, we draw on DCV as the theoretical lens of this study to explore AM-enabled resilience practices for building SC capabilities, and by doing so, help firms enhance their SCR against disruption vulnerabilities. Figure 1 illustrates the research design.



RG1. Understand and conceptualize how AM technology adoption affects the state of the SC, consequently affecting the SC capabilities and vulnerabilities that underlie SCR.

RG2. Explore how AM technology adoption affects the state of the SC.

RG3. Explore different practices in the context of AM technology adoption for building SC capabilities aimed at decreasing SC vulnerabilities, and therefore enhancing SCR.

Figure 1. Research design

First a systematic search and critical review of the existing literature was performed to understand and propose how AM technology adoption affects the state of the SC, as well as the SC capabilities and vulnerabilities that underlie SCR, thereby theoretically addressing RQs 1, 2, and 3. Subsequently, a comprehensive conceptual framework i.e., Additive Manufacturing-Supply Chain Resilience (AM-SCR), was conceived that conceptually illustrates the subject matter. Hence, by taking advantage of a systematic search of the existing literature followed by a critical review of the findings, we managed to be comprehensive in our search for relevant evidence and produce “best evidence synthesis” (Grant & Booth, 2009). This review approach is termed “systematic search and review” because it integrates the strengths of a systematic search process with those of a critical review (Grant & Booth, 2009). Therefore, it was considered suitable in serving the first goal of this research as it not only motivated a transparent and replicable procedure to comprehensively search the literature for relevant evidence, but it also justified the critical review of the gathered evidence to set forth propositions and conceive a comprehensive conceptual framework (i.e., AM-SCR) that together capture and reflect the findings.

Next, an exploratory survey in different industries that are at the forefront of AM technology was performed whereby both quantitative and qualitative data were gathered and analyzed to understand how and to what extent AM adoption affects different SC state variables that represent the state of the SC, thereby addressing RQs 1 and 2 based on empirical evidence. Given the lack of empirical research and evidence regarding the subject matter, an exploratory survey research was conducted. This research method is especially useful at “the early stages of research into a phenomenon, when the objective is to gain preliminary insight on a topic” (Forza, 2002), providing the foundation for in-depth future research. The employed survey method in this research is similar to that of Durach et al. (2017), who gathered empirical data from a heterogeneous sample using Likert scale questions and text fields to answer interlinked, forecasting oriented RQs regarding the impacts of AM technology adoption on SCs. Likewise, utilizing a similar method provided the opportunity to gather the necessary quantitative and qualitative empirical data through an anonymous survey from a heterogeneous sample including experts from different industries with first-hand experience and knowledge of AM technology adoption, which otherwise would have not been viable through conventional methods such as focus group discussions where it is difficult to bring together such experts in one place and encourage them to freely express their ideas. Subsequently, based on the analysis of the gathered empirical evidence, propositions were put forward and an Additive Manufacturing-Supply Chain State (AM-SCS) framework was conceived, outlining the empirical findings.

Moreover, the collected data from the mentioned survey were analyzed to understand how and to what extent AM adoption affects different resilience practices that are used to build the SC capabilities necessary for dealing with SC vulnerabilities and enhancing SCR, thus addressing RQs 3 and 4 based on empirical evidence. Likewise, relevant propositions were put forward and an empirical practice-based framework was conceived, i.e., Additive Manufacturing-Supply Chain Resilience Practices (AM-SCR*P*), outlining different AM-enabled resilience practices for enhancing the SC capabilities that are needed to counteract SC vulnerabilities, and therefore enhance SCR.

Furthermore, a case study of a leading original equipment manufacturer (OEM) that uses AM technology to produce high-end metal parts for different industries is conducted, based on which the existing interrelations between the barriers of AM technology adoption and potential SC vulnerabilities are empirically analyzed, thereby addressing RQs 2, 3, and 4 even further in a case study setting. Given the exploratory nature of this research area, i.e., the SC implications of AM technology adoption, case study is often considered to be a suitable research approach (Mellor et al., 2014; Davies et al., 2022). Generally, case studies are suitable for exploratory research in nascent research fields such as this one and show great potential for discovering unexplored interrelations between different research variables in a real-life context (Yin, 2018). Hence, similar to successful single case studies conducted in this research area by different researchers such as Mellor et al. (2014), Chen et al. (2015), Stentoft et al. (2020), and Davies et al. (2022) among others, we also chose to perform a single case study as it would allow us to gain an in-depth understanding of the subject matter (Voss et al., 2002; Yin, 2018). More specifically, the results of the case study would indicate which AM adoption barriers (and how they) can give rise to different SC vulnerabilities, which negatively affect SCR. Hence, using the case study findings, relevant practices aimed at building the necessary SC capabilities to mitigate the SC vulnerabilities caused by AM adoption barriers were identified and illustrated in an empirical framework, i.e., Additive Manufacturing-Supply Chain Vulnerabilities (AM-SCV).

5. Thesis structure

The summary structure of the thesis is presented in Table 1. Chapter 1 presents the research gap, RQs, and the employed research approach. In Chapter 2, a systematic literature search and review has been performed that critically analyzes dispersed pieces of evidence throughout the literature and synthesizes them to theoretically address RQs 1, 2, and 3. In Chapter 3, an exploratory survey is performed to empirically investigate the effects of AM technology adoption on the state of the SC, hence addressing RQs 2 and 3. Subsequently, in Chapter 4, the gathered data via the exploratory survey has been analyzed to understand and propose how AM technology adoption enables different resilience practices for building SC capabilities that are needed to counteract SC vulnerabilities and improve SCR, thus addressing RQs 3 and 4 based on empirical evidence. In Chapter 5, a case study is performed that investigates the potential interrelations between AM adoption barriers and SC vulnerabilities and how they affect SCR. Subsequently, practices for dealing with the identified AM adoption barriers and their interrelated SC vulnerabilities are put forward, thereby addressing RQs 2, 3, and 4 based on empirical findings. Lastly, in Chapter 6, the thesis overview is presented, followed by a discussion of the main results and contributions, as well as the description of limitations and directions for future work.

Table 1. Thesis structure

Thesis outline	**Chapters**	**Content**
Introduction	Chapter 1	Research gap Research questions Research approach
Theoretical analysis	Chapter 2	Systematic search and review that theoretically addresses RQs 1, 2, 3.
Empirical analysis	Chapter 3	Exploratory survey that empirically addresses RQs 1 and 2.
	Chapter 4	Exploratory survey that empirically addresses RQs 3 and 4.
	Chapter 5	Case study that empirically addresses RQs 2, 3, and 4.
Conclusion	Chapter 6	Thesis overview Main results Main Contributions Limitations and future work

This thesis is comprised of four main journal papers, each representing a specific Chapter (see Table 2). It should be noted that in the conference paper mentioned in Table 2, the candidate conceived a preliminary research model and proposed the use of partial least squares structural equation modeling (PLS-SEM) methodology to estimate the cause-and-effect relationships between AM adoption as the independent variable and SCR (comprised of only SC capabilities) as the dependent variable. This paper was later used for receiving feedback on the proposed preliminary research model and methodology. The feedback indicated that as the research theme is quite nascent and AM technology is not widely adopted and diffused in all industries, employing a deductive research approach (i.e., theory testing via a large-scale survey) is high-risk and most likely will lead to false results; hence, the use of exploratory research methods was suggested as a viable alternative. This feedback helped the candidate in improving the research model and modifying the research methodology accordingly.

Table 2. Papers related to this thesis

Title	Main findings	Related Chapter
*"The Impact of Additive Manufacturing on Supply Chain Resilience" (Published in the *Doctoral Conference on Computing, Electrical and Industrial Systems* (DoCEIS) https://doi.org/10.1007/978-3-030-45124-0_20)	Conception of a preliminary conceptual research model to appraise the effects of AM adoption on SC capabilities that underlie SCR.	-
"The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review" (Published in the *International Journal of Production Economics*. https://doi.org/10.1016/j.ijpe.2021.108387)	Based on the critical review of the gathered evidence from literature: • Identification of how AM technology adoption affects the state of the SC. • Identification of the barriers that inhibit the effects of AM adoption on the state of the SC. • Identification of how AM adoption influences certain SC capabilities and vulnerabilities that underlie SCR by affecting the state of the SC.	Chapter 2
"Exploring the effects of additive manufacturing technology adoption on the state of the supply chain: A resilience perspective" (Undergoing peer review in a refereed journal)	Based on the analysis of empirical data from the exploratory survey: • Identification of how different AM technology features and barriers affect the state of the SC. • Estimation of the extent to which AM technology adoption affects the state of the SC.	Chapter 3
"Towards a practice-based framework for supply chain resilience in the context of additive manufacturing technology adoption " (Undergoing peer review in a refereed journal)	Based on the analysis of empirical data from the exploratory survey: • Explication of how AM technology adoption affects the SC capabilities and vulnerabilities that underlie SCR via different resilience practices. • Estimation of the extent to which AM technology adoption affects different resilience practices.	Chapter 4
"Exploring the interrelations between additive manufacturing adoption barriers and supply chain vulnerabilities: the case of an original equipment manufacturer" (Published in the *Journal of Manufacturing Technology Management*.https://doi.org/10.1108/JMTM-04-2022-0148)	Based on the analysis of empirical data from a case study: • Identification of how certain AM adoption barriers can lead to SC vulnerabilities and affect SCR. • Identification of potential resilience practices for mitigating the SC vulnerabilities caused by AM adoption barriers.	Chapter 5

*Note: This paper was later used in EurOMA 2020 doctoral seminar to receive feedback and help the candidate make the necessary corrections to the initial methodology and research model.

2

The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review

This chapter consists of the following paper:

Naghshineh, B. & Carvalho, H. (2022a). The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review. *International Journal of Production Economics*, *247*, 108387. https://doi.org/10.1016/j.ijpe.2021.108387

The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review

Abstract

As a disruptive digital technology, adopting additive manufacturing impacts the state and structural dynamics of supply chains, thus affecting their capability to be resilient. Supply chain resilience is essential for business continuity and dealing with unforeseen disruptions such as the COVID-19 pandemic. To date, no research has exclusively investigated the implications of adopting additive manufacturing technology for supply chain resilience, and this study aims to overcome this knowledge gap by using the existing literature and drawing on the dynamic capabilities view. Hence, a systematic search of the literature followed by a critical review of the gathered evidence from 87 peer-reviewed journal papers is performed, leading to the generation of propositions on how additive manufacturing adoption impacts the state of the supply chain, thus influencing certain supply chain capabilities and vulnerabilities that affect supply chain resilience. These propositions provide a research agenda to empirically examine how adopting different processes and applications of additive manufacturing technology can affect supply chain resilience in different industries. Additionally, this study puts forward a detailed framework that indicates how and to what extent adopting additive manufacturing can influence the supply chain capabilities and vulnerabilities that underlie supply chain resilience. While the results suggest that adopting additive manufacturing is expected to improve supply chain resilience by mainly enhancing the state of the supply chain and positively influencing certain supply chain capabilities, it can also cause certain supply chain vulnerabilities to arise, which seem to be interrelated with some of the present additive manufacturing adoption barriers.

Keywords: Additive manufacturing, Supply chain resilience, Literature review, Propositions, Framework, Research agenda

1. Introduction

Supply chains (SCs) almost always prove to be vulnerable to disruptions. A recent example is the outbreak of COVID-19 pandemic that has caused drastic reductions in supply availability on a global scale (Ivanov, 2020)**.** This shortcoming drives SCs to become more resilient to disruptions (Pettit et al., 2019; Ivanov & Dolgui, 2020), especially when considering that most of the contemporary SCs are overextended around the globe, which makes them even more vulnerable to disruptions (Tang & Tomlin, 2008; Kamalahmadi & Parast, 2016). The latter statement explains why supply chain management (SCM) has become vastly cognizant of SC risks and vulnerabilities that lead to disruptions and has taken great interest in developing SC capabilities as a countermeasure (Kochan & Nowicki, 2018). SC capabilities are a means of mitigating SC vulnerabilities (Tang & Tomlin, 2008; Ponomarov & Holcomb, 2009) and building resilience against possible disruptions (Pettit et al., 2019), i.e., supply chain resilience (SCR). SCR is a highly multidimensional construct that is operationalized via different SC capabilities (Ponomarov & Holcomb, 2009; Chowdhury & Quaddus, 2017). While there is no consensus on a unique set of SC capabilities that constitute SCR, many scholars consider SC flexibility, redundancy, collaboration, visibility, and agility as the main antecedent SC capabilities of SCR (Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Ali et al., 2017; Kochan & Nowicki, 2018; Han et al., 2020). SC capabilities are considered to be essential elements of SCR that lead to enhanced SC performance and less vulnerability to disruptions (Ponomarov & Holcomb, 2009; Hosseini et al., 2019; Pettit et al., 2019). In view of these considerations, SC vulnerabilities are regarded as factors that put the SC at risk and make it susceptible to disruptions, whereas SC capabilities are features that help to mitigate SC vulnerabilities and overcome their ensuing disruptions (Pettit et al., 2010), thus indicating to what extent the SC is resilient to disruptions (Ali et al., 2017; Han et al., 2020). In this sense, the existing vulnerabilities and capabilities in the SC project the status of SCR (Kochan & Nowicki, 2018; Pettit et al., 2019).

However, a "fundamental pre-requisite" for projecting SCR is to have an understanding of the *state* of the SC (Carvalho et al. 2012). According to Carvalho et al. (2012), the "state of the SC is a specific arrangement of SC entities and relational links between them and others SCs, material and information flows, management policies and lead times", which can be indicated by certain SC state variables. We find the aforementioned definition to be an elaborate description of the "supply chain macro-state" by Ivanov (2018, p.5), which he defines as "a general supply chain state in which one or more supply chain objects can operate and fulfil jobs and processes.", whereas the "structural dynamics" of the SC signify the transitioning of the SC from one macro-state to another (Ivanov 2018, p.6) representing changes in the state of the SC. In light of these considerations, SCR exists if the state of the SC is maintained or transitioned to a more favorable one while dealing with SC vulnerabilities and disruptions (Christopher & Peck 2004), thus highlighting the relevance of the *state* of the SC when assessing SCR.

In the meantime, the adoption of new disruptive technologies such as additive manufacturing (AM) impacts the *state* and consequently the structural dynamics of SCs (Dolgui & Ivanov, 2020), influencing their capacity to be resilient to SC vulnerabilities and disruptions (Ivanov et al., 2019). In other words, such impacts can lead to increased SC capabilities such as higher flexibility in dealing with time and demand risk factors (Ivanov et al., 2019; Dolgui & Ivanov, 2020) as well as increased SC risks and vulnerabilities, e.g., “industrial espionage, IP leakage, or even production sabotage” (Tang & Veelenturf, 2019). AM is an advanced computer technology capable of digitizing SCs (Verboeket & Krikke, 2019), which produces objects layer-by-layer using 3D computer-aided design (CAD) software and models (Berman, 2012; Petrick & Simpson, 2013). In their research, Durach et al. (2017) point out that the adoption of AM technology for different applications, e.g., rapid prototyping, production tooling, end-use parts production, and spare parts production, impacts the structure and capabilities of SCs, which consequently affect SCR. They also mention the existing barriers that inhibit the widespread adoption of AM technology. Such barriers play an important role in determining the extent to which adopting AM technology impacts the state of the SC (Durach et al., 2017; Verboeket & Krikke, 2019), and therefore they are expected to affect SCR as well.

The importance of investigating the implications of AM adoption for SCR is highlighted by Zouari et al. (2020) and Spieske and Birkel (2021), among other authors, who call for research in this regard. Nonetheless, to the best of our knowledge, the existing literature falls short of comprehensive research that solely focuses on addressing this knowledge gap. While there may be a limited number of studies in extant literature such as the ones by Zouari et al. (2020) and Spieske and Birkel (2021) that have investigated the impacts of SC digitalization and Industry 4.0 technologies on SCR, to date, no research has exclusively addressed the implications of AM adoption for SCR, providing detailed results. In a recent study, Naghshineh and Carvalho (2020) proposed a conceptual research model for investigating the impacts of AM adoption on SCR, however, they did not provide conclusive results.

In the present study, we take a deductive research approach and perform a systematic search and review of the literature to lay the foundation for future empirical research by propositioning how AM adoption can affect SCR. To do this, we first investigate the impacts of AM adoption on the SC based on the premise that adopting AM technology affects the state of the SC and causes structural dynamics (Dolgui & Ivanov, 2020). Considering the impacts of AM adoption on the state of the SC as well as the barriers that inhibit such impacts, we then analyze the implications of AM adoption for SCR based on the concepts of

SC capabilities and SC vulnerabilities that underlie SCR (Kochan & Nowicki, 2018; Pettit et al., 2019). More specifically, we aim to discover how and in what ways the adoption of AM technology changes the state of the SC that would either create opportunities to improve certain SC capabilities or cause certain SC vulnerabilities, thus affecting SCR (Ivanov et al., 2019; Pettit et al., 2019; Dolgui & Ivanov, 2020).

The theoretical underpinning of this research is in line with the dynamic capabilities view, which is an extension to the resource-based view (Teece et al., 1997). The resource-based view of the firm considers technology as a resource that can be adopted to enhance performance (Wernerfelt, 1984; Cavusgil et al., 2007), e.g., SCR performance (Ponomarov & Holcomb, 2009). However, the resource-based view does not reflect the dynamic nature of SCs, whereas the dynamic capabilities view tends to overcome this shortfall by considering the important role that SCM plays in continuously reconfiguring the resources and developing the capabilities that the firm needs to deal with SC vulnerabilities and disruptions (Ponomarov & Holcomb, 2009). Hence, in line with the dynamic capabilities view of the firm to strategy analysis, the results of this research will aid SCM in inferring how and to what extent adopting AM technology can contribute to enhancing certain SC capabilities that mitigate certain SC vulnerabilities, thus improving SCR.

The rest of this paper is organized as follows. In section two the methodological approach of the research is explained. In section three the critical review that leads to the generation of fourteen sets of propositions is elaborated. In section four an additive manufacturing-supply chain resilience (AM-SCR) framework is put forward and explained. In section five, the theoretical and managerial implications of the research are discussed. Lastly, in section six conclusions, research limitations, and directions for future research are presented.

2. Methodological approach

In this study, we have performed a systematic search of the literature followed by a critical review of its findings to produce “best evidence synthesis”. This review approach, which is known as “systematic search and review”, integrates the strengths of a systematic search process with a critical review (Grant & Booth, 2009). Hence, it was deemed suitable for the purpose of the current study since it not only motivates a transparent and replicable method to comprehensively search the literature to find evidence but also justifies the critical review of the gathered evidence in order to derive new theory. Moreover, the broad scope of this review approach allows the inclusion of multiple study types, thus leading to a more complete sample for the research topic under study (Grant & Booth, 2009). Therefore, to follow a systematic search process, we performed the below-mentioned steps that are in line with Denyer & Tranfield (2009):

- 1st step: Research questions formulation
- 2nd step: Literature search
- 3rd step: Article assessment and selection
- 4th step: Analysis and synthesis
- 5th step: Reporting and using the results

Later, in step four we analyzed and synthesized the sample data based on a critical review approach. A critical review is more than just describing the literature and requires a degree of analysis, synthesis, and conceptual innovation to derive new theory, which is normally expressed in the form of hypotheses/propositions (Grant & Booth, 2009). Figure 1 summarizes the methodological approach that is used in this paper, whereas each step of the approach is explained in detail in the following subsections.

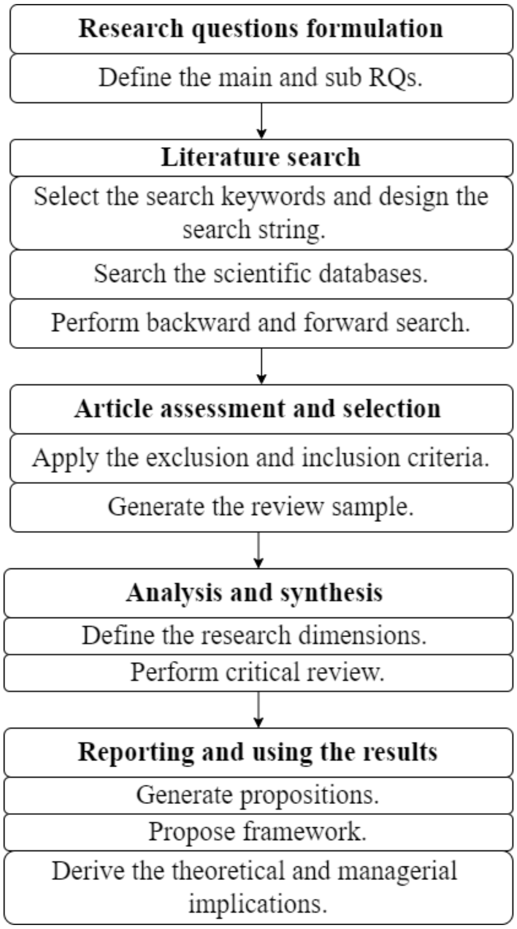


Figure 1. Methodological approach

1.1. Research questions formulation

In this research, we aim to look into the implications of AM technology adoption for SCR using evidence from the existing literature. Drawing on the dynamic capabilities view, we investigate how adopting AM technology can influence the SC capabilities and SC vulnerabilities that underlie SCR, taking into consideration the mediating effects of the state of the SC in doing so. In line with Ivanov et al. (2019) and Dolgui and Ivanov (2020), the underlying premise of this research is that adopting AM technology impacts (i.e., directly affects) the state of the SC, which in turn influences (i.e., indirectly affects) certain SC vulnerabilities as well as certain SC capabilities that mitigate SC vulnerabilities, thus affecting SCR (Kochan and Nowicki, 2018; Pettit et al., 2019). Also, in line with the state-of-the-art literature, we consider the existing AM adoption barriers in the context of this research since certain barriers can inhibit the impacts of AM adoption on the state of the SC (Durach et al., 2017; Verboeket & Krikke, 2019) and consequently affect SCR. Therefore, to address the main research question (RQ) "what are the implications of AM technology adoption for SCR?", we aim to find answers to the following sub RQs:

- RQ1. How does AM adoption impact the state of the SC?
- RQ2. Which barriers inhibit the impacts of AM adoption on the state of the SC?
- RQ3. How does AM adoption influence certain SC capabilities by impacting the state of the SC?
- RQ4. How does AM adoption influence certain SC vulnerabilities by impacting the state of the SC?

The conceptual path model represented in Figure 2 depicts the relationships between the research variables and puts the aforementioned RQs into perspective. It should be noted that in this model SCR is indicated by its two underlying constructs and the existing linkage between them in the sense that "Supply chain capabilities" are developed to reduce "Supply chain vulnerabilities" and improve "Supply chain resilience" (Pettit et al., 2010, 2013, 2019).

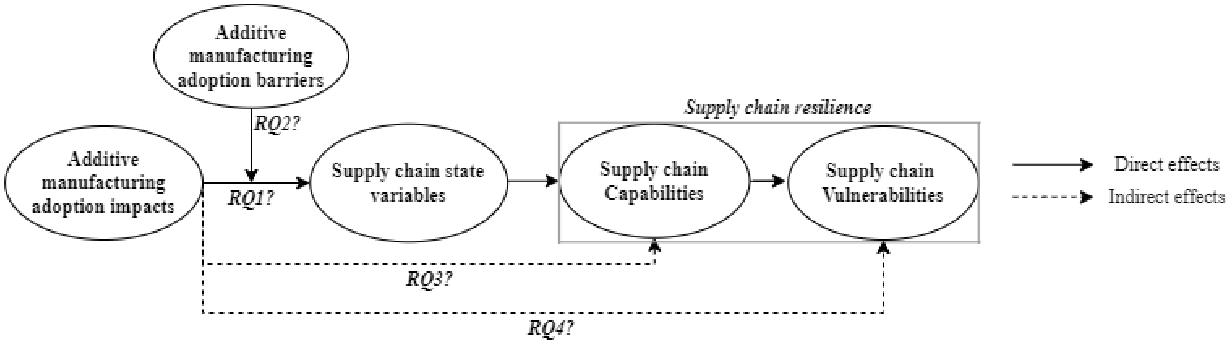


Figure 2. Conceptual path model

2.2 Literature search

Considering the RQs and the main variables of the research, we determined “additive manufacturing”, “supply chain”, “impacts”, “state variables”, “resilience”, “capabilities”, “vulnerabilities”, and “adoption barriers” as the primary search keywords and used different synonyms of each term to formulate the search string. Since using the right search string can greatly affect the efficiency of the search (Denyer & Tranfield, 2009), we formulated and tested different search strings to ensure accurate results and at last proceeded with the following search string:

(("additive manufacturing" OR "3D printing" OR "layer manufacturing" OR "direct digital manufacturing" OR "freeform fabrication" OR "digital fabrication" OR "rapid manufacturing" OR "rapid prototyping" OR "rapid tooling") AND ("supply chain" OR "supply network" OR "value chain" OR "logistics" OR "transportation") AND ("impacts" OR "implications") AND ("state variables" OR "adoption barriers" OR "adoption obstacles" OR "bottlenecks" OR "resilience" OR "resilient" OR "resiliency" OR "supply chain capabilities" OR "resilience capabilities" OR "capability factors" OR "resilience dimensions" OR "resilience elements" OR "resilience competencies" OR "resilience antecedents" OR "resilience principles" OR "resilience enhancers" OR "resilience enablers" OR "vulnerabilities" OR "disruptions" OR "disturbances"))

We applied the aforementioned search string to the advanced document search function of Scopus and Web of Science (WOB) databases, searching the titles, abstracts, and keywords of articles published until April 2021. No constraints were imposed on the starting date of the search. The search returned 32 articles. Since this number was relatively low (due to the search string being stringent but accurate), we also performed a backward search followed by a forward search using the cited literature in the identified articles to find additional sources (Webster & Watson, 2002). Performing the backward/forward search would not have been viable without looking into the results of the keyword search as it revealed relevant references and citations to explore (Thomé et al., 2016).

2.3. Article assessment and selection

After excluding the duplicate articles, in order to ensure data quality, we considered including papers (written in English) that were published only in peer-reviewed journals (Light & Pillemer, 1984) with mainly an AJG (previously known as ABS) ranking by the Chartered Association of Business Schools (2021). We read through the titles, abstracts, and keywords of the papers to ensure relevance, and in the cases where doing this was not enough, we screened the entire content of the paper. With regard to topics, papers containing information about the implications of different AM processes (e.g., powder bed fusion, vat photopolymerization, material extrusion, among others) as well as their different applications (e.g., rapid prototyping, end-use parts production, spare parts production, among others) in different SC types (e.g., aeronautic, electronics, medical, among others) were considered relevant. After completing this process, 87 peer-reviewed journal papers were selected for full-text analysis, which comprised the review sample (available as supplementary data). The review sample includes 45 papers that provide empirical results (52%), whereas the remaining 42 papers are theoretical as well as literature reviews (48%). The journals' AJG rankings (2021) and the number of papers belonging to each journal (along with some other journal statistics) are presented in Table 1, which were retrieved from the "Scimago Journal & Country Rank" (SJR) database (as of April 2021). Also, the year-wise distribution of the selected papers is shown in Figure 3.

Table 1. Journal statistics, and the number of papers in each journal

Journal	**Journal AJG ranking (2021)**	**Journal Quartile (SJR)**	**Journal H index (SJR)**	**Journal Impact Factor (SJR)**	**No. of papers**
International Journal of Production Economics	3	Q1	185	2.41	18
Journal of Manufacturing Technology Management	1	Q1	70	1.29	12
International Journal of Production Research	3	Q1	142	1.91	8
Technological Forecasting and Social Change	3	Q1	117	2.23	7
International Journal of Physical Distril tion and Logistics Management	2	Q1	111	1.74	6
Computers in Industry	3	Q1	100	1.43	5
International Journal of Advanced Manufacturing Technology	-	Q1	124	0.95	5
Journal of Cleaner Production	2	Q1	200	1.94	4
Production Planning and Control	3	Q1	76	1.33	4
Journal of Business Logistics	3	Q1	79	2.61	3
Supply Chain Management: An International Journal	3	Q1	115	2.04	3
Business Horizons	2	Q1	87	2.17	2
Energy Policy	2	Q1	217	2.09	1
Industrial Management and Data Systems	2	Q1	103	0.99	1
International Journal of Operations and Production Management	4	Q1	138	2.16	1
International Journal of Services and Operations Management	1	Q3	27	0.26	1
Journal of Business Economics	2	Q1	21	0.74	1
Journal of Engineering and Technology Management	2	Q1	65	0.83	1

Journal of International Entrepreneurship	1	Q1	44	0.81	1
Operations Management Research	1	Q1	28	0.7	1
Research-Technology Management	2	Q1	68	0.81	1
Technovation	3	Q1	130	2.3	1

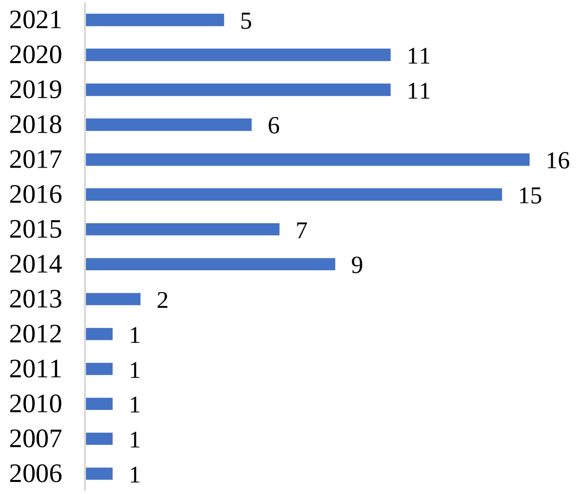


Figure 3. Year-wise distribution of the selected papers

2.4. Analysis and synthesis

2.4.1 Research dimensions

In order to perform a conclusive analysis and synthesis, we required certain research dimensions (aka coding dimensions/criteria) that would ensure each paper was analyzed based on the same underlying criteria (Tranfield et al., 2003; Seuring et al. 2005; Grant & Booth, 2009). Thus, after considering the RQs and the main variables of the research (Centre for Reviews and Dissemination, 2009), we identified the following research dimensions.

In a first step, we identified the SC impacts of AM adoption using the review sample. In doing so, we compiled a comprehensive list of 34 AM adoption impacts and their expected performance outcomes (Appendix A) that allowed us to consider the impacts of AM adoption on the state of the SC. We also compiled a comprehensive list of 32 AM adoption barriers along with their expected inhibiting effects (Appendix B) that were used to help us infer which barriers would inhibit the impacts of AM adoption on the state of the SC. Next, we used the SC state variables defined by Carvalho (2012) to indicate the state of the SC. However, as there are 29 SC state variables defined by Carvalho (2012), for the sake of brevity in this paper we had to select the ones that were considered more relevant. Thus, 12 SC state variables were selected (Table 2), which are well-grounded as they are derived from the existing literature and are validated via case study research by Carvalho (2012). The identified impacts and barriers of AM adoption together with the selected SC state variables enabled us to address RQs 1 and 2.

Table 2. SC state variables and their metrics selected from Carvalho (2012)

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

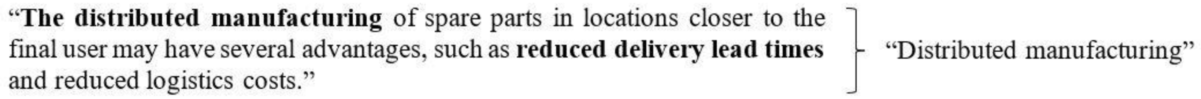
Moreover, to be able to address RQs 3 and 4, we required a reference model that could lay out the necessary SCR dimensions in terms of SC capabilities and SC vulnerabilities. Thus, we used the comprehensive "Supply Chain Resilience Assessment and Management" (SCRAM^{TM}) framework by Pettit et al. (2013) that enabled us in fulfilling our research objective since it not only includes the majority of the SC capabilities that are considered to be the main antecedents of SCR (Kochan & Nowicki, 2018; Han et al., 2020) but also links them to a set of relevant SC vulnerabilities, providing a holistic perspective on the concept of SCR. Moreover, the SC capabilities and SC vulnerabilities in the SCRAM^{TM} framework are complemented by a set of SC capability and SC vulnerability subfactors that define the concept of SCR on a granular level. The comprehensiveness of this SCR framework is acknowledged in the present literature by authors such as Zouari et al. (2020), who state: "Pettit et al.'s (2010, 2013) classification of capabilities and sub-capabilities offers the most exhaustive assessment of SCR in empirical studies compared to others" and use the same SC capability subfactors in the SCRAM^{TM} framework to investigate the implications of SC digitalization for SCR. Hence, in this study we have adapted and used the definitions that Pettit et al.

(2013) have used to develop the SCRAM^{TM} framework, which are stated in Appendices C and D. Lastly, we used the SCRAM^{TM} framework to identify linkages between SC capabilities and SC vulnerabilities based on the premise that SC capabilities are developed by firms to mitigate SC vulnerabilities and improve SCR (Pettit et al., 2010, 2013, 2019).

2.4.2 Analysis and synthesis approach

In this subsection, we explain how the sample data were critically analyzed and synthesized leading to the generation of propositions. It is worth noting that we performed this step more than once to ensure relevance and transparency in the results (Denyer & Tranfield, 2009). Overall, we reached a consensus on the relations we identified between the research variables through multiple discussions and revisions (Tranfield et al., 2003).

We analyzed the review sample with a focus on finding evidence in terms of how adopting AM technology can impact the state of the SC. Text segments that contained relevant information regarding the SC impacts of AM adoption and their expected performance outcomes as well as AM adoption barriers and their expected inhibiting effects were coded (Appendix E). For instance, the text segment shown in Figure 4 was coded as the AM adoption impact "Distributed manufacturing". Analyzing this text segment implies that "Distributed manufacturing" (enabled by AM) impacts the SC state variable "Delivery lead time" and its designated metric "Ease (cost) of reducing delivery lead time". We also used the identified expected performance outcomes of each AM adoption impact to infer how each SC state variable would be affected. For instance, based on the existing literature (e.g., Durão et al., 2017), "reduced delivery lead times" was identified as an expected performance outcome of "Distributed manufacturing" that affects the SC state variable "Delivery lead time". Furthermore, the barriers that inhibit the impacts of AM adoption on the state of the SC were identified during the analysis. For instance, "ICT inadequacies" (i.e., information and communication technology inadequacies) was identified as an adoption barrier that can inhibit the effect of "Distributed manufacturing" (Chekurov et al., 2018) by causing issues such as data management problems (Do, 2017). The output of this process provided the necessary information based on the evidence in the sample to answer RQs 1 and 2.



"**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." — "Distributed manufacturing"

Figure 4. Coded text segment from Durão et al. (2017)

Next, each SC state variable along with its metric was related to relevant SC capabilities available in the SCRAM^{TM} framework. For instance, “Delivery lead time” and its metric “Ease (cost) of reducing delivery lead time” were related to the SC capability “Adaptability”, since the former is an SC state variable that represents the capability of the SC in adapting its operations to respond to challenges (as well as opportunities) that may suddenly arise, e.g., unpredictable customer demand. Subsequently, from the multiple SC capability subfactors that represent each SC capability in the SCRAM^{TM} framework, those that were considered relevant to the SC state variables (in the context of this study) were identified. For instance, in the case of the SC state variable “Delivery lead time”, “Lead time reduction” was identified as a relevant SC capability subfactor since it indicates the capability of the firm that chooses to adopt AM in reducing (i.e., adapting) its lead times to respond to unpredictable customer demands. The identified SC capability subfactors were then related to relevant SC vulnerability subfactors using the existing linkages in the SCRAM^{TM} framework. For instance, in the case of the previous example, “Lead time reduction” was related to “Unpredictability in customer demand” based on the knowledge that AM adoption can help reduce “Delivery lead time” by enabling “Distributed manufacturing”, and thus allowing for easier adaptability to unpredictable customer demands through “reduced delivery lead times”. Since each identified SC vulnerability subfactor represents a specific SC vulnerability in the SCRAM^{TM} framework, relevant SC vulnerabilities were identified as well, e.g., “Turbulence”. Figure 5 represents the aforementioned example, illustrating how the research variables depicted in the conceptual path model (Figure 2) relate to one another. Performing this step allowed us to identify paths that signify the indirect effects of AM adoption on certain SC capability and SC vulnerability subfactors.

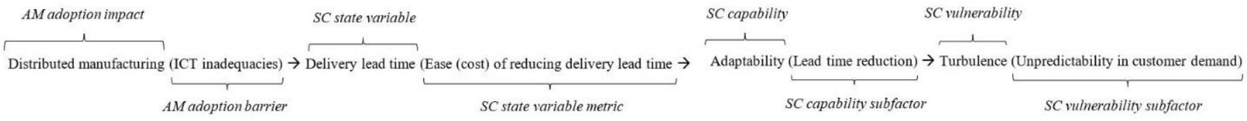


Figure 5. An example of how AM adoption affects SCR

Similarly, relevant SC vulnerability subfactors that would solely deteriorate due to AM adoption were identified using the existing linkages between the SC vulnerability subfactors and the already identified SC capability subfactors. For instance, in the case of the SC state variable “Production lead time”, after examining the SC vulnerability subfactors that were linked to “Lead time reduction” in the SCRAM^{TM} framework, “Unforeseen technology failures” was identified as a relevant SC vulnerability subfactor that would deteriorate due to “Unstable AM processes”. Performing this step allowed us to discover paths that exclusively signify the indirect effects of AM adoption on certain SC vulnerability subfactors that would deteriorate. Completing the aforementioned steps allowed us to discover 88 paths in total that indicate the indirect effects of AM adoption on the underlying SC capabilities and SC vulnerabilities of SCR, allowing us to answer RQs 3 and 4.

2.5 Reporting and using the results

The outcome of a critical review normally leads to the generation of hypotheses/propositions (Grant & Booth, 2009), which are considered to be informative statements regarding the relationships between the variables of the research (Meredith, 1993). Hence, by performing the critical review we managed to put forward fourteen sets of propositions that elaborate the identified relationships between the research variables stated earlier (see Figure 2). Each proposition set is composed of four sub-propositions (denoted by *Proposition ia*, *Proposition ib*, *Proposition ic* and *Proposition id*, with *i* taking values from 1 to 14) that reflect the implications of AM adoption for SCR by proposing:

Proposition ia. how AM adoption impacts the state of the SC.
Proposition ib. the barriers that inhibit the impacts of AM adoption on the state of the SC.
Proposition ic. how AM adoption influences certain SC capabilities by impacting the state of the SC.
Proposition id. how AM adoption influences certain SC vulnerabilities by impacting the state of the SC.

Apart from putting forward the aforementioned propositions that lay out a research agenda for future empirical research, performing the critical review allowed us to conceive an AM-SCR framework, which summarizes the findings of this research by depicting the identified relationships between the AM adoption impacts, AM adoption barriers, SC state variables, SC capabilities, and SC vulnerabilities. Academics and practitioners can use this framework to better understand how the identified relationships between the aforementioned research variables lead to implications for SCR. Lastly, the theoretical and managerial implications of the research were derived and reported in detail in section five.

3. Critical review and propositions

As described in detail in subsection 2.4.2, the critical review explains the impacts of AM adoption and its barriers on the SC state variables, which consequently influence certain SC capabilities and SC vulnerabilities that underlie SCR. To follow a clear structure, in each of the following subsections the critical review is presented based on the mediating SC state variable that is mentioned in the subsection's heading. It should also be noted that since the first listed SC state variable (i.e., "Available alternatives for production processes") is indicated by three different metrics (as stated in Table 2), it is therefore discussed in three consecutive subsections. In order to conclude our findings, we present a set of propositions at the end of each subsection. Finally, in subsection 3.13, the proposition sets are ranked according to different scores that were used to estimate their strength.

1.2. Available alternatives for production processes

3.1.1 Possibility to outsource production processes

The possibility to outsource production processes can enhance a firm's ability to respond to disruptions when facing production capacity shortages (Jiang et al., 2006). AM enables the possibility to outsource production processes to external entities (Rogers et al., 2016), which would facilitate the quick reallocation of production and rerouting of requirements in case of distribution or production capacity shortages, thus enhancing the flexibility (in order fulfilment) and adaptability of the SC against resource limits. This AM feature also allows the firm to mitigate the consequences of internal/external disruptive events such as failure of production equipment or geopolitical turmoil, and therefore, enhances the recovery capability of the SC by allowing it to quickly return to the normal state of operations. Also, by facilitating the outsourcing of production processes to external sources, AM allows producers to protect themselves against potential unionized labor activities, e.g., strikes. Another possibility is to use the existing printer hubs (Petrick & Simpson, 2013) to pool the dispersed production capacity (i.e., capacity pooling/sharing) available in different locations (Kietzmann et al., 2015) to promote distributed manufacturing (aka localized production) and avoid the concentration of capacity in one geographical location. However, when firms outsource the production of parts to external entities, their control over tracing the quality of the input material becomes somewhat limited.

The distributed manufacturing method enabled by AM allows for the production processes to be outsourced to external entities in different ways (Eyers & Potter, 2015). For instance, apart from outsourcing production to AM service providers (Rogers et al., 2016), another option is to outsource the production phase to the customers who own compatible printers (Rayna & Striukova, 2016; Jiang et al., 2017; Kleer & Piller, 2019), i.e., customer-centric production (aka user manufacturing). This AM feature not only allows the firm to protect itself against unpredictability in customer demand but also facilitates the distribution of products by relocating production closer to the customers and relieving the firm from stringent distribution capacity and logistics requirements (Ford & Despeisse, 2016; Kunovjanek et al., 2020). However, in doing so, control over the use of regulated and restricted materials by consumers becomes limited.

The possibility to outsource AM production processes is further supported by the digital nature of AM technology, e.g., digital file distribution (Ford & Despeisse, 2016) and digital inventory (Dwivedi et al., 2017). For instance, designs in the form of digital files can be created and stored in databases. If need be, these designs can then be shared with AM service providers in order to outsource the production phase, which consequently improves the production capacity as well as the distribution capacity of firms. Also, maintaining inventory in the form of digital files protects firms against possible thefts and damages to the finished goods inventory (FGI). However, some SC vulnerabilities become more likely when using these AM features. For instance, information flow will become a critical success factor in the outsourcing process (i.e., reliance upon information flow). Another vulnerability is the increased possibility of industrial espionage and knowledge leak due to the dispersed nature of such operations.

Nevertheless, outsourcing AM production processes requires stable and secure information exchange, e.g., secure transmission of a 3D model to an AM service provider, which makes information flow a crucial factor. ICT inadequacies, e.g., data management problems (Do, 2017; Chan et al., 2018), between the involved parties will have an inhibiting effect in this context. Also, due to the high risk of data and knowledge leaks, the protection of intellectual property (IP) rights, e.g., proprietary 3D models, becomes an issue (Dwivedi et al., 2017; Chekurov et al., 2018). Another barrier is the lack of AM process standards, which are necessary to control the present variability in production rate and product quality. Since such variability may not be in accordance with the standards of the firm that is outsourcing production, in-process monitoring and process certification may be required (Thomas-seale et al. 2018), which would make outsourcing a less viable option. Lack of AM material standardization, AM material regulations, and the limited traceability of AM material are also interrelated barriers that inhibit the outsourcing of AM production processes, since they can give rise to potential issues such as low material quality (Wagner & Walton, 2016), the use of unregulated material (Kietzmann et al., 2015), or difficulty in tracing the origins of the AM material (Chan et al., 2018). Lastly, the high cost of AM processes inhibits the possibility to outsource the production to service providers. Based on the above considerations, we put forward the following propositions:

Proposition 1a. AM adoption has an enhancing effect on the possibility to outsource production processes.
Proposition 1b. ICT inadequacies, IP rights protection, lack of AM process standards, lack of AM material standardization, AM material regulations, limited traceability of AM material, and high cost of AM processes inhibit the enhancing effect of AM adoption on the possibility to outsource production processes.
Proposition 1c. AM adoption positively influences the reallocation of production, rerouting of requirements, consequence mitigation, distributed capacity, and logistics multisourcing due to its enhancing effect on the possibility to outsource production processes.
Proposition 1d. While AM adoption positively influences certain SC capabilities that reduce the vulnerability of the SC to distribution capacity, production capacity, reliability of equipment, exposure to

geopolitical disruptions, union activities, concentration of capacity, unpredictability in customer demand, and piracy and theft, it can also cause SC vulnerability to the importance of product purity, utilization of restricted materials, reliance upon information flow, and industrial espionage.

3.1.2 Operations versatility

Operations versatility indicates the capability of a production system in performing various operations (Tsourveloudis & Valavanis, 2002). AM can enhance operations versatility through its unique features (Weller et al., 2015; Kunovjanek & Reiner, 2020). For instance, by allowing the design to be part of the production phase rather than an isolated phase (Holmström et al., 2016), AM creates more versatility in production operations and allows for quick responses to erratic customer demands. Also, by taking advantage of AM to complement conventional manufacturing (CM), i.e., hybrid manufacturing model, a production system can become more versatile when predicting and responding to demand, e.g., using AM for slow-moving or specialty parts with erratic demand patterns (Rylands et al., 2016; Sasson & Johnson, 2016). Other AM features such as the reduced need for manual operations (i.e., automated manufacturing), tools (i.e., tool-less production), and facilities (Weller et al., 2015; Holmström et al., 2016) as well as the ability to work remotely (Pérès & Noyes, 2006) or operate multiple AM machines by a single operator (i.e., economies of technology) augment the operations versatility. Mobile manufacturing, i.e., part production while in transit (Pérès & Noyes, 2006; Ryan et al., 2017), also enhances the versatility of operations by enabling the SC to be more adaptable to demand unpredictability (Ryan et al., 2017). These AM features are expected to support multiple pathways to production via enhancing operations versatility, leading to more SC flexibility against unpredictable customer demands and customer disruptions.

Firms can use AM as an alternate technology to increase versatility in their production operations and subsequently reduce the complexity of process operations. For example, a wide range of products can be manufactured in one AM process (Chen et al. 2015), i.e., process integration, reducing the complexity of process operations. Another example is part consolidation enabled by AM, which is to integrate multiple parts into one part and consequently reduce the number of components and assembly steps required to manufacture an end-use part (Knofius et al., 2019). When adopted as an alternate technology, these versatile features of AM not only decrease the complexity of process operations and make it easier to modify the operations in response to sudden SC disruptions, but they also downsize the scale of the SC and help manufacturers become less dependent on specialty items and their suppliers.

Nevertheless, there are technical barriers that prevent the full potential of AM adoption in enhancing operations versatility. For instance, the inability to multi-print materials inhibits operations versatility.

Furthermore, the limited size of build envelopes, which leads to the limited part size, as well as the need for excessive post-processing are other AM's shortcomings that restrict its operational versatility. Also, unstable processes can offset AM's ability in decreasing the complexity of process operations, whereas slow production speed and limited automation question AM's ability to meet the erratic customer demands on time. Lastly, the current lack of guidelines to fully exploit AM makes it difficult to efficiently take advantage of the versatility that this technology can offer, e.g., optimization of product designs (Weller et al., 2015; Steenhuis & Pretorius, 2017).

Proposition 2a. AM adoption has an enhancing effect on operations versatility.
Proposition 2b. Lack of multi-material printing, limited build envelope, excessive post-processing, unstable AM processes, slow production speed, limited automation, and lack of guidelines inhibit the enhancing effect of AM adoption on operations versatility.
Proposition 2c. AM adoption positively influences multiple pathways (to production) as well as alternate technology due to its enhancing effect on operations versatility.
Proposition 2d. AM adoption positively influences certain SC capabilities that reduce the vulnerability of the SC to unpredictability in customer demand, customer disruptions, complexity of process operations, scale and extent of supply network, and reliance upon specialty sources.

3.1.3 Redundancy in production processes

Redundancy in production processes enables a production system to change its production volume when necessary (Swafford et al., 2006). When adopted as a redundant asset, AM can enable the hybrid manufacturing model (Khajavi et al., 2015) where it complements CM in meeting the portion of demand that is volatile, providing the manufacturer with the production capacity buffer needed to address this issue (Khajavi et al., 2014). When compared with CM, AM is a more viable option for providing such redundancy in production capacity since it requires fewer personnel and decreases the overhead costs, which is mainly because of the reduced need for tools, machines, and facilities (Tuck et al., 2007). In addition, provisioning redundancy in production processes using AM may be advantageous since it can contribute to resilience against deliberate threats, e.g., terrorism and sabotage, and allow the SC to revert to its normal production capacity levels more quickly.

However, choosing to adopt AM as backup equipment to provision redundancy in production processes questions the reliability of AM machines to successfully produce the required parts on time while meeting the expected quality standards. For instance, the present instabilities in AM production processes, which may lead to variable production rates and quality, raise concerns in this regard. Another issue is the limited long-term usability of AM machines that turns them into an inefficient option for providing production capacity buffer. Furthermore, the AM process limitations such as slow production speed, limited automation, and low throughput rate are barriers that limit AM's capability in meeting the volatile portion of demand on time. Other (cost-related) barriers that should be considered are the high cost of industrial AM machines as well as their high cost of repair and maintenance. Last but not least, in the absence of skilled operators and designers, the effective use of AM as backup equipment becomes difficult and would require personnel education and training.

Proposition 3a. AM adoption has an enhancing effect on redundancy in production processes.

Proposition 3b. Unstable AM processes, limited long-term usability of AM machines, slow production speed, limited automation, low throughput rate, high cost of AM machines, high cost of repair and maintenance, lack of AM knowledge and design skills, and lack of personnel education and training inhibit the enhancing effect of AM adoption on redundancy in production processes.

Proposition 3c. AM adoption positively influences redundant assets due to its enhancing effect on redundancy in production processes.

Proposition 3d. While AM adoption positively influences redundant assets that reduce the vulnerability of the SC to production capacity as well as terrorism and sabotage, it can also cause SC vulnerability to the reliability of equipment (i.e., AM machines).

3.2 Available alternatives for production sites

This SC state variable indicates the number of available alternatives for production sites (Carvalho, 2012). AM can provide alternatives for production facilities by enabling distributed ways of manufacturing, e.g., cyber-physical production systems (Durão et al., 2017), allowing manufacturers to have access to geographically dispersed facilities to quickly reroute the production capacity requirements in case of disruptions, e.g., natural disasters, equipment failures, labor issues, or vandalism in the main production site. The use of dispersed backup facilities helps to avoid the concentration of capacity in one location and can provide the firm with the distributed capacity (Zanoni et al., 2019) and assets it needs to protect itself against deliberate threats, e.g., terrorism and sabotage, piracy or theft. AM also allows the production to take place in-situ and on-demand (Pérès & Noyes, 2006) since portable AM devices can be installed at the customer's location turning it into an alternative production site. Another alternative in case of disruptions can be the use of mobile manufacturing to temporarily address essential customers' demands and requirements until capacity in the main production plant is back to normal. Having access to alternative production facilities in different locations or the use of mobile manufacturing can help to augment the distribution capacity of the firm by producing and delivering parts to customers from the closest location possible. Such distributed capacity gives manufacturers higher flexibility in order fulfilment as well as the possibility to reroute customer orders to different production facilities if need be. Furthermore, dispersed production facilities via AM provide the firm with the opportunity to gain access to different markets at various locations, extending the scale of its supply network and the range of its outsourcing possibilities. This way the firm can gain access to a large number of customers as well as suppliers and become part of a globally distributed SC, thus expanding its import/export channels. Such decentralization not only facilitates access to dispersed markets but also protects the firm against regional supplier/customer disruptions.

However, to make the rerouting of requirements possible, continuous information flow between such dispersed AM facilities is necessary (Chekurov et al., 2018). This necessity highlights the significance of the existing ICT inadequacies, e.g., data management problems. Moreover, the existing lack of support from IT vendors further delays the resolution of problems such as potential software issues. Also, the distributed nature of the aforementioned AM features heavily rely on the use of ICT and information exchange that can expose the firm to instances of industrial espionage, e.g., hacking of the 3D model database that leads to knowledge leak, thus highlighting the importance of IP rights protection.

Proposition 4a. AM adoption has an enhancing effect on the available alternatives for production sites.
Proposition 4b. ICT inadequacies, lack of support from IT vendors, and IP rights protection inhibit the enhancing effect of AM adoption on the available alternatives for production sites.
Proposition 4c. AM adoption positively influences the rerouting of requirements, distributed capacity, reallocation of production, and dispersion of markets due to its enhancing effect on the available alternatives for production sites.
Proposition 4d. While AM adoption positively influences certain SC capabilities that reduce the vulnerability of the SC to production capacity, concentration of capacity, terrorism and sabotage, piracy and theft, distribution capacity, scale and extent of supply network, degree of outsourcing, import/export channels, supplier disruptions, and customer disruptions, it can also cause SC vulnerability to reliance upon information flow and industrial espionage.

3.3 Production capacity scalability

Production capacity scalability is estimated based on how easy it is to increase the production capacity when demand increases (Swafford et al., 2006). AM enables production capacity scalability by providing the required reserve capacity to complement CM, i.e., hybrid manufacturing model (Khajavi et al., 2014, 2015). This way, the erratic customer demand for products that are difficult to forecast (e.g., low-volume as well as low-demand parts) can be met with less effort (Sasson & Johnson, 2016). Also, in the case of early-stage production of new products that have no stable demand, AM can be used for small and medium production runs until demand becomes relatively stable so as to shift to CM methods (Berman, 2012). Moreover, the ability to rapidly manufacture the necessary tools for production (i.e., rapid tooling) or even the rapid manufacture of the end-use parts on-demand (i.e., rapid manufacturing) can help to quickly increase the production capacity to deal with sudden shifts in customer demand (Holmström et al., 2010, 2017). Therefore, adopting AM as a complementary production method to provide reserve capacity facilitates the scalability of the production capacity, which in turn reduces the complexity of production operations such as production planning (Holmström et al., 2016). Moreover, in case of deliberate disruptions in the CM processes, e.g., labor strikes, AM can be used to temporarily scale up the production capacity to meet the demand, since it is not a labor-intensive technology (Gebler et al., 2014) and can operate with fewer personnel. As opposed to CM, AM requires fewer tools and manual operations due to the automated manufacture of products (Weller et al., 2015) that leads to reduced setup times as well as fewer personnel, making it a suitable production method (in terms of time and cost) to scale up the production capacity in case of sudden disruptions.

However, for AM to scale up the production capacity effectively, the availability of stable sources of energy, e.g., electricity, is crucial (Schniederjans, 2017) as many AM processes are energy-intensive and consume high amounts of energy during the actual production phase. In the meantime, AM technology barriers such as the limited build envelope, limited automation, slow production speed, low throughput rate, and unstable AM processes can inhibit the positive impact of AM since such barriers can make the on-time scalability of the production capacity difficult.

Proposition 5a. AM adoption has an enhancing effect on production capacity scalability.

Proposition 5b. High energy consumption, limited build envelope, limited automation, slow production speed, low throughput rate, and unstable AM processes inhibit the enhancing effect of AM adoption on production capacity scalability.

Proposition 5c. AM adoption positively influences reserve capacity due to its enhancing effect on production capacity scalability.

Proposition 5d. While AM adoption positively influences reserve capacity that reduces the vulnerability of the SC to unpredictability in customer demand, complexity of process operations, union activities, and production capacity, it can also cause SC vulnerability to utilities availability.

3.4 Production lead time

This SC state variable indicates how easy it is to reduce production lead time (Swafford et al., 2006). One of AM's advantages over CM is its ability in reducing production lead times (Ghobadian et al., 2020), which helps the SC to become more adaptable to sudden shifts in customer demands. For instance, the reduced need for production tools leads to shorter setup and changeover times (Tuck et al., 2007), which incentivizes the use of AM to rapidly manufacture parts, especially when time is a crucial cost factor (Kunovjanek et al., 2020). Also, rapid manufacturing of parts can be performed on-demand and just-in-time, considerably reducing the production lead time (Holmström et al., 2010, 2016). Moreover, the reduced need for manual operations and assembly efforts together with other AM features such as reduced warehousing, packaging, and product handling (Pérès & Noyes, 2006; Gebler et al., 2014) contribute to reducing the production and delivery lead times as well as chances of theft and vandalism throughout the production process. Overall, such AM features shorten the SC by eliminating many redundant steps, leading to simplified SC with reduced lead times (Ghobadian et al., 2020; Naghshineh et al., 2021).

The reduced time-to-market enabled by rapid prototyping, which bridges the gap between the design and production phases (Berman, 2012), can lower the risk of disruptions caused by competitive innovation. This is the case since market demand can be met in a shorter time span, giving the competition a lower chance of disrupting the product launch (Khajavi et al., 2015), especially for products that possess complex geometries as AM creates them much faster and with fewer requirements due to its design freedom (Knofius et al., 2019). However, as AM processes are yet unstable, unforeseen technology failures are likely to take place that can offset the contributions of AM towards reducing production lead times.

Nevertheless, the current slow production speeds, limited automation, low throughput rates, and excessive post-processing requirements inhibit AM's great potential in reducing the production lead times. Also, the instability and low accuracy of AM processes may lead to scrap and rework (Chen et al., 2015; Colosimo et al., 2020), which consequently prolongs the production lead time.

Proposition 6a. AM adoption has an enhancing effect on reducing production lead time.
Proposition 6b. Slow production speed, limited automation, low throughput rate, excessive post-processing, and unstable AM processes inhibit the enhancing effect of AM adoption on reducing production lead time.
Proposition 6c. AM adoption positively influences lead time reduction due to its enhancing effect on reducing production lead time.

Proposition 6d. While AM adoption positively influences lead time reduction, which in turn reduces the vulnerability of the SC to unpredictability in customer demand, piracy and theft, and competitive innovation, it can also cause SC vulnerability to unforeseen technology failures.

3.5 Production schedule adaptability

Production schedule adaptability is defined by the "ease with which production schedules may be changed to accommodate customer needs" (Ramasesh et al., 2001). AM facilitates production schedule adaptability by allowing the actual production phase to be postponed (Waller & Fawcett, 2014). Many features of AM technology, e.g., the possibility to carry out the design and production steps almost simultaneously via rapid prototyping and rapid manufacturing (Niaki & Nonino, 2017), support production postponement. Also, different methods of distributed manufacturing enabled by AM technology (e.g., mobile manufacturing, on-demand manufacturing, or customer-centric production) contribute to production schedule flexibility since production can take place closer to where demand originates, thus reducing the delivery lead time and making it easier to postpone the production phase. Moreover, opting for an engineer/make-to-order production policy via AM (Christopher & Ryals, 2014) makes it easier to adapt the production schedules and postpone production if necessary.

The fact that AM does not require intermediary components to manufacture an end-use part (Knofius et al., 2019) and that inventories are normally kept in the form of fewer basic materials rather than FGI (Ford & Despeisse, 2016) makes it easier to change the production schedules. The automated nature of AM eliminates production requirements such as assembly efforts or manual interventions, making production planning easier (Weller et al., 2015). Moreover, short machine changeover times and small setup costs (Tuck et al., 2007, Kunovjanek et al., 2020) facilitate the postponing of production, which turns AM into an ideal manufacturing method to deal with the unpredictability in customer demands. Also, these AM features improve the firm's capacity to better handle customer disruptions, e.g., failure to pay on time, since production can be postponed.

Among the present AM adoption barriers, mainly the instability of AM processes raises concerns over AM's capability to punctually fulfil an order that is already postponed, since there may not be enough time left to rectify potential issues such as low quality of the produced part or instances of scrap and rework.

Proposition 7a. AM adoption has an enhancing effect on production schedule adaptability.
Proposition 7b. Unstable AM processes inhibit the enhancing effect of AM adoption on production schedule adaptability.

Proposition 7c. AM adoption positively influences production postponement due to its enhancing effect on production schedule adaptability.

Proposition 7d. AM adoption positively influences production postponement, which reduces the vulnerability of the SC to unpredictability in customer demand and customer disruptions.

3.6 Production capacity slack

This SC state variable indicates how easy it is to adjust the production capacity to meet erratic customer demands (Swafford et al., 2006). AM enables production capacity slack since "it facilitates the adjustment of production output to meet fluctuating customer demand" (Weller et al., 2015). For instance, by using a CM line to produce products with stable demand and designating the specialty items with unpredictable demand to an AM line (i.e., hybrid manufacturing model), adjusting production capacity becomes much easier. In other words, AM can be used "for variable production, aiding CM" (Verboeket & Kirkke, 2019), increasing asset utilization and making the production system more time- and cost-efficient. However, the present unstable AM processes raise concerns over the reliability of AM machines to successfully produce a part without causing scrap and rework (Colosimo et al., 2020), which would offset the production efficiency that AM brings about. Also, the limited long-term usability of AM machines can offset efficiency in terms of asset utilization. Other technological limitations of AM such as limited build envelope, limited automation, slow production speed, and low throughput rate, may as well inhibit the efficient adjusting of production capacity.

Proposition 8a. AM adoption has an enhancing effect on production capacity slack.

Proposition 8b. Unstable AM processes, limited long-term usability of AM machines, limited build envelope, limited automation, slow production speed, and low throughput rate inhibit the enhancing effect of AM adoption on production capacity slack.

Proposition 8c. AM adoption positively influences asset utilization due to its enhancing effect on production capacity slack.

Proposition 8d. While AM adoption positively influences asset utilization, which in turn reduces the vulnerability of the SC to unpredictability in customer demand, it can also cause SC vulnerability to the reliability of equipment (i.e., AM machines).

3.7 Distribution channels

This SC state variable indicates the ease with which a firm can switch between the existing distribution channels (Ramasesh et al., 2001). The transition from physical inventory to digital inventory via an AM production system (Chekurov et al., 2018) allows for easier logistics multisourcing (Ford & Despeisse, 2016). For instance, by replacing a wide range of stock-keeping units with digital inventory (Zanoni et al., 2019), there will be less FGI in the system leading to reduced stock levels as well as reduced requirements for warehousing, packaging, and transportation (Liu et al., 2014). This freedom in such requirements makes it easier to switch between distribution channels, which positively influences logistics multisourcing. This way the SC becomes more flexible in providing the necessary distribution capacity to deal with unpredictable customer demand as well as potential supplier/customer disruptions in different geographic locations. Other AM adoption impacts such as distributed manufacturing, mobile manufacturing, digital file distribution (instead of transporting FGI), and sourcing fewer raw materials (Li et al., 2017; Chan et al., 2018) facilitate logistics multisourcing and the use of alternate distribution channels. However, for such enhancing SC impacts of AM adoption to come to fruition, reliable ICT is essential since it enables the SC members to safely store and distribute digital files.

Proposition 9a. AM adoption has an enhancing effect on distribution channels.

Proposition 9b. ICT inadequacies inhibit the enhancing effect of AM adoption on distribution channels.

Proposition 9c. AM adoption positively influences logistics multisourcing and alternate distribution channels due to its enhancing effect on distribution channels.

Proposition 9d. AM adoption positively influences certain SC capabilities that reduce the vulnerability of the SC to distribution capacity, unpredictability in customer demand, customer disruptions, supplier disruptions, and exposure to geopolitical disruptions.

3.8 Transport mode

This SC state variable indicates the present number of alternatives for delivering different types of goods and materials (Swafford et al., 2006). Since AM input materials are fewer (Li et al., 2017; Chan et al., 2018) and are normally present in basic form, e.g., powder, sheet, wax, wire, etc. (Zanoni et al., 2019), they can be more easily adapted "to different transportation modalities", especially in the upstream SC (Verboeket & Krikke, 2019). Therefore, a variety of transport options can be used, which facilitates the use of alternate distribution channels. Another AM feature that can disentangle the present state of transportation in the SC is the "digital transportation of products" (Verboeket & Krikke, 2019), i.e., the possibility to distribute digital files instead of transporting actual goods (Ford & Despeisse, 2016). Also, different methods of distributed manufacturing (enabled by AM) such as mobile manufacturing, which is a simultaneous production and transport method (Ryan et al., 2017), enhance both the distribution capacity and the production capacity of the SC. These AM features create more flexible distribution channels that help to deal with geopolitical and supplier disruptions that can hinder the distribution of goods and materials. However, using different methods of distributed manufacturing via AM calls for advanced ICT requirements to be in place (Pérès & Noyes, 2006; Durão et al., 2017).

Proposition 10a. AM adoption has an enhancing effect on transport mode.
Proposition 10b. ICT inadequacies inhibit the enhancing effect of AM adoption on transport mode.
Proposition 10c. AM adoption positively influences alternate distribution channels due to its enhancing effect on transport mode.
Proposition 10d. AM adoption positively influences alternate distribution channels that reduce the vulnerability of the SC to distribution capacity, production capacity, exposure to geopolitical disruptions, and supplier disruptions.

3.9 Delivery lead time

This SC state variable indicates how easy it is to reduce the delivery lead time (Swafford et al., 2006). The localized structure of AM SCs results in closer proximity between manufacturers and customers (Ghobadian et al., 2020), reducing the transportation of goods and their delivery lead times. Also, the distributed methods of manufacturing via AM (e.g., on-demand manufacturing, customer-centric production, or mobile manufacturing) improve the distribution capacity of the SC by relocating production closer to customers, thus reducing the transportation and delivery lead times downstream SC (Ghadge et al., 2018). Even, in some cases, the need to transport an actual part is overcome by distributing a digital file instead (Ford & Despeisse, 2016). Additionally, the shift to the local supply of raw materials in AM SCs (Verboeket & Kirkke, 2019) leads to shorter distances between suppliers and manufacturers, resulting in reduced transportation and delivery lead times as well as fewer cases of inventory damage and theft upstream SC. Overall, shorter and simpler SCs via AM contribute to faster delivery lead times (Ghobadian et al., 2020; Kunovjanek et al., 2020). This improvement in delivery lead times can help firms better protect themselves against supplier disruptions as well as unpredictable customer demands. However, for the aforementioned AM features to function seamlessly, the existence of adequate ICT is essential. For instance, in the case of AM-enabled distributed manufacturing, the uninterrupted exchange of digital files becomes a crucial success factor (Durão et al., 2017).

Proposition 11a. AM adoption has an enhancing effect on reducing delivery lead time.
Proposition 11b. ICT inadequacies inhibit the enhancing effect of AM adoption on reducing delivery lead time.
Proposition 11c. AM adoption positively influences lead time reduction due to its enhancing effect on reducing delivery lead time.

Proposition 11d. AM adoption positively influences lead time reduction, which in turn reduces the vulnerability of the SC to distribution capacity, piracy and theft, supplier disruptions, and unpredictability in customer demand.

3.10 Available alternatives for sources of supply

This SC state variable indicates the number of available alternatives for sources of supply (Ramasesh et al., 2001) that enable manufacturers to get the necessary input material for their production operations. The limited number of AM material suppliers (Niaki & Nonino, 2017) as well as the limited variety and high cost of AM material (Durach et al., 2017), make it difficult for manufacturers to find alternative sources of supply, which in turn can increase the risk of raw material unavailability and limited production capacity. This is the case since the production capacity of the manufacturers becomes highly reliant on the capacity of (a limited number of) suppliers to deliver the promised AM material (i.e., reliance upon specialty sources) at the right time, in the right quantity, and at the right price. Under such circumstances, any delay, disruption, or breach of the agreement by the suppliers can result in a shortage of AM input material that can prevent the manufacturers from fulfilling their customers' orders on time. Also, other barriers that can inhibit the availability of raw material are the lack of AM material standardization, AM material regulations, and the limited traceability of AM material that further restrict the options of manufacturers in choosing the appropriate AM material suppliers. Hence, the ensuing inflexibility in sourcing caused by such inhibitions makes it very difficult to deal with unpredictability in customer demand. Also, such sourcing inflexibility can make the SC become very vulnerable to acts of terrorism and sabotage that would significantly disrupt the limited supply of material, thus restricting the manufacturers' production operations (due to material shortage) and their ability to fulfil customer orders.

Proposition 12a. AM adoption has a limiting effect on the available alternatives for sources of supply.

Proposition 12b. Limited variety and supply of AM material, high cost of AM material, lack of AM material standardization, AM material regulations, and limited traceability of AM material reinforce the limiting effect of AM adoption on the available alternatives for sources of supply.

Proposition 12c. AM adoption negatively influences (the availability of) alternate suppliers due to its limiting effect on the available alternatives for sources of supply.

Proposition 12d. AM adoption negatively influences (the availability of) alternate suppliers, which in turn increases the vulnerability of the SC to raw material availability, supplier capacity, production capacity, reliance upon specialty sources, unpredictability in customer demand, and terrorism and sabotage.

3.11 Relationship type

Relationship type is defined by the degree of cooperation with other firms in the SC (Lin et al., 2006). AM's features affect the relationship type between SC members in different ways. With respect to supply, the high dependency of the manufacturing firms on the supply of AM machines and raw materials drives them to closely collaborate with their suppliers (Oettmeier & Hofmann, 2016), which positively affects the postponement of orders in case of supplier disruptions. The demand side of the SC, however, can be affected by different AM adoption impacts. For instance, engineer/make-to-order production, mass customization, customer-centric production, co-creation/co-design, and production postponement are AM features that allow the manufacturers to closely collaborate with their customers, enabling them to effectively deal with the unpredictability in customer demands as well as potential customer disruptions. The possibility to strengthen customer relationships via such AM features may grant manufacturers a strong market position, allowing them to better deal with erratic customer demands. Also, new possibilities for product and SC innovation as well as new business models via AM gives firms an edge against the fierce competition in contemporary markets (Beltagui et al., 2020). The main barrier, however, is the lack of awareness and acceptance of AM technology by the customers (Durach et al., 2017), which can inhibit the degree of cooperation in the SC.

Proposition 13a. AM adoption has an enhancing effect on relationship type.

Proposition 13b. Lack of customer awareness and acceptance inhibits the enhancing effect of AM adoption on relationship type.

Proposition 13c. AM adoption positively influences the postponement of orders and customer relationships due to its enhancing effect on relationship type.

Proposition 13d. AM adoption positively influences certain SC capabilities that reduce the vulnerability of the SC to supplier disruptions, unpredictability in customer demand, customer disruptions, and competitive innovation.

3.12 Information sharing

This SC state variable indicates how easy it is to exchange reliable and timely information with SC partners (Ramasesh et al., 2001). When operating in an AM setting, the significant changes in terms of how inventory can be stored in the form of digital files (rather than FGI) and distributed digitally (Chekurov et al., 2018) will impact the use of information systems and information exchange among the SC partners to a great extent. This evolution will not only make inventory management more efficient but will also create more visible SCs. Collaborative information sharing as well as collaborative demand forecasting will become easier, allowing the SC partners to better anticipate customer demands as well as customer/supplier disruptions. This advancement can also lead to improved degrees of outsourcing since digital files can be easily shared among the SC partners, augmenting the production capacity of the SC. Overall, it can be expected that the adoption of AM technology will stimulate information sharing, and therefore reliance on information flow will increase turning it into a critical success factor. In such circumstances, cases of industrial espionage can increase in the absence of reliable ICT, creating cybersecurity vulnerabilities to knowledge leaks that can lead to IP rights complications. Also, timely support from IT vendors will be crucial for resolving IT-related problems such as software issues (Thomas-Seale et al., 2018).

Proposition 14a. AM adoption has an enhancing effect on information sharing.

Proposition 14b. ICT inadequacies, IP rights protection, and lack of support from IT vendors inhibit the enhancing effect of AM adoption on information sharing.

Proposition 14c. AM adoption positively influences information exchange, demand forecasting, inventory management, collaborative forecasting, and collaborative information sharing due to its enhancing effect on information sharing.

Proposition 14d. While AM adoption positively influences certain SC capabilities that reduce the vulnerability of the SC to unpredictability in customer demand, degree of outsourcing, supplier disruptions, production capacity, and customer disruptions, it can also cause SC vulnerability to reliance upon information flow and industrial espionage.

3.13 Propositions' rankings

In an attempt to estimate the strength of the generated propositions, we presumed each paper in the sample as a unit of analysis and considered the following ranking criteria: i) the number of papers that provided supporting evidence for a proposition set (denoted by *x*), ii) the sum of journal impact factors of the papers that provided supporting evidence for a proposition set (denoted by *y*), and iii) the number of citations received by the papers that provided supporting evidence for a proposition set (denoted by *z*). The values for *y* and *z* were retrieved from the SJR database (as of April 2021). Next, considering that the sum of journal impact factors for all the 87 papers in the sample was (about) 155 and the total number of citations received by all the papers in the sample was 9768, the following scores were computed for each proposition set (denoted by *Proposition i*):

- Score 1: *x*/87. This score indicates the ratio of the papers that provide supporting evidence for a proposition set to all papers in the sample.
- Score 2: *y*/155. This score indicates the journal reputation of the papers that provide supporting evidence for a proposition set relative to the journal reputation of all the papers in the sample.

- Score 3: *z*/9768. This score partly indicates the notability of the papers that provide supporting evidence for a proposition set relative to the notability of the entire sample.

Assuming equal weights for all three scores, a final score was computed by their summation (ranging from maximum 3 to minimum 0). Table 3 presents the computed scores and lists the proposition sets based on their specified rankings. The scores indicate that proposition set 7 is highly supported by the sample, implying that adopting AM technology is expected to considerably enhance the possibility to change production schedules, which adds to the flexibility of the SC in fulfilling customer orders and dealing with erratic customer demands. Contrariwise, proposition set 12 has the lowest final score, which implies that evidence in the sample regarding the limiting effect of AM adoption on the availability of alternative sources of supply and its ensuing SCR implications is not substantial.

Table 3. Propositions' rankings

Proposition i	**Score 1**	**Score 2**	**Score 3**	**Final Score**	**Ranking**
P7	0.85	0.85	0.91	2.61	1st
P6	0.78	0.78	0.92	2.48	2nd
P11	0.78	0.77	0.83	2.38	3rd
P5	0.71	0.71	0.88	2.30	4th
P13	0.72	0.71	0.79	2.22	5th
P1	0.68	0.66	0.85	2.20	6th
P2	0.67	0.64	0.82	2.12	7th
P4	0.66	0.63	0.74	2.02	8th
P3	0.60	0.59	0.79	1.98	9th
P9	0.56	0.54	0.71	1.82	10th
P14	0.55	0.52	0.71	1.78	11th
P10	0.53	0.51	0.69	1.74	12th
P8	0.44	0.43	0.52	1.39	13th
P12	0.34	0.33	0.54	1.22	14th

4. AM-SCR framework

The proposed AM-SCR framework (Figure 6) represents the results of the critical analysis and synthesis that was performed on the gathered evidence from the sample, illustrating the identified relationships between 32 AM adoption impacts, 25 AM adoption barriers, 12 SC state variables (designated by 14 different metrics), 10 SC capabilities (represented by 22 different SC capability subfactors), and 7 SC vulnerabilities (represented by 25 different SC vulnerability subfactors) in the context of SCR. It should be noted that two of the identified AM adoption impacts (in Appendix A), i.e., “Sustainable production” and “Product life cycle extension”, and 7 of the AM adoption barriers (in Appendix B) were not used in the critical review since we did not find relevant supporting evidence for their inclusion.

The proposed AM-SCR framework provides answers to the main RQ by indicating the implications of AM adoption for SCR. In other words, using the AM-SCR framework, one can observe and trace the changes that take place in the state of the SC (due to AM adoption), which consequently influence certain SC capabilities and SC vulnerabilities that affect SCR. For instance, in the case of the SC state variable “Available alternatives for production sites”, it can be observed that AM adoption will influence “Adaptability”, “Dispersion”, and “Flexibility” SC capabilities due to its impacts on the number of available alternatives for production sites. Additionally, it is possible to clearly understand how each SC capability is influenced as there are specified SC capability subfactors (for each SC capability) that help capture the actual indirect effects of AM adoption. For instance, in the previous example, it can be seen that “Adaptability” is influenced by enhancements in “Rerouting of requirements”, which indicates how quickly a firm can reallocate its jobs/orders to alternative production facilities in case of unforeseen disruptions (Pettit et al., 2013). Hence, by highlighting the indirect effects of AM adoption on the SC capability subfactors, the proposed AM-SCR framework allows academics and practitioners to speculate if (and how) adopting AM technology enables firms to develop the SC capabilities they need to deal with SC vulnerabilities and their ensuing disruptions.

Similarly, another observation based on the AM-SCR framework is how adopting AM influences certain SC vulnerabilities. For instance, when outsourcing the AM production processes to external entities (i.e., “Possibility to outsource production processes”), it can be observed that the SC vulnerabilities “Resource limits”, “Sensitivity”, “Turbulence”, “Deliberate threats”, and “Connectivity” are influenced. Moreover, it is possible to trace the changes in each SC vulnerability via the specified SC vulnerability subfactors. For instance, the enhancements in the “Rerouting of requirements” due to the outsourcing of AM production processes would partly reduce the vulnerability of the SC to “Production capacity”, which represents the SC vulnerability “Resource limits”, whereas “Reliance upon information flow”, which represents the SC vulnerability “Connectivity”, can become an issue (as explained in section three). This is an important observation that allows academics and practitioners to recognize how the impacts of AM adoption would affect SCR in terms of SC vulnerabilities. Additionally, the AM adoption barriers that are highlighted in red are likely to intensify certain SC vulnerabilities (that are also highlighted in red). For instance, throughout the framework, it can be seen that in the cases where “Reliance upon information flow” is an

SC vulnerability subfactor, “ICT inadequacies” is also identified as an AM adoption barrier. This is an important observation since it highlights the AM adoption barriers that can deteriorate SCR.

There are in total 88 distinct paths in the AM-SCR framework that draw attention to possible effects of AM adoption on SCR. Figure 6 indicates that:

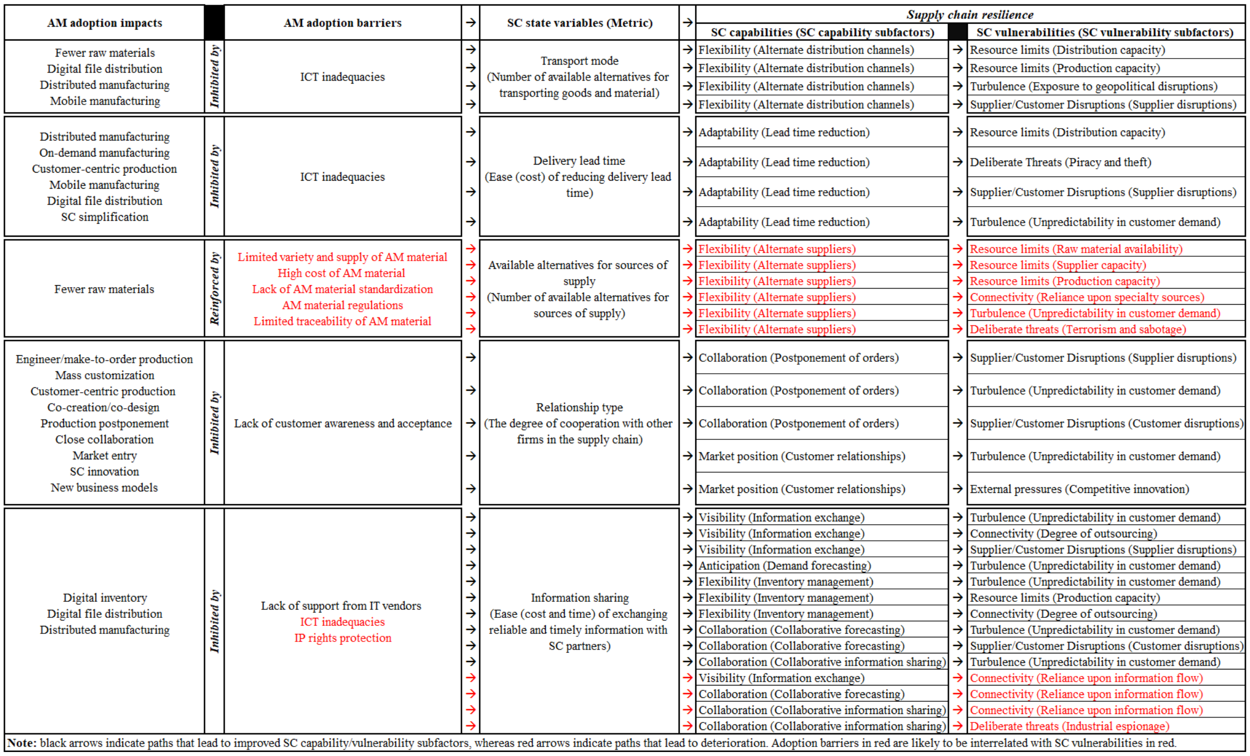
- There are 68 paths (indicated by black arrows) that lead to improvements in the SC capability subfactors and consequently the SC vulnerability subfactors linked to them.
- There are 6 paths (indicated by red arrows) that lead to deterioration in the SC capability subfactor “Alternate suppliers”.
- There are 20 paths (indicated by red arrows) that lead to deterioration in the SC vulnerability subfactors.

It is worth noting that the SC capability/vulnerability subfactors that are highlighted in red are those that deteriorate. In light of these considerations, the extent to which AM adoption would affect SCR will be estimated (in section five) based on the 74 paths that influence the SC capabilities and the 88 paths that influence the SC vulnerabilities. In section five, we discuss in detail the distribution of the AM adoption’s indirect effects among the identified SC capabilities and SC vulnerabilities as well as their respective sub-factors.

AM adoption impacts		AM adoption barriers	→	SC state variables (Metric)	→	*Supply chain resilience*		
						SC capabilities (SC capability subfactors)	→	**SC vulnerabilities (SC vulnerability subfactors)**
Outsourcing production Capacity pooling Distributed manufacturing Customer-centric production Digital file distribution Digital inventory	*Inhibited by*	Lack of AM process standards High cost of AM processes Lack of AM material standardization Limited traceability of AM material AM material regulations ICT inadequacies IP rights protection	→	Available alternatives for production processes (Possibility to outsource production processes)	→	Flexibility (Reallocation of production)	→	Resource limits (Distribution capacity)
			→		→	Adaptability (Rerouting of requirements)	→	Resource limits (Production capacity)
			→		→	Recovery (Consequence mitigation)	→	Sensitivity (Reliability of equipment)
			→		→	Recovery (Consequence mitigation)	→	Turbulence (Exposure to geopolitical disruptions)
			→		→	Adaptability (Rerouting of requirements)	→	Deliberate threats (Union activities)
			→		→	Dispersion (Distributed capacity)	→	Sensitivity (Concentration of capacity)
			→		→	Recovery (Consequence mitigation)	→	Turbulence (Unpredictability in customer demand)
			→		→	Dispersion (Distributed capacity)	→	Resource limits (Distribution capacity)
			→		→	Flexibility (Logistics multisourcing)	→	Resource limits (Distribution capacity)
			→		→	Flexibility (Logistics multisourcing)	→	Resource limits (Production capacity)
			→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Piracy and theft)
			→		→	Flexibility (Reallocation of production)	→	Sensitivity (Importance of product purity)
			→		→	Recovery (Consequence mitigation)	→	Sensitivity (Utilization of restricted materials)
			→		→	Adaptability (Rerouting of requirements)	→	Connectivity (Reliance upon information flow)
			→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Industrial espionage)
Design freedom Hybrid manufacturing model Automated manufacturing Tool-less production Remote work Economies of technology Mobile manufacturing Process integration	*Inhibited by*	Lack of multi-material printing Limited build envelope Excessive post-processing Unstable AM processes Slow production speed Limited automation Lack of guidelines to fully exploit AM	→	Available alternatives for production processes (Operations versatility)	→	Flexibility (Multiple pathways)	→	Turbulence (Unpredictability in customer demand)
			→		→	Flexibility (Multiple pathways)	→	Supplier/Customer Disruptions (Customer disruptions)
			→		→	Adaptability (Alternate technology)	→	Sensitivity (Complexity of process operations)
			→		→	Adaptability (Alternate technology)	→	Connectivity (Scale and extent of supply network)
			→		→	Adaptability (Alternate technology)	→	Connectivity (Reliance upon specialty sources)
Hybrid manufacturing model Tool-less production	*Inhibited by*	Slow production speed Limited automation Low throughput rate High cost of AM machines High cost of repair and maintenance Lack of AM knowledge and design skills Lack of personnel education and training Unstable AM processes Limited long-term usability of AM machines	→	Available alternatives for production processes (Redundancy in production processes)	→	Capacity (Redundant assets)	→	Resource limits (Production capacity)
			→		→	Capacity (Redundant assets)	→	Deliberate threats (Terrorism and sabotage)
			→		→	Capacity (Redundant assets)	→	Sensitivity (Reliability of equipment)
Distributed manufacturing On-demand manufacturing Mobile manufacturing Market entry Import/export substitution	*Inhibited by*	Lack of support from IT vendors ICT inadequacies IP rights protection	→	Available alternatives for production sites (Number of available alternatives for production sites)	→	Adaptability (Rerouting of requirements)	→	Resource limits (Production capacity)
			→		→	Dispersion (Distributed capacity)	→	Sensitivity (Concentration of capacity)
			→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Terrorism and sabotage)
			→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Piracy and theft)
			→		→	Flexibility (Reallocation of production)	→	Resource limits (Distribution capacity)
			→		→	Adaptability (Rerouting of requirements)	→	Resource limits (Distribution capacity)
			→		→	Dispersion (Distributed capacity)	→	Resource limits (Distribution capacity)
			→		→	Dispersion (Dispersion of markets)	→	Connectivity (Scale and extent of supply network)
			→		→	Dispersion (Dispersion of markets)	→	Connectivity (Degree of outsourcing)
			→		→	Dispersion (Dispersion of markets)	→	Connectivity (Import/export channels)
			→		→	Dispersion (Dispersion of markets)	→	Supplier/Customer Disruptions (Supplier disruptions)
			→		→	Dispersion (Dispersion of markets)	→	Supplier/Customer Disruptions (Customer disruptions)
			→		→	Adaptability (Rerouting of requirements)	→	Connectivity (Reliance upon information flow)
			→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Industrial espionage)
Hybrid manufacturing model Small production runs Medium production runs Rapid tooling Rapid manufacturing Tool-less production Automated manufacturing	*Inhibited by*	Limited build envelope Limited automation Slow production speed Low throughput rate Unstable AM processes High energy consumption	→	Production capacity scalability (Ease (cost and time) of increasing production capacity)	→	Capacity (Reserve capacity)	→	Turbulence (Unpredictability in customer demand)
			→		→	Capacity (Reserve capacity)	→	Sensitivity (Complexity of process operations)
			→		→	Capacity (Reserve capacity)	→	Deliberate threats (Union activities)
			→		→	Capacity (Reserve capacity)	→	Resource limits (Production capacity)
			→		→	Capacity (Reserve capacity)	→	Resource limits (Utilities availability)
Tool-less production Rapid manufacturing On-demand manufacturing Just-in-time production Automated manufacturing SC simplification Rapid prototyping Design freedom	*Inhibited by*	Slow production speed Limited automation Low throughput rate Excessive post-processing Unstable AM processes	→	Production lead time (Ease (cost) of reducing production time)	→	Adaptability (Lead time reduction)	→	Turbulence (Unpredictability in customer demand)
			→		→	Adaptability (Lead time reduction)	→	Deliberate threats (Piracy and theft)
			→		→	Adaptability (Lead time reduction)	→	External pressures (Competitive innovation)
			→		→	Adaptability (Lead time reduction)	→	Turbulence (Unforeseen technology failures)
Production postponement Design freedom Rapid prototyping Rapid manufacturing Distributed manufacturing Mobile manufacturing On-demand manufacturing Customer-centric production Engineer/make-to-order production Fewer raw materials Automated manufacturing	*Inhibited by*	Unstable AM processes	→	Production schedule adaptability (Ease (cost and time) of changing the production schedules)	→	Flexibility (Production postponement)	→	Turbulence (Unpredictability in customer demand)
			→		→	Flexibility (Production postponement)	→	Supplier/Customer Disruptions (Customer disruptions)
Hybrid manufacturing model	*Inhibited by*	Limited build envelopes Limited automation Slow production speed Low throughput rate Unstable AM processes Limited long-term usability of AM machines	→	Production capacity slack (Ease (cost and time) of adjusting the production capacity)	→	Efficiency (Asset utilization)	→	Turbulence (Unpredictability in customer demand)
			→		→	Efficiency (Asset utilization)	→	Sensitivity (Reliability of equipment)
Digital inventory Digital file distribution Distributed manufacturing Mobile manufacturing Fewer raw materials	*Inhibited by*	ICT inadequacies	→	Distribution channels (Ease (cost and time) of switching between distribution channels)	→	Flexibility (Logistics multisourcing)	→	Resource limits (Distribution capacity)
			→		→	Flexibility (Logistics multisourcing)	→	Turbulence (Unpredictability in customer demand)
			→		→	Flexibility (Logistics multisourcing)	→	Supplier/Customer Disruptions (Customer disruptions)
			→		→	Flexibility (Alternate distribution channels)	→	Supplier/Customer Disruptions (Supplier disruptions)
			→		→	Flexibility (Alternate distribution channels)	→	Turbulence (Exposure to geopolitical disruptions)

Note: black arrows indicate paths that lead to improved SC capability/vulnerability subfactors, whereas red arrows indicate paths that lead to deterioration. Adoption barriers in red are likely to be interrelated with SC vulnerabilities in red.

Figure 6. AM-SCR framework



AM adoption impacts		AM adoption barriers	→	SC state variables (Metric)	→	*Supply chain resilience*		
						SC capabilities (SC capability subfactors)		SC vulnerabilities (SC vulnerability subfactors)
Fewer raw materials Digital file distribution Distributed manufacturing Mobile manufacturing	*Inhibited by*	ICT inadequacies	→	Transport mode (Number of available alternatives for transporting goods and material)	→	Flexibility (Alternate distribution channels)	→	Resource limits (Distribution capacity)
			→		→	Flexibility (Alternate distribution channels)	→	Resource limits (Production capacity)
			→		→	Flexibility (Alternate distribution channels)	→	Turbulence (Exposure to geopolitical disruptions)
			→		→	Flexibility (Alternate distribution channels)	→	Supplier/Customer Disruptions (Supplier disruptions)
Distributed manufacturing On-demand manufacturing Customer-centric production Mobile manufacturing Digital file distribution SC simplification	*Inhibited by*	ICT inadequacies	→	Delivery lead time (Ease (cost) of reducing delivery lead time)	→	Adaptability (Lead time reduction)	→	Resource limits (Distribution capacity)
			→		→	Adaptability (Lead time reduction)	→	Deliberate Threats (Piracy and theft)
			→		→	Adaptability (Lead time reduction)	→	Supplier/Customer Disruptions (Supplier disruptions)
			→		→	Adaptability (Lead time reduction)	→	Turbulence (Unpredictability in customer demand)
Fewer raw materials	*Reinforced by*	Limited variety and supply of AM material High cost of AM material Lack of AM material standardization AM material regulations Limited traceability of AM material	→	Available alternatives for sources of supply (Number of available alternatives for sources of supply)	→	Flexibility (Alternate suppliers)	→	Resource limits (Raw material availability)
			→		→	Flexibility (Alternate suppliers)	→	Resource limits (Supplier capacity)
			→		→	Flexibility (Alternate suppliers)	→	Resource limits (Production capacity)
			→		→	Flexibility (Alternate suppliers)	→	Connectivity (Reliance upon specialty sources)
			→		→	Flexibility (Alternate suppliers)	→	Turbulence (Unpredictability in customer demand)
			→		→	Flexibility (Alternate suppliers)	→	Deliberate threats (Terrorism and sabotage)
Engineer/make-to-order production Mass customization Customer-centric production Co-creation/co-design Production postponement Close collaboration Market entry SC innovation New business models	*Inhibited by*	Lack of customer awareness and acceptance	→	Relationship type (The degree of cooperation with other firms in the supply chain)	→	Collaboration (Postponement of orders)	→	Supplier/Customer Disruptions (Supplier disruptions)
			→		→	Collaboration (Postponement of orders)	→	Turbulence (Unpredictability in customer demand)
			→		→	Collaboration (Postponement of orders)	→	Supplier/Customer Disruptions (Customer disruptions)
			→		→	Market position (Customer relationships)	→	Turbulence (Unpredictability in customer demand)
			→		→	Market position (Customer relationships)	→	External pressures (Competitive innovation)
Digital inventory Digital file distribution Distributed manufacturing	*Inhibited by*	Lack of support from IT vendors ICT inadequacies IP rights protection	→	Information sharing (Ease (cost and time) of exchanging reliable and timely information with SC partners)	→	Visibility (Information exchange)	→	Turbulence (Unpredictability in customer demand)
			→		→	Visibility (Information exchange)	→	Connectivity (Degree of outsourcing)
			→		→	Visibility (Information exchange)	→	Supplier/Customer Disruptions (Supplier disruptions)
			→		→	Anticipation (Demand forecasting)	→	Turbulence (Unpredictability in customer demand)
			→		→	Flexibility (Inventory management)	→	Turbulence (Unpredictability in customer demand)
			→		→	Flexibility (Inventory management)	→	Resource limits (Production capacity)
			→		→	Flexibility (Inventory management)	→	Connectivity (Degree of outsourcing)
			→		→	Collaboration (Collaborative forecasting)	→	Turbulence (Unpredictability in customer demand)
			→		→	Collaboration (Collaborative forecasting)	→	Supplier/Customer Disruptions (Customer disruptions)
			→		→	Collaboration (Collaborative information sharing)	→	Turbulence (Unpredictability in customer demand)
			→		→	Visibility (Information exchange)	→	Connectivity (Reliance upon information flow)
			→		→	Collaboration (Collaborative forecasting)	→	Connectivity (Reliance upon information flow)
			→		→	Collaboration (Collaborative information sharing)	→	Connectivity (Reliance upon information flow)
			→		→	Collaboration (Collaborative information sharing)	→	Deliberate threats (Industrial espionage)

Note: black arrows indicate paths that lead to improved SC capability/vulnerability subfactors, whereas red arrows indicate paths that lead to deterioration. Adoption barriers in red are likely to be interrelated with SC vulnerabilities in red.

Figure 6. AM-SCR framework (cont.)

5. Research implications

5.1. Theoretical implications

In the following subsections, an overview of the theoretical implications of AM adoption for the state of the SC as well as the identified SC capabilities and SC vulnerabilities are presented, which are complemented by illustrative examples from the AM-SCR framework (Figure 6). Moreover, to project the extent to which AM adoption would affect SCR, two typologies (i.e., Figure 7 and Figure 8) are presented that depict the extent of AM adoption's indirect effects on the identified SC capabilities and SC vulnerabilities respectively.

5.1.1 AM adoption and the state of the SC

Based on the critical review findings, almost in all cases, the adoption of AM technology has an enhancing effect on the state of the SC (refer to *Propositions ia*). The propositions' rankings (Table 3) suggest that "Production schedule adaptability" would be enhanced considerably by AM adoption. The only case where adopting AM seems to cause limitations is related to the "Available alternatives for sources of supply", which however according to the propositions' rankings would be the least affected SC state variable. The AM adoption impacts that cause such effects are stated in the AM-SCR framework. For instance, the framework indicates that the use of “Fewer raw materials” has an enhancing effect on “Production schedule adaptability”, “Distribution channels”, and “Transport mode”, whereas it limits the “Available alternatives for sources of supply”. Also, the identified AM adoption barriers “Limited variety and supply of AM material”, “High cost of AM material”, “Lack of AM material standardization”, “AM material regulations”, and “Limited traceability of AM material” tend to further reinforce the limiting effect of AM adoption on the SC state variable “Available alternatives for sources of supply”, which is an instance of *Propositions ib*. Similar observations can be made by academics and practitioners in order to examine how different impacts and barriers of AM adoption can affect the state of the SC that would consequently affect SCR.

It is worth noting that there seem to be existing interrelations between the identified AM adoption impacts that affect the state of the SC. For example, in all cases where “Digital file distribution” is identified as an AM adoption impact, “Distributed manufacturing” is also present. Also, in line with Dwivedi et al. (2017), we presume that there are existing interrelations between some of the AM adoption barriers. For instance, in the cases where “IP rights protection” appears to be a barrier, “ICT inadequacies” is present as well. The same appears to be the case between the adoption barriers “Lack of AM material standardization”, “Limited traceability of AM material”, and “AM material regulations”.

5.1.2 AM adoption and SCR

To gain a broader perspective on the results of the critical review regarding the indirect effects of AM adoption on SCR, we present and discuss two typologies. The projected percentages in Figure 7 and Figure 8 indicate the extent to which AM adoption (based on the critical review findings) influences the SC capabilities and SC vulnerabilities by means of considering the number of identified paths, which were explained in section four. Each percentage indicates the ratio between the number of paths that lead to a specific SC capability/vulnerability and the total number of identified paths (i.e., 74 for SC capabilities and 88 for SC vulnerabilities), which are indicated by black/red arrows in the AM-SCR framework (Figure 6). In the following subsections, illustrative examples are discussed that further clarify the percentages. Also, it should be noted that the percentages in Figure 7 and Figure 8 were rounded up to the nearest second decimal place for simplicity.

5.1.2.1 AM adoption and SC capabilities

The first typology depicts the extent to which AM adoption indirectly affects the identified SC capabilities. At first glance, Figure 7 indicates that AM adoption considerably contributes to improving the “Flexibility” of the SC. This indirect effect is illustrated in the AM-SCR framework by the 20 paths (represented by black arrows) that connect various SC state variables to “Flexibility”, indicating the positive influence of AM adoption on this SC capability, which by itself accounts for about 27% (20/74) of the total indirect effects of AM adoption on the SC capabilities. Also, it is possible to further analyze this indirect effect by examining the SC capability subfactors that represent “Flexibility”. For instance, the AM-SCR framework indicates that AM adoption positively influences “Production postponement” by making it easier to change production schedules, which in turn makes the SC more flexible in dealing with “Unpredictability in customer demand” as well as “Customer disruptions”. Moreover, AM adoption positively influences the “Flexibility” of the SC by creating opportunities to improve “Reallocation of production”, “Logistics multisourcing”, “Multiple pathways”, “Alternate distribution channels”, and “Inventory management”. These insights regarding the positive impacts of AM adoption on SC flexibility are mainly in line with the findings of Delic and Eyers (2020). However, it should be noted that according to our findings, adopting AM can also deteriorate the sourcing flexibility of the SC mainly due to the present AM adoption barriers explained in subsection 3.10. The negative influence of this impact is indicated in the AM-SCR framework by the 6 paths that lead to “Flexibility (Alternate suppliers)” (indicated by red arrows), which accounts for about 8% (6/74) of the indirect effects. Nonetheless, altogether “Flexibility” accounts for almost 35% (26/74) of the total indirect effects of AM adoption on the SC capabilities shown in Figure 7.

The second most influenced SC capability is “Adaptability”, which is considerably improved by reducing the production and delivery lead times (i.e., “Lead time reduction”) as well as facilitating the “Rerouting of requirements” and the use of “Alternate technology”. “Dispersion” takes third place due to considerable improvements in the “Distributed capacity” and “Dispersion of markets”, which can be attributed to AM’s capability in enabling different forms of distributed manufacturing. The fourth most influenced SC capability is “Collaboration” since different methods of collaborating with other SC members such as “Postponement of orders”, “Collaborative information sharing”, and “Collaborative forecasting” are supported by the digital characteristics of AM. The fifth SC capability is “Capacity”, which is improved by “Redundant assets” as well as the “Reserve capacity” that AM can provide mainly through a hybrid manufacturing model (as explained in section 3). “Visibility”, “Recovery”, “Market position”, “Efficiency”, and “Anticipation” account for the remaining 13% of AM adoption’s influence on the SC capabilities.

Figure 7 classifies the main SC capabilities that were identified in this review to help project SCR (refer to *Propositions ic*). It also summarizes the results of the critical review by showing the distribution of the identified indirect effects of AM adoption among the SC capabilities and their subfactors respectively.

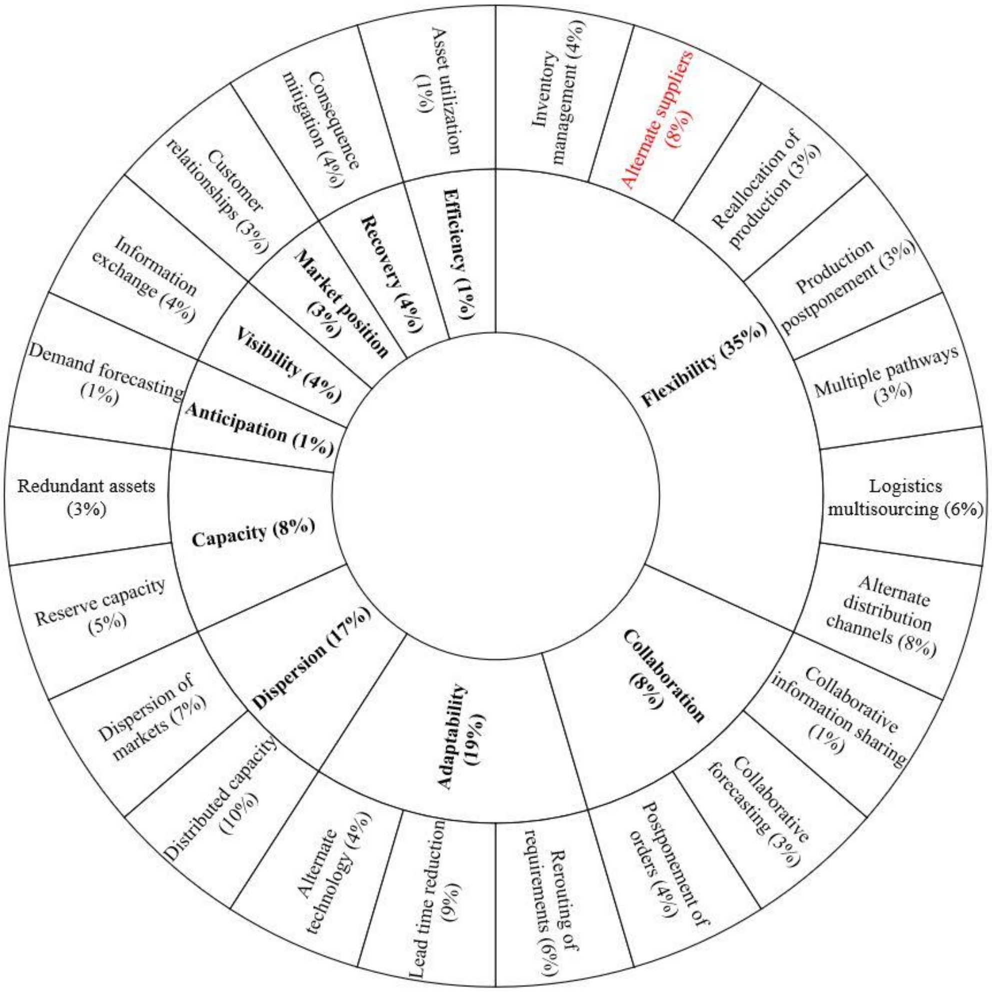


Figure 7. Distribution of the identified AM adoption's indirect effects among SC capabilities

5.1.2.2 AM adoption and SC vulnerabilities

When considering the SC vulnerabilities that are influenced by AM adoption, "Resource limits" and "Turbulence" take first place (Figure 8). As indicated in the AM-SCR framework (Figure 6), in four cases the adoption of AM leads to an increase in SC vulnerability to "Resource limits" (explained in section 3), whereas in 16 other cases AM adoption reduces this SC vulnerability by mitigating "Production capacity" and "Distribution capacity" shortages. Nevertheless, when considering the SC state variable "Available alternatives for sources of supply", SC vulnerability to "Production capacity" tends to increase mainly because of the present barriers to sourcing AM materials, i.e., "Limited variety and supply of AM material", "High cost of AM material", "Lack of AM material standardization", "AM material regulations", and "Limited traceability of AM material". This instance may raise the question of why only in this specific case “Production capacity” appears to be an SC vulnerability subfactor and whether rectifying the aforementioned AM adoption barriers would help alleviate this SC vulnerability subfactor. Also, in this case, “Production capacity” seems to be interrelated with two other SC vulnerability subfactors that amplify “Resource limits”, i.e., “Raw material availability” and “Supplier capacity”.

As for “Turbulence”, only in two cases, AM adoption increases this SC vulnerability, whereas in 18 other cases AM adoption has a mitigating effect on it. AM adoption mainly reduces “Turbulence” by improving the SC capability subfactors that reduce “Unpredictability in customer demand”. However, when considering the “Available alternatives for sources of supply”, AM tends to increase the vulnerability of the SC to “Unpredictability in customer demand”. This seems to be the case since the present barriers to sourcing AM materials would limit the number of sources of supply, thus making the SC less flexible (in sourcing). Based on this observation, it can be assumed that resolving the present barriers to sourcing AM materials would reduce the SC vulnerability to “Unpredictability in customer demand”. Similarly, rectifying the AM adoption barrier “Unstable AM processes” may mitigate “Unforeseen technology failures” and consequently reduce “Turbulence”. These observations also imply that there may be existing interrelations between some of the AM adoption barriers and the identified SC vulnerabilities.

While AM adoption tends to decrease the vulnerability of the SC to “Supplier/Customer Disruptions”, there is a mixed effect regarding “Connectivity”, i.e., SC vulnerability tends to increase in the case of “Reliance upon information flow” and “Reliance upon specialty sources” contrary to other “Connectivity” vulnerability subfactors. When examining the AM-SCR framework, in all cases where “Reliance upon information flow” is an SC vulnerability subfactor, “ICT inadequacies” is also identified as an AM adoption barrier, which once again compels the assumption that there are interrelations between certain AM adoption barriers and SC vulnerabilities. Also, “Reliance upon specialty sources” in the case of AM materials increases, whereas in the case of specialty items and components this SC vulnerability subfactor decreases (mainly because of AM’s design freedom and manufacture possibilities, e.g., component consolidation).

Regarding “Deliberate threats”, AM adoption tends to mitigate this SC vulnerability in most cases. However, vulnerability tends to increase with respect to “Industrial espionage” due to higher levels of information exchange in AM settings that expose the SC to vulnerabilities caused by ICT issues. In all cases where “Industrial espionage” is identified as an SC vulnerability subfactor, “ICT inadequacies” and “IP rights protection” turn out to be two of the main identified AM adoption barriers, implying another instance of AM adoption barriers being potentially interrelated with certain SC vulnerabilities. Moreover, AM adoption can increase “Sensitivity” to process and product integrity due to vulnerabilities concerning the

"Reliability of equipment", "Utilization of restricted materials", and "Importance of product purity", which may be improved over time as the AM adoption barriers "Unstable AM processes", "Limited long-term usability of AM machines", "AM material regulations", "Limited traceability of AM material" and "Lack of AM material standardization" are addressed. Lastly, "External pressures" caused by "Competitive innovation" is likely to subside as explained in Section 3.

Figure 8 classifies the main SC vulnerabilities that were identified in this review to help project SCR (refer to *Propositions id*). It also summarizes the critical review findings by showing the distribution of the identified indirect effects of AM adoption among the SC vulnerabilities and their subfactors respectively.

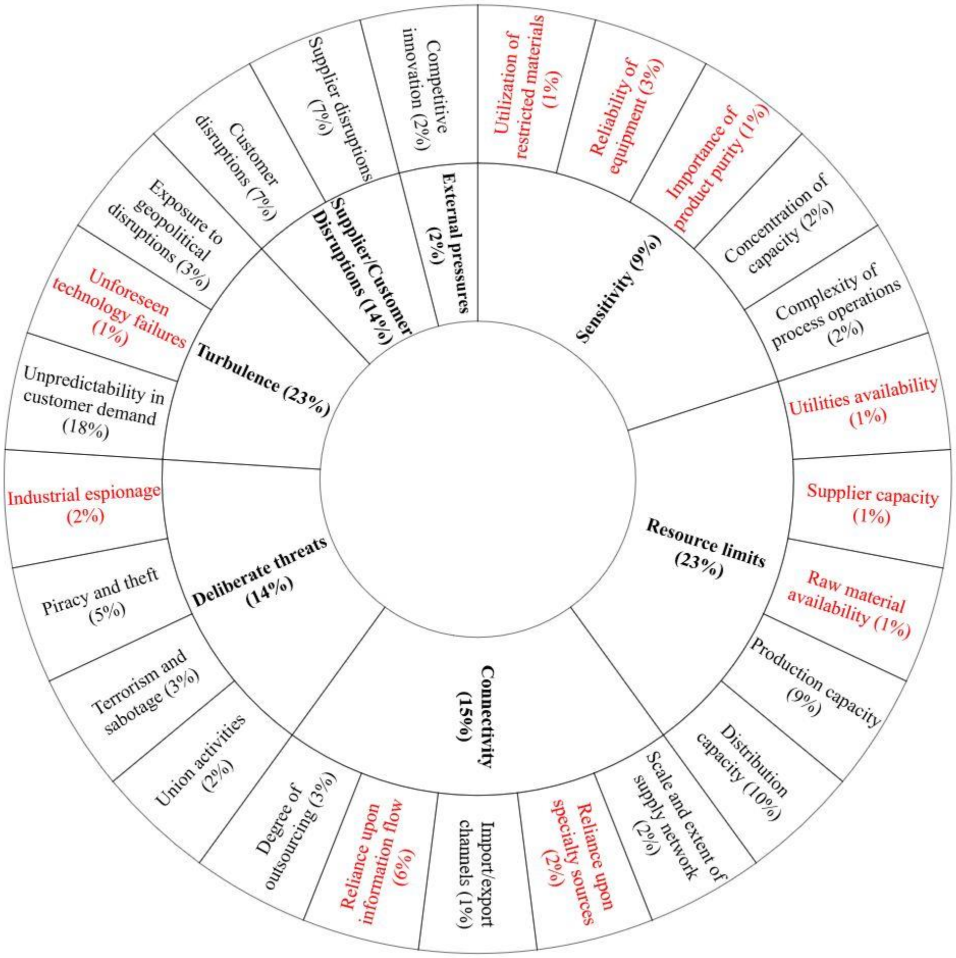


Figure 8. Distribution of the identified AM adoption's indirect effects among SC vulnerabilities

5.2 Managerial implications

In line with the dynamic capabilities view of the firm to strategy analysis, in this study we considered AM technology as a resource that SCM may choose to exploit in order to promote SCR. Overall, the review results suggest that adopting AM technology enhances the state and structural dynamics of the SC, providing opportunities to improve SC capabilities (e.g., flexibility, adaptability, dispersion, among others) that are necessary for mitigating different SC vulnerabilities (e.g., resource limits, turbulence, deliberate threats, among others) and building resilience against disruptions. The only contrasting instance where AM adoption is likely to have a limiting effect on the state of the SC is related to the availability of alternative sources of supply. It seems that this negative impact is reinforced by certain adoption barriers, i.e., limited variety and supply of AM material, high cost of AM material, lack of AM material standardization, AM material regulations, and limited traceability of AM material. In this instance, not only the sourcing flexibility of the SC would deteriorate but also the production capacity of the manufacturing firm would be compromised due to possible cases of material shortage. Relying on a limited number of special sources that supply the necessary AM materials (with specific quality standards) can limit the flexibility in sourcing and cause vulnerability to material shortage. Therefore, it is important that SC managers and decision-makers carefully consider the supply availability of the required AM materials, as well as their cost and quality standards, before committing to substantial AM technology adoption investments. Considerations regarding the use of restricted materials are also important since the traceability of AM materials is currently limited and until widely accepted standards are in place, caution should be exercised when sourcing AM materials to avoid potential complications.

While the adoption of AM technology is expected to largely improve several SC capabilities, it can also cause certain SC vulnerabilities. For instance, reliance upon information flow in an AM SC is one vulnerability subfactor that can create connectivity issues, and therefore adequate ICT requirements need to be in place before proceeding with information sharing. Also, providing an adequate ICT infrastructure can facilitate digital file storage/distribution and reduce instances of industrial espionage, e.g., cyber theft of proprietary CAD models, which consequently helps the firms to protect their IP rights. Another important vulnerability subfactor that needs to be considered is the reliability of equipment (i.e., AM machines) since the present instability in AM processes can cause scrap and rework, leading to production capacity shortages that consequently compromise the manufacturer’s ability to deliver the promised parts/products on time. Thus, continuous monitoring of the AM production processes may be required to avoid unforeseen technology failures until more reliable AM machines are available. Another SC vulnerability subfactor that requires attention is the importance of product purity and the use of restricted materials, especially when outsourcing the AM production processes to external entities since the traceability of AM materials as well as compliance with the regulations concerning AM materials (e.g., biocompatibility) become rather limited. Furthermore, the availability of reliable utility infrastructure (e.g., electricity) should be ensured since many of the contemporary AM processes are energy-intensive during the production phase, and therefore it is important to thoroughly consider such requirements before committing to large-scale adoption of AM technology to avoid failures.

Examining the present AM adoption barriers in the AM-SCR framework (Figure 6) reveals that “ICT inadequacies”, “Unstable AM processes”, “Slow production speed”, and “Limited automation” are mentioned more often. Considering that these AM adoption barriers are technological, their inhibiting effects are expected to diminish as the technology advances. However, at this time such barriers should be carefully considered before proceeding with AM adoption since can cause certain SC vulnerabilities, and as a consequence debilitate the resilience of the SC. The AM adoption barriers highlighted in red throughout the AM-SCR framework are those that are likely to be interrelated with the SC vulnerabilities that are also highlighted in red. For instance, “ICT inadequacies” and “IP rights protection” are likely to intensify the vulnerability of the SC to “Reliance upon information flow” and “Industrial espionage” whereas “Unstable AM processes” and “Limited long-term usability of AM machines” are likely to intensify the vulnerability of the SC to “Reliability of equipment” (i.e., AM machines). Therefore, potential interrelations between AM adoption barriers and SC vulnerabilities should be considered and controlled to avoid negative SCR outcomes.

In light of these considerations, it is most likely that the adoption of AM technology would lead to improving SCR on condition that the aforementioned adoption barriers are under control. The details of how AM adoption can result in SCR improvements have been elaborated in section three by considering the main variables of the research (i.e., AM adoption impacts, AM adoption barriers, SC state variables, SC capabilities, and SC vulnerabilities). Moreover, propositions that capture the essence of the review have been generated and are available at the end of each subsection. Additionally, the summary of the results is presented in the form of an AM-SCR framework, which SC managers and decision-makers can take advantage of to trace the implications of AM adoption for SCR.

6. Conclusions

In the present study, we adopted a theoretical perspective based on the dynamic capabilities view and performed a systematic search and critical review of the existing literature to infer how adopting AM technology impacts the state and structural dynamics of SCs (Dolgui & Ivanov, 2020), thus influencing the antecedent SC capabilities and SC vulnerabilities that underlie SCR (Kochan & Nowicki, 2018; Pettit et al., 2019). The introduction of the SC state variables played an important role in making it possible to employ a dynamic perspective and relate the impacts of AM adoption to SC capabilities and SC vulnerabilities based on the changes that take place in the state of the SC. In this manner, we put forward relevant propositions regarding the impacts of AM adoption on the state of the SC and its ensuing implications for SCR using the identified AM adoption impacts and their expected performance outcomes, the SC state variables, and the comprehensive SCRAM^{TM} framework by Petti et al. (2013). Additionally, in line with the state-of-the-art literature, we considered the importance of the present AM adoption barriers and their expected inhibiting effects in the context of SCR and put forward propositions accordingly.

While a limited number of studies (e.g., Zouari et al. (2020) and Spieske and Birkel (2021)) investigate the impacts of SC digitalization and Industry 4.0 technologies on SCR, none exclusively address the implications of AM adoption for SCR on a granular level. This knowledge shortfall is highlighted by many scholars such as Ali and Gölgeci (2019), Zouari et al. (2020), Dolgui and Ivanov (2020), Ivanov and Dolgui (2020), Ivanov et al. (2021), and Spieske and Birkel (2021), who state that further research is required to identify the potential contributions of adopting new digital technologies such as AM towards SCR. Therefore, by carrying out this review, not only we responded to the call for research at the intersection of AM technology adoption and SCR and addressed an important gap in the body of literature, but we also provided a research agenda and directions for future research by putting forward fourteen sets of elaborate propositions as well as a detailed AM-SCR framework for empirical validation. Moreover, the identified paths leading to linkages between the SC capabilities and SC vulnerabilities, which are represented in the AM-SCR framework, can be considered as pathways to SCR in the context of AM adoption. From a theoretical standpoint, future research can use the proposed AM-SCR framework to further investigate the implications of AM adoption for SCR, whereas from a practical standpoint, the AM-SCR framework can be put into practice by SC managers and decision-makers to evaluate the potential SCR outcomes of AM technology adoption for their firms. While the overall review results indicate that AM adoption is expected to improve SCR by mainly enhancing the state of the SC, thus positively influencing multiple SC capabilities that are antecedents to SCR, it can also give rise to certain SC vulnerabilities, which are likely to be interrelated with (and intensified by) certain AM adoption barriers that were identified during the critical review.

This research like any other faces some limitations. Although a large number of AM adoption impacts and barriers were identified (as stated in Appendices A and B), a minority of them were not used in the critical review due to lack of supporting evidence for their analysis and synthesis, and therefore they can be further investigated by future research. We had to limit the number of SC state variables to be able to control the scope of research, and therefore researchers can examine the impacts of AM adoption on other possible SC state variables to extend the framework. Furthermore, three SC capabilities present in the SCRAM^{TM} framework, namely organization, security, and financial strength were not included in this study due to the absence of adequate supporting evidence in the review sample. Also, among the well-known SC capabilities, agility is absent in the SCRAM^{TM} framework, and thus it was not analyzed. Therefore, we urge future research to closely investigate these SC capabilities in the context of AM adoption and SCR. In order to gain a holistic perspective, in this review we considered different kinds of AM processes as well as different applications of AM in various SC types. Hence, case studies and surveys that target specific processes and applications of AM in certain SCs and industries can test and refine the propositions contextually. Using the AM-SCR framework as the guideline, future research can also examine whether potential interrelations exist between the identified AM adoption barriers and SC vulnerabilities. Sensitivity analysis can help determine the extent to which the specified AM adoption barriers may intensify the SC vulnerabilities and deteriorate SCR. Also, through conducting longitudinal research, the veracity of the research results can be examined over time, especially as the AM adoption barriers are gradually overcome.

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Appendix A- Additive manufacturing adoption impacts and their expected performance outcomes

AM adoption impacts	**Examples of supporting evidence**	**Expected performance outcomes**		**References**
Automated manufacturing	"[…], in 3-D printing, the manufacturing process is automated and based on CAD software." (Berman, 2012)	• Increased production efficiency • Reduced assembly steps • Reduced changeover and setup times • Reduced labor	• Reduced manual operations • Reduced need for tools, machines, and certain facilities • Reduced work-in-progress	(Berman, 2012) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Holmström & Partanen, 2014) (Ivanov et al., 2019) (Naghshineh et al., 2021) (Oettmeier & Hofmann, 2016) (Pérès & Noyes, 2006) (Thomas-Seale et al., 2018) (Weller et al., 2015)
Capacity pooling (aka capacity sharing)	"Another option is to consult the online service MakeXYZ to find neighbors who will share their 3-D printers for free or for a nominal fee." (Kietzmann et al., 2015)	• Increased equipment utilization • Increased production capacity • Increased production efficiency • Increased SC responsiveness • Reduced capital investments in facilities and equipment • Reduced overhead costs	• Reduced need for accurate demand forecasting • Reduced need for tools, machines, and certain facilities • Reduced production planning and management effort • Reduced overall repair and maintenance costs	(Holmström et al., 2010) (Holmström et al., 2016) (Jiang et al., 2017) (Khajavi et al., 2014) (Kietzmann et al., 2015) (Ryan et al., 2017) (Verboeket & Krikke, 2019)
Close collaboration	"On the supply-side, AM technology adoption seems to increase the need for a close collaboration between material and machine suppliers, because the material and machines for AM need to be compatible with each other in order to achieve optimal outcomes." (Oettmeier & Hofmann, 2016)	• Increased customer interaction • Increased SC responsiveness	• Reduced need for accurate demand forecasting • Reduced stockouts and backorders	(Jiang et al., 2017) (Kunovjanek & Wankmüller, 2020) (Luomaranta & Martinsuo, 2020) (Mellor et al., 2014) (Oettmeier & Hofmann, 2016) (Petrick & Simpson, 2013) (Thomas, 2016) (Verboeket & Krikke, 2019)

Co-creation/co-design	"AM enables customers to co-design products that perfectly fit their demand." (Weller et al., 2015)	• Increased customer interaction • Increased customer satisfaction • Increased product customization	• Increased product functionality • Reduced product returns	(Bogers et al., 2016) (Chiu & Lin, 2016) (Delic et al., 2019) (Durach et al., 2017) (Eyers & Potter, 2015) (Hannibal, 2020) (Kunovjanek et al., 2020) (Naghshineh et al., 2021) (Niaki & Nonino, 2017) (Oettmeier & Hofmann, 2016) (Oettmeier & Hofmann, 2017) (Rayna et al., 2015) (Rylands et al., 2016) (Verboeket & Krikke, 2019) (Weller et al., 2015)
Customer-centric production (aka user manufacturing)	"Fully customer-centric production systems emphasize the personalization of manufacturing. Manufacturers can increase the individualization of a specific consumer by offering consumers who own a 3D printer the possibility to print their own parts." (Bogers et al., 2016)	• Increased customer interaction • Increased customer satisfaction • Increased product customization • Increased SC localization • Reduced capital investments in facilities and equipment • Reduced export of finished goods • Reduced inventory (e.g., FGI) • Reduced labor • Reduced logistics • Reduced material/product handling and packaging • Reduced need for accurate demand forecasting	• Reduced need for tools, machines, and certain facilities • Reduced obsolescence risk • Reduced overall production costs • Reduced product returns • Reduced production planning and management effort • Reduced overall repair and maintenance costs • Reduced storage and warehousing • Reduced transportation • Reduced work-in-progress	(Afshari et al., 2020) (Bogers et al., 2016) (Chen et al., 2015) (Christopher & Ryals, 2014) (Do, 2017) (Eyers & Potter, 2015) (Fawcett & Waller, 2014) (Ford & Despeisse, 2016) (Jiang et al., 2017) (Kleer & Piller, 2019) (Naghshineh et al., 2021) (Petrick & Simpson, 2013) (Potstada & Zybura, 2014) (Rayna & Striukova, 2016) (Rayna et al., 2015) (Ryan et al., 2017) (Steenhuis & Pretorius, 2016) (Steenhuis & Pretorius, 2017) (Thomas, 2016) (Verboeket & Krikke, 2019) (Waller & Fawcett, 2014)

Design freedom	"While complex parts are often difficult to produce with conventional manufacturing (CM) technologies, the high degree of design freedom of additive manufacturing (AM) facilitates consolidation." (Knofius et al., 2019)	• Increased product customization • Increased product functionality • Increased production efficiency • Increased resource efficiency • Reduced assembly steps • Reduced manual operations • Reduced overall production costs	• Reduced production planning and management effort • Reduced production process complexity • Reduced time-to-market • Reduced waste generation • Reduced work-in-progress	(Achillas et al., 2017) (Berman, 2012) (Eyers et al., 2018) (Ford & Despeisse, 2016) (Ghobadian et al., 2020) (Huang et al., 2013) (Khorram Niaki & Nonino, 2017) (Knofius et al., 2016) (Knofius et al., 2019) (Kunovjanek et al., 2020) (Mellor et al., 2014) (Naghshineh et al., 2021) (Niaki & Nonino, 2017) (Oettmeier & Hofmann, 2016) (Oettmeier & Hofmann, 2017) (Petrick & Simpson, 2013) (Petrovic et al., 2011) (Rylands et al., 2016) (Verboeket & Krikke, 2019) (Wagner & Walton, 2016) (Weller et al., 2015) (Zanoni et al., 2019)
Digital file distribution	"This shift towards the delivery of digital files and basic material rather than complex assembled products implies that AM will have substantial positive effects on the environmental impacts of transportation" (Ford & Despeisse, 2016)	• Increased SC responsiveness • Reduced delivery lead times • Reduced environmental impacts • Reduced logistics	• Reduced export of finished goods • Reduced material/product handling and packaging • Reduced transportation	(Beltagui et al., 2020) (Berman, 2012) (Caviggioli & Ughetto, 2019) (Chekurov et al., 2018) (Do, 2017) (Dwivedi et al., 2017) (Eyers & Potter, 2015) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Jiang et al., 2017) (Kietzmann et al., 2015) (Kunovjanek & Wankmüller, 2020) (Luomaranta & Martinsuo, 2020) (Pérès & Noyes, 2006) (Rayna & Striukova, 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Weller et al., 2015)
Digital inventory	"With respect to inventory management, physical inventories of stock-keeping units (SKUs) would take a new form and be translated into a virtual inventory of CADs" (Zanoni et al., 2019)	• Reduced inventory (e.g., FGI) • Reduced labor • Reduced logistics • Reduced material/product handling and packaging	• Reduced need for accurate demand forecasting • Reduced obsolescence risk • Reduced overhead costs • Reduced storage and warehousing • Reduced transportation	(Berman, 2012) (Chekurov et al., 2018) (Dwivedi et al., 2017) (Ford & Despeisse, 2016) (Ghobadian et al., 2020) (Holmström et al., 2016) (Jiang et al., 2017) (Oettmeier & Hofmann, 2016) (Rogers et al., 2016) (Rylands et al., 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Zanoni et al., 2019)
Distributed manufacturing	"The distributed manufacturing of spare parts in locations closer to the final user may have	• Increased SC localization	• Reduced material/product	(Bogers et al., 2016) (Braziotis et al., 2019) (Christopher & Ryals, 2014) (Do, 2017) (Durach et

(aka localized production)	several advantages, such as reduced delivery lead times and Reduced logistics costs.” (Durão et al., 2017)	• Reduced delivery lead times • Reduced export of finished goods • Reduced inventory • Reduced logistics • Reduced transportation	handling and packaging • Reduced overall production costs • Reduced proximity • Reduced storage and warehousing	al., 2017) (Durão et al., 2017) (Dwivedi et al., 2017) (Eyers & Potter, 2015) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Ghobadian et al., 2020) (Holmström et al., 2010) (Holmström et al., 2016) (Huang et al., 2013) (Ivanov et al., 2019) (Khajavi et al., 2014) (Kietzmann et al., 2015) (Kleer & Piller, 2019) (Kohtala, 2015) (Kunovjanek & Wankmüller, 2020) (Kunovjanek et al., 2020) (Naghshineh et al., 2021) (Oettmeier & Hofmann, 2017) (Petrick & Simpson, 2013) (Potstada & Zybura, 2014) (Ryan et al., 2017) (Sasson & Johnson, 2016) (Schniederjans, 2017) (Shukla et al., 2018) (Thomas, 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Wagner & Walton, 2016) (Weller et al., 2015) (Zanoni et al., 2019)
Economies of technology	“Multiple RM machinery can currently be operated by a single operator, thus reducing the demands placed on the labour force, and consequently, bringing manufacturing back from low wage economies. Thus the economies of the global work place could be replaced by the economies of technology.” (Tuck et al., 2007)	• Increased production efficiency • Increased resource efficiency • Increased SC localization	• Reduced labor • Reduced production planning and management effort	(Berman, 2012) (Naghshineh et al., 2021) (Tuck et al., 2007)
Engineer/make-to-order production	“In addition, direct processing of 3D data combined with design-to-order or make-to-order processes helps to reduce total order fulfillment times” (Weller et al., 2015)	• Increased customer interaction • Increased customer satisfaction • Increased low-demand part production • Increased low-volume part production • Increased product customization • Increased product functionality	• Increased profits • Increased SC responsiveness • Increased service level • Reduced inventory (e.g., FGI) • Reduced need for accurate demand forecasting • Reduced obsolescence risk	(Christopher & Ryals, 2014) (Ford & Despeisse, 2016) (Huang et al., 2013) (Jiang et al., 2017) (Li et al., 2019) (Niaki & Nonino, 2017) (Oettmeier & Hofmann, 2016) (Verboeket & Krikke, 2019) (Weller et al., 2015) (Zanoni et al., 2019)

			• Reduced storage and warehousing	
Fewer raw materials	"Instead, the reduction of the carbon emissions might be achieved due to the fact that fewer raw material are needed for manufacturing" (Li et al., 2017)	• Increased transport mode adaptability • Reduced environmental impacts • Reduced inventory (e.g., FGI) • Reduced logistics • Reduced material/product handling and packaging	• Reduced production planning and management effort • Reduced SC complexity • Reduced storage and warehousing • Reduced transportation	(Chan et al., 2018) (Ford & Despeisse, 2016) (Li et al., 2017) (Verboeket & Krikke, 2019) (Weller et al., 2015)
Hybrid manufacturing model	"A novel and emerging production method that we looked at for this purpose is DDM in a hybrid combination with conventional tool-based methods." (Khajavi et al., 2015)	• Increased equipment utilization • Increased low-demand part production • Increased low-volume part production • Increased production capacity	• Increased production efficiency • Increased service level • Reduced need for accurate demand forecasting • Reduced obsolescence risk • Reduced stockouts and backorders	(Achillas et al., 2017) (Bogers et al., 2016) (Braziotis et al., 2019) (Chiu & Lin, 2016) (Ford & Despeisse, 2016) (Ghadge et al., 2018) (Holmström & Partanen, 2014) (Huang et al., 2013) (Khajavi et al., 2015) (Ryan et al., 2017) (Rylands et al., 2016) (Sasson & Johnson, 2016) (Steenhuis & Pretorius, 2017) (Verboeket & Krikke, 2019) (Wagner & Walton, 2016)
Import/export substitution	"Exports are projected to shift back to consumer countries as 3DP reduces the labour cost-related comparative advantage of countries such as China and the technological advantage of countries like Germany or Japan" (Gebler et al., 2014)	• Increased SC localization	• Reduced export of finished goods • Reduced transportation	(Gebler et al., 2014) (Naghshineh et al., 2021) (Ryan et al., 2017) (Steenhuis & Pretorius, 2017)
Just-in-time production	"First, AM can improve the efficiency of a lean supply chain through just-in-time (JIT) manufacture and waste elimination." (Huang et al., 2013)	• Increased production efficiency • Increased resource efficiency	• Reduced inventory (e.g., FGI)	(Holmström et al., 2016) (Huang et al., 2013) (Rogers et al., 2016) (Tuck et al., 2007)

		• Increased SC responsiveness • Reduced obsolescence risk • Reduced proximity • Reduced waste generation	• Reduced need for accurate demand forecasting • Reduced storage and warehousing • Reduced work-in-progress	
Market entry	"Our findings demonstrate that consumer 3DP may support market entry when small firms leverage open design to overcome their resource constraints." (Beltagui et al., 2020)	• Increased low-volume part production • Increased product customization	• Increased profits • Increased SC localization • Reduced time-to-market	(Beltagui et al., 2020) (Berman, 2012) (Chan et al., 2018) (Chen et al., 2015) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Ghadge et al., 2018) (Hartl & Kort, 2017) (Holmström et al., 2016) (Holmström et al., 2017) (Jiang et al., 2017) (Khajavi et al., 2015) (Kleer & Piller, 2019) (Naghshineh et al., 2021) (Niaki & Nonino, 2017) (Petrick & Simpson, 2013) (Rayna et al., 2015) (Rogers et al., 2016) (Weller et al., 2015)
Mass customization	"Additive manufacturing production technologies design products exactly the way consumers want. This falls into the category of mass customization" (Hartl & Kort, 2017)	• Increased customer interaction • Increased customer satisfaction • Increased low-demand part production • Increased low-volume part production • Increased product customization	• Increased profits • Increased SC responsiveness • Reduced need for accurate demand forecasting • Reduced product returns • Reduced overall production costs • Reduced obsolescence risk	(Achillas et al., 2017) (Afshari et al., 2020) (Berman, 2012) (Bogers et al., 2016) (Caviggioli & Ughetto, 2019) (Chan et al., 2018) (Christopher & Ryals, 2014) (Eyers et al., 2018) (Ford & Despeisse, 2016) (Hartl & Kort, 2017) (Holmström et al., 2017) (Hopkins, 2021) (Huang et al., 2013) (Ivanov et al., 2019) (Knofius et al., 2016) (Kunovjanek et al., 2020) (Niaki & Nonino, 2017) (Petrick & Simpson, 2013) (Rayna et al., 2015) (Rogers et al., 2016) (Shukla et al., 2018) (Steenhuis & Pretorius, 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Wagner & Walton, 2016) (Waller & Fawcett, 2014) (Weller et al., 2015) (Zanoni et al., 2019)
Medium production runs (aka bridge manufacturing)	"3-D printing is also used in bridge manufacturing, 'bridging' the time span from when a part design is complete and when the part is ready for mass production." (Berman, 2012)	• Increased production capacity • Increased SC responsiveness	• Reduced need for tools, machines, and certain facilities	(Berman, 2012) (Ding et al., 2021) (Ford & Despeisse, 2016) (Khajavi et al., 2015) (Verboeket & Krikke, 2019)

		• Reduced production lead times	• Reduced need for accurate demand forecasting • Reduced stockouts and backorders	
Mobile manufacturing	“A wider adoption of mobile 3DP has the potential to offer several important advantages in terms of lead-time reduction and production capacity flexibility compared to other scenarios.” (Ryan et al., 2017)	• Increased production capacity • Increased SC responsiveness	• Reduced delivery lead times • Reduced export of finished goods • Reduced proximity	(Ford & Despeisse, 2016) (Holmström et al., 2010) (Kenger et al., 2021) (Pérès & Noyes, 2006) (Ryan et al., 2017) (Verboeket & Krikke, 2019)
New business models	“we explore the implications that AM technologies have for manufacturing systems in the new business models that they enable” (Bogers et al., 2016)	• Increased profits • Increased SC responsiveness	• Increased SC localization • Increased customer interaction	(Afshari et al., 2020) (Baumers et al., 2016) (Beltagui et al., 2020) (Bogers et al., 2016) (Caviggioli & Ughetto, 2019) (Chan et al., 2018) (Despeisse et al., 2017) (Durach et al., 2017) (Eyers & Potter, 2015) (Ford & Despeisse, 2016) (Ghobadian et al., 2020) (Hannibal, 2020) (Jiang et al., 2017) (Khorram Niaki & Nonino, 2017) (Luomaranta & Martinsuo, 2020) (Naghshineh et al., 2021) (Nascimento et al., 2019) (Petrick & Simpson, 2013) (Potstada & Zybura, 2014) (Rayna & Striukova, 2016) (Ryan et al., 2017) (Steenhuis & Pretorius, 2017) (Tuck et al., 2007)
On-demand manufacturing	“Using AM technology, manufacturers can produce parts on demand and thus reduce the need of maintaining safety inventory” (Liu et al., 2014)	• Increased customer interaction • Increased low-demand part production • Increased low-volume part production • Increased product customization • Increased resource efficiency • Increased SC localization	• Reduced material/product handling and packaging • Reduced need for accurate demand forecasting • Reduced obsolescence risk • Reduced overall production costs	(Berman, 2012) (Bogers et al., 2016) (Braziotis et al., 2019) (Delic & Eyers, 2020) (Dwivedi et al., 2017) (Eyers et al., 2018) (Ford & Despeisse, 2016) (Ghadge et al., 2018) (Holmström et al., 2010) (Holmström et al., 2017) (Huang et al., 2013) (Kleer & Piller, 2019) (Knofius et al., 2016) (Liu et al., 2014) (Niaki & Nonino, 2017) (Pérès & Noyes, 2006) (Rodríguez-Espíndola et al., 2020) (Sasson & Johnson, 2016) (Sgarbossa et al., 2021) (Verboeket & Krikke, 2019) (Zanoni et al., 2019)

		• Increased SC responsiveness • Reduced delivery lead times • Reduced export of finished goods • Reduced inventory (e.g., FGI) • Reduced logistics	• Reduced production planning and management effort • Reduced proximity • Reduced overall repair and maintenance costs • Reduced storage and warehousing • Reduced transportation • Reduced work-in-progress	
Outsourcing production	"By outsourcing manufacturing, companies can reduce inventory to a minimum, printing products and replacement parts solely on demand. Using local printing facilities further reduces the costs associated with the transportation and handling of products." (Rogers et al., 2016)	• Reduced capital investments in facilities and equipment • Reduced inventory • Reduced logistics • Reduced material/product handling and packaging • Reduced need for accurate demand forecasting • Reduced need for tools, machines, and certain facilities	• Reduced overhead costs • Reduced production planning and management effort • Reduced proximity • Reduced overall repair and maintenance costs • Reduced storage and warehousing • Reduced transportation • Reduced work-in-progress	(Berman, 2012) (Durach et al., 2017) (Eyers & Potter, 2015) (Ford & Despeisse, 2016) (Jiang et al., 2017) (Kietzmann et al., 2015) (Rogers et al., 2016) (Ryan et al., 2017) (Verboeket & Krikke, 2019)

Process integration	"Process integration and SC simplification reduce planning and management efforts." (Kunovjanek et al., 2020)	• Increased equipment utilization • Increased production efficiency • Reduced assembly steps • Reduced capital investments in facilities and equipment	• Reduced production planning and management effort • Reduced production process complexity • Reduced work-in-progress	(Chen et al., 2015) (Do, 2017) (Ford & Despeisse, 2016) (Holmström et al., 2016) (Kunovjanek & Reiner, 2020) (Kunovjanek et al., 2020) (Verboeket & Krikke, 2019) (Weller et al., 2015)
Product life cycle extension	"Finally, AM can extend the product's life cycle via in situ remanufacturing of machine parts." (Verboeket & Krikke, 2019)	• Increased equipment utilization • Increased product functionality	• Increased resource efficiency • Reduced overall repair and maintenance costs	(Colosimo et al., 2020) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Ghobadian et al., 2020) (Holmström & Partanen, 2014) (Holmström et al., 2017) (Naghshineh et al., 2021) (Petrick & Simpson, 2013) (Rodríguez-Espíndola et al., 2020) (Verboeket & Krikke, 2019)
Production postponement	"Moreover, by exploiting the potential of postponement flexibility to pause production until the product is actually needed, Additive Manufacturing could help automotive firms manage the challenge of deploying design changes in-lifecycle." (Delic & Eyers, 2020)	• Increased product customization • Reduced need for accurate demand forecasting	• Reduced obsolescence risk • Reduced production planning and management effort	(Delic & Eyers, 2020) (Holmström & Partanen, 2014) (Shukla et al., 2018) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Waller & Fawcett, 2014)
Rapid manufacturing	"The objective of the implementation of AM is usually divided into two main activities. RM *(Rapid manufacturing)* for producing finished parts and RP *(Rapid prototyping)* for producing prototypes, which represent different performance and features." (Niaki & Nonino, 2017)	• Increased customer satisfaction • Increased low-volume part production • Increased low-demand part production • Increased service level • Increased order fill rate • Increased preparedness for disruptions	• Reduced changeover and setup times • Reduced manual operations • Reduced need for accurate demand forecasting • Reduced need for tools, machines, and certain facilities	(Holmström et al., 2010) (Hopkins, 2021) (Mellor et al., 2014) (Naghshineh et al., 2021) (Niaki & Nonino, 2017) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Weller et al., 2015) (Zanoni et al., 2019)

		• Increased product customization • Increased SC responsiveness • Reduced assembly steps	• Reduced overall production costs • Reduced production lead times • Reduced work-in-progress • Reduced production process complexity	
Rapid prototyping	“3D printing allows for rapid prototyping, reducing the product development process cycle time. With a shorter product development process, the time horizon required for forecasting decreases, reducing inventory costs, out of stock costs, transshipment costs, and other related costs.” (Waller & Fawcett, 2014)	• Increased low-volume part production • Increased product functionality • Increased SC responsiveness • Reduced inventory (e.g., FGI) • Reduced logistics	• Reduced need for accurate demand forecasting • Reduced overall production costs • Reduced production lead times • Reduced time-to-market	(Berman, 2012) (Candi & Beltagui, 2019) (Colosimo et al., 2020) (Fawcett & Waller, 2014) (Ford & Despeisse, 2016) (Holmström et al., 2016) (Holmström et al., 2017) (Khorram Niaki & Nonino, 2017) (Kietzmann et al., 2015) (Luomaranta & Martinsuo, 2020) (Mellor et al., 2014) (Niaki & Nonino, 2017) (Pérès & Noyes, 2006) (Petrick & Simpson, 2013) (Rayna & Striukova, 2016) (Schniederjans, 2017) (Steenhuis & Pretorius, 2017) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Waller & Fawcett, 2014) (Zanoni et al., 2019)
Rapid tooling	“However, when considering low-volume production, both rapid tooling and additive manufacturing may offer an alternative that could result into shorter lead times and decreased total production costs.” (Achillas et al., 2017)	• Increased equipment utilization • Increased low-volume part production • Increased production efficiency	• Reduced need for tools, machines, and certain facilities • Reduced overall production costs • Reduced production lead times	(Achillas et al., 2017) (Ford & Despeisse, 2016) (Holmström et al., 2016) (Holmström et al., 2017) (Khajavi et al., 2015) (Kunovjanek & Reiner, 2020) (Rayna & Striukova, 2016) (Verboeket & Krikke, 2019) (Zanoni et al., 2019)
Remote work	“This study uses only remotely controllable 3D printers without management services.” (Do, 2017)	• Increased resource efficiency	• Reduced logistics	(Do, 2017) (Durão et al., 2017) (Naghshineh et al., 2021) (Pérès & Noyes, 2006)

			• Reduced proximity	
SC innovation	“Supply chain innovations are also a means for the entire supply chain to benefit from AM and to help firms leverage AM effectively.” (Luomaranta & Martinsuo, 2020)	• Increased customer interaction • Increased customer satisfaction • Increased product customization • Increased profits • Increased SC responsiveness	• Increased SC localization • Increased resource efficiency • Increased product functionality • Reduced time-to-market • Reduced SC complexity	(Afshari et al., 2020) (Beltagui et al., 2020) (Bogers et al., 2016) (Candi & Beltagui, 2019) (Caviggioli & Ughetto, 2019) (Ford & Despeisse, 2016) (Holmström et al., 2016) (Ivanov et al., 2019) (Khorram Niaki & Nonino, 2017) (Kleer & Piller, 2019) (Kunovjanek & Wankmüller, 2020) (Luomaranta & Martinsuo, 2020) (Niaki & Nonino, 2017) (Petrick & Simpson, 2013) (Rayna & Striukova, 2016) (Steenhuis & Pretorius, 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Wagner & Walton, 2016) (Waller & Fawcett, 2014)
SC simplification (aka SC disintermediation)	“The use of 3DP to produce some of the items in the affected areas can be beneficial to reduce lead times for distribution and to mitigate the congestion in the supply chain by reducing the number of items being requested, sorted and managed.” (Rodríguez-Espíndola et al., 2020)	• Increased SC responsiveness • Reduced delivery lead times • Reduced environmental impacts • Reduced logistics • Reduced material/product handling and packaging • Reduced production lead times	• Reduced production planning and management effort • Reduced proximity • Reduced SC complexity • Reduced storage and warehousing • Reduced transportation	(Chen et al., 2015) (Chiu & Lin, 2016) (Eyers & Potter, 2015) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Ghadge et al., 2018) (Ghobadian et al., 2020) (Holmström & Partanen, 2014) (Holmström et al., 2010) (Holmström et al., 2016) (Huang et al., 2013) (Ivanov et al., 2019) (Jiang et al., 2017) (Khorram Niaki & Nonino, 2017) (Knofius et al., 2019) (Kothman & Faber, 2016) (Kunovjanek et al., 2020) (Li et al., 2017) (Naghshineh et al., 2021) (Oettmeier & Hofmann, 2017) (Rodríguez-Espíndola et al., 2020) (Rogers et al., 2016) (Verboeket & Krikke, 2019) (Zanoni et al., 2019)

Small production runs (aka small batch production)	"3D printing has been used for more than two decades, primarily for rapid part prototyping and small run production in a variety of industries." (Petrick & Simpson, 2013)	• Increased customer satisfaction • Increased low-demand part production • Increased low-volume part production • Increased product customization • Increased profits • Increased SC responsiveness • Increased service level • Increased order fill rate	• Reduced need for accurate demand forecasting • Reduced need for tools, machines, and certain facilities • Reduced overall production costs • Reduced production lead times • Reduced stockouts and backorders	(Achillas et al., 2017) (Berman, 2012) (Chan et al., 2018) (Chen et al., 2015) (Christopher & Ryals, 2014) (Ding et al., 2021) (Durach et al., 2017) (Eyers et al., 2018) (Ford & Despeisse, 2016) (Ghobadian et al., 2020) (Hartl & Kort, 2017) (Holmström et al., 2010) (Holmström et al., 2016) (Holmström et al., 2017) (Huang et al., 2013) (Jiang et al., 2017) (Khajavi et al., 2015) (Kunovjanek & Reiner, 2020) (Liu et al., 2014) (Luomaranta & Martinsuo, 2020) (Mellor et al., 2014) (Naghshineh et al., 2021) (Pérès & Noyes, 2006) (Petrick & Simpson, 2013) (Rayna & Striukova, 2016) (Rayna et al., 2015) (Rogers et al., 2016) (Shukla et al., 2018) (Thomas, 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Wagner & Walton, 2016) (Weller et al., 2015) (Zanoni et al., 2019)
Sustainable production	"Additive manufacturing (AM) promises to revolutionise manufacturing beyond recognition by eliminating or drastically removing the waste thereby achieving sustainability" (Ghobadian et al., 2020)	• Increased product functionality • Increased production efficiency • Increased resource efficiency • Reduced environmental impacts • Reduced transportation	• Reduced need for tools, machines, and certain facilities • Reduced overhead costs • Reduced waste generation • Reduced logistics	(Afshari et al., 2020) (Chen et al., 2015) (Chiu & Lin, 2016) (Despeisse et al., 2017) (Ford & Despeisse, 2016) (Gebler et al., 2014) (Ghobadian et al., 2020) (Holmström et al., 2017) (Huang et al., 2013) (Jiang et al., 2017) (Khorram Niaki & Nonino, 2017) (Kothman & Faber, 2016) (Kunovjanek et al., 2020) (Li et al., 2017) (Naghshineh et al., 2021) (Nascimento et al., 2019) (Rogers et al., 2016) (Tuck et al., 2007) (Verboeket & Krikke, 2019) (Zanoni et al., 2019)
Tool-less production	"This is possible since AM is a tool-less manufacturing approach, with no or very limited setup times." (Sgarbossa et al., 2021)	• Increased production efficiency • Reduced capital investments in facilities and equipment • Reduced changeover and setup times	• Reduced overall production costs • Reduced production lead times • Reduced production	(Baumers et al., 2016) (Berman, 2012) (Bogers et al., 2016) (Chen et al., 2015) (Ding et al., 2021) (Eyers et al., 2018) (Ford & Despeisse, 2016) (Holmström et al., 2010) (Holmström et al., 2016) (Huang et al., 2013) (Khajavi et al., 2014) (Khajavi et al., 2015) (Kleer & Piller, 2019) (Knofius et al., 2019) (Kunovjanek et al., 2020) (Mellor et al., 2014) (Niaki & Nonino, 2017) (Petrovic et al., 2011) (Sgarbossa

	• Reduced manual operations • Reduced need for tools, machines, and certain facilities	planning and management effort • Reduced production process complexity • Reduced time-to-market	et al., 2021) (Steenhuis & Pretorius, 2017) (Tuck et al., 2007) (Weller et al., 2015) (Zanoni et al., 2019)

Notes: AM = additive manufacturing, CAD = computer-aided design, DDM = direct digital manufacturing, RM = rapid manufacturing, SC = supply chain

Appendix B - Additive manufacturing adoption barriers and their expected inhibiting effects

Adoption barrier type	AM adoption barriers	Expected inhibiting effects
Technological	Limited build envelope [d, e, j, k, l, h′, v′]	Limited part size [a, b, c, e, g, b′, f′, h′, m′], making part size scalability an issue [e, m′].
	Imprecise 3D scanning [d, g]	Imprecise scanned 3D models, which can lead to scrap and rework [l, q].
	Limited automation [i, g, n, p, v, r, s′]	Limited production capacity.
	Slow production speed [a, b, c, e, g, i, j, n, o, p, r, u, v, x, b′, d′, e′, h′, j′, n′, r′]	
	Low throughput rate [b, g, j, l]	
	High energy consumption [f, i, l, n, o, r, s, t, m′, q′, z′]	
	Unstable AM processes [a, b, d, g, n, q, y, e′, k′, n′, v′]	Variable production rates [e′] as well as low production accuracy [a, g, z, b′, h′] that can lead to scrap and rework [l, q], which calls for in-process monitoring and process certification [e, g, n, e′, i′, n′].
	Excessive post-processing [d, f, l, v]	Increase in production lead time and costs.
	Lack of multi-material printing [n, w, l′]	Limited AM application, since the number of products that can be produced are limited.
	Limited long-term usability of AM machines [a]	High repair and maintenance costs [b] as well as expensive (re)investments in purchasing new machines [c, t, b′, d′, m′, p′, w′]
	Limited variety and supply of AM material [a, b, c, e, f, g, k, l, o, n, v, z, b′, f′, g′, h′, i′, j′, k′, u′]	Limited AM application, since the limited variety of AM material restricts product features such as desired strength and surface finish. Also, high supplier dependency [y] can be caused due to lack of frequent AM material availability.
	ICT inadequacies [d, g, s, p′, x′]	Poor ICT infrastructure [g] or lack of ICT infrastructure conformity among SC members that causes issues such as data management problems [d, s, g′], e.g., file version management [d], which consequently causes difficulty in successfully implementing and using AM [g, o].
	Lack of support from IT vendors [b]	Difficulty in successfully implementing and using AM [g, o] due to issues that require IT vendor support, e.g. software issues [e] or CAD software complexities [c, e].
	Lack of AM process standards [e, o, n, e′, i′, k′, p′]	Lack of knowledge or control over machine process parameters [d, g, p′] may cause variable production quality between different AM machines and production runs [n′], requiring strict inspection, quality control and product quality certification [e, f, g, h, m, e′, f′, n′, p′].
	Lack of guidelines to fully exploit AM [l, p′]	Limited application of AM technology.
Quality-related	Poor surface finish [b, c, e, g, h, b′, e′, h′, i′, m′, n′]	Post-processing is required [d, e, g, k, n, o, y, e′, g′], which increases production lead time and costs.
	Inadequate part fatigue strength and resistance to heat [e, n, z, t′, y′]	Inadequate part quality [a, f, h, l, w, f′, g′, l′, n′], e.g., poor structural rigidity [c, g, r′].

	Limited traceability of AM material [e, s, h′, i′]	Difficulty in quality assurance, e.g., degradability of AM material (e.g., powder) [e].
	Lack of AM material standardization [a, d, g, n, i′, n′, p′]	Variable AM material quality between different batches and shipments, i.e., supplier quality imparity [d, e, g, k′].
Firm-related	Lack of AM knowledge and design skills [a, b, c, e, f, g, i, l, n, j′, l′, p′, s′, u′]	Unavailability of skilled AM machine operators [b, g, p′] as well as unavailability of 3D models [d].
	Lack of personnel education and training [a, b, e, l, n, j′, p′, s′]	
	Lack of management support [b, g, o, t]	Difficulty in successfully implementing and using AM [g, o], leading to a low adoption rate of AM in different industries [s].
	Lack of trust in AM [b, g]	Resistance to change [b, g, n], which can cause difficulty in successfully implementing and using AM [g, o] and leading to a low adoption rate of AM in different industries [s].
Cost-related	High cost of AM processes [a, d, e, g, i, k, n, o, r, s, z, d′, n′, t′, u′]	Production cost increases.
	High cost of AM machines [a, b, c, d, f, g, k, m, n, o, p, t, d′, h′, j′, k′, l′, m′, p′, r′, s′]	
	High cost of repair and maintenance [b, k]	
	High cost of AM material [a, b, c, e, f, g, i, k, l, o, s, z, k′, m′, p′, z′]	
	High cost of research and development for AM technology [j, j′]	
Regulatory	IP rights protection [b, g, t, u, a′, c′, j′, n′, o′]	IP rights complications [d, h, l, m, n, s, z, e′, o′, p′, u′] due to high risk of piracy, knowledge leak, and copyright infringements [d, g, n′].
	Lack of government support [b, g, t, z, o′]	Potential legal disputes [t, u, o′] that can cause difficulty in successfully implementing and using AM [g, o]
	AM material regulations (e.g., biocompatibility) [a, g, m, n]	
Market-related	Lack of customer awareness and acceptance [a, g, o]	Low adoption rate of AM in different industries [s].

Sources: [a] (Durach et al., 2017); [b] (Dwivedi et al., 2017); [c] (Shukla et al., 2018); [d] (Chekurov et al., 2018); [e] (Thomas-Seale et al., 2018); [f] (Kunovjanek et al., 2020); [g] (Verboeket & Krikke, 2019); [h] (Kunovjanek & Wankmüller, 2020); [i] (Thomas, 2016); [j] (Baumers et al., 2016); [k] (Niaki & Nonino, 2017) ; [l] (Weller et al., 2015); [m] (Kietzmann et al., 2015); [n] (Ford & Despeisse, 2016); [o] (Mellor et al., 2014); [p] (Khajavi et al., 2014), [q] (Colosimo et al., 2020); [r] (Afshari et al., 2020); [s] (Chan et al., 2018); [t] (Schniederjans, 2017); [u] (Steenhuis & Pretorius, 2017); [v] (Achillas et al., 2017); [w] (Chiu & Lin, 2016); [x] (Chen et al., 2015); [y] (Knofius et al., 2019); [z] (Berman, 2012); [a′] (Jiang et al., 2017); [b′] (Pérès & Noyes, 2006); [c′] (Holmström et al., 2016); [d′] (Ryan et al., 2017); [e′] (Petrick & Simpson, 2013); [f′] (Steenhuis & Pretorius, 2016); [g′] (Do, 2017); [h′] (Tuck et al., 2007); [i′] (Petrovic et al., 2011); [j′] (Gebler et al., 2014); [k′] (Ghobadian et al., 2020); [l′] (Rayna et al., 2015); [m′] (Huang et al., 2013); [n′] (Wagner & Walton, 2016); [o′] (Naghshineh et al., 2021); [p′] (Zanoni et al., 2019); [q′] (Li et al., 2017); [r′] (Braziotis et al., 2019); [s′] (Eyers et al., 2018); [t′] (Sgarbossa et al., 2021);[u′] (Caviggioli & Ughetto, 2019); [v′] (Ding et al., 2021); [w′] (Liu et al., 2014); [x′] (Durão et al., 2017); [y′] (Fawcett & Waller, 2014); [z′] (Sasson & Johnson, 2016)

Appendix C - Definitions for the SC capabilities and their subfactors adapted from Pettit et al. (2013)

SC capability	Definition	SC capability subfactor(s)	Definition
Flexibility (in sourcing)	Capability to promptly adjust inputs or the mode of receiving inputs.	Alternate suppliers	Capability to find alternative sources of supply for key inputs, e.g., raw material.
		Multiple pathways	Capability to make products using a diverse range of methods, machines, and labor.
Flexibility (in order fulfilment)	Capability to promptly adjust outputs or the mode of delivering outputs.	Reallocation of production	Capability to promptly reallocate jobs/orders to different production units or among alternative suppliers.
		Production postponement	Capability to postpone production to better respond to demand.
		Logistics multisourcing	Capability to promptly change the logistics services such as distribution or outsourced storage.
		Inventory management	Capability to efficiently manage inventory (e.g., cycle stock, safety stock) at different SC nodes (e.g., warehouses, distribution centers, retail locations, etc.).
		Alternate distribution channels	Capability to promptly alter modes of transport as well as the routing options for outbound shipments.
Adaptability	Capability to adjust operations to respond to challenges or opportunities.	Lead time reduction	Capability to further reduce lead times.
		Rerouting of requirements	Capability to promptly reallocate jobs/orders to different production facilities or among alternative suppliers.
		Alternate technology	Capability to adopt innovative technologies to revamp operations.
Dispersion	Capability to widely distribute or decentralize assets.	Distributed capacity	Capability to distribute the production facilities at various locations.
		Dispersion of markets	Capability to sell products to customers in different geographic locations.
Collaboration	Capability to work effectively with other firms for mutual interest.	Collaborative forecasting	Capability to utilize collaborative demand forecasting techniques through information sharing.
		Collaborative information sharing	Capability to transparently share information among SC members to improve collaborative decision making.
		Postponement of orders	Capability to postpone orders when the production capacity is disrupted.
Capacity	Capability to have the necessary assets available to enable sustained levels of production.	Reserve capacity	Capability to gain access to additional equipment, material, or labor to promptly increase output if necessary.
		Redundant assets	Capability to gain access to redundant or duplicate equipment and facilities.

Visibility	Capability to gain knowledge about the SC environment as well as the status of the operating assets.	Information exchange	Capability to regularly exchange information with other SC members, e.g., customers, suppliers, etc.
Recovery	Capability to quickly return to the normal state of operations after being disrupted.	Consequence mitigation	Capability to act immediately to mitigate the disruption effects despite the short-term costs.
Efficiency	Capability to generate outputs with minimal resource requirements.	Asset utilization	Capability to efficiently utilize assets to generate outputs.
Market Position	Capability of a firm in maintaining its position in specific markets.	Customer relationships	Capability to maintain strong, long-term relationships with customers.
Anticipation	Capability to detect impending events.	Demand forecasting	Capability to use forecasting methods effectively.

Appendix D - Definitions for the SC vulnerabilities and their subfactors adapted from Pettit et al. (2013)

SC vulnerability	Definition	SC vulnerability subfactor(s)	Definition
Turbulence	Recurrent changes in external factors that are beyond the firm's control.	Unpredictability in customer demand	Erratic customer demand for products.
		Exposure to geopolitical disruptions	Recurrent disruptions in imports/exports because of geopolitical turmoil.
		Unforeseen technology failures	Frequent unforeseen failures in technology that disrupt operations.
Resource limits	Output constraints caused by the unavailability of production factors.	Distribution capacity	Limited capacity for product distribution.
		Production capacity	Limited production capacity.
		Raw material availability	Limited supply of raw materials for production.
		Supplier capacity	Limited supplier capacity.
		Utilities availability	Limited access to utilities as well as reliable utility infrastructure.
Connectivity	Degree of interdependence on external entities.	Scale and extent of supply network	The number of members in the SC.
		Reliance upon specialty sources	Dependence on specialty components or materials for production.
		Import/export channels	Access to globally distributed SCs.
		Reliance upon information flow	Dependence on continuous information flow for everyday operations.
		Degree of outsourcing	The extent to which operations are outsourced to external entities.
Deliberate threats	Deliberate misconducts to cause financial/human harm or disrupt operations.	Industrial espionage	Technologies or products being compromised by industrial espionage.
		Piracy and theft	Vandalism and theft of products.
		Terrorism and sabotage	Acts of terrorism or sabotage that target personnel or facilities.
		Union activities	Dependence on unionized labor that can become hostile to the firm.
Supplier/Customer disruptions	Vulnerability of customers and suppliers to outside forces or disruptions.	Supplier disruptions	Suppliers frequently facing serious disruptions.
		Customer disruptions	Customers frequently facing serious disruptions.
Sensitivity	Importance of carefully controlled conditions for process and product integrity.	Utilization of restricted materials	Dependence on the use of regulated or restricted material.
		Reliability of equipment	Vulnerability of production equipment to failure.

		Importance of product purity	High dependence of product quality on the quality of supplies/inputs.
		Concentration of capacity	Geographic concentration and/or co-dependence of production facilities or suppliers.
		Complexity of process operations	Highly complex production operations.
External pressures	Business constraints or barriers caused by external influences, which do not specifically target the firm.	Competitive innovation	Frequent competitive innovations threatening the firm's product portfolio.

Appendix E – Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpe.2021.108387.

3

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

This chapter consists of the following paper:

Naghshineh, B. & Carvalho, H.
Undergoing peer review in a refereed journal

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

Abstract

As a digital technology, adopting additive manufacturing, otherwise known as 3D printing, affects the state of the supply chain, consequently affecting supply chain resilience. Hence, to investigate the subject matter based on the holistic viewpoint of industry, an exploratory survey was conducted whereby quantitative and qualitative data were collected from experts working for companies involved in different industries that had adopted one or more additive manufacturing processes for different applications. Drawing on the gathered quantitative data, the extent to which additive manufacturing adoption affects the state of the supply chain was estimated as moderate, which in turn is expected to moderately affect supply chain resilience as well. Moreover, qualitative data were analyzed, explaining how different features of additive manufacturing affect the state of the supply chain as well as identifying the barriers that inhibit such effects. Subsequently, propositions were put forward that reflect the theoretical implications of this study, as well as avenues for future empirical research at the intersection of additive manufacturing technology adoption and supply chain resilience. Lastly, an empirical framework was conceived based on the research findings that outlines the managerial implications of the study.

Keywords: Additive manufacturing; 3D printing; 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 the improvement of supply chain (SC) resilience (Spieske & Birkel, 2021; Belhadi et al. 2021; Iftikhar et al., 2022). Among these emerging digital technologies, additive manufacturing (AM) has received remarkable attention, especially in response to the COVID-19 outbreak (Kunovjanek & Wankmüller, 2020), which is mainly due to its versatility in promoting different applications that can improve the resilience of the SC in an efficient manner (Belhadi et al., 2022). However, the adoption of AM technology by active firms for different applications changes the structure of the SC (Durach et al. 2017;

Dolgui & Ivanov, 2020), thus affecting the underlying SC capabilities and vulnerabilities that define SC resilience (Pettit et al., 2019; Naghshineh & Carvalho, 2022a). Therefore, to better comprehend these structural changes in the SC (aka SC structural dynamics (Dolgui & Ivanov, 2020)), which consequently affect the resilience of the SC, it is important to first understand how AM adoption affects the state of the SC (Naghshineh & Carvalho, 2022a). The "state of the SC is a specific arrangement of SC entities and relational links between them and others SCs, material and information flows, management policies and lead times.", which can be indicated by different SC state variables (Carvalho et al. 2012). This definition extends upon 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), whereas SC structural dynamics takes place when the SC transitions from one macro-state to another, thereby indicating changes in the state of the SC (Ivanov 2018, p.6). In view of these explanations, as well as the highly referred to definition of SC resilience by Christopher and Peck (2004), which is "the ability of a system to return to its original state or move to a new, more desirable state after being disturbed.", 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", thus calling attention to the importance of understanding how the state of the SC is affected when addressing the implications of AM technology adoption for SC resilience (Naghshineh & Carvalho, 2022a).

Nonetheless, after reviewing the existing literature, we could not find any empirical research that addresses this knowledge gap in detail. While there are dispersed pieces of information available throughout the literature that implicit the changes that take place in the state of the SC due to AM adoption, to the best of our knowledge, to date, there has been no single empirical research that comprehensively addresses this knowledge gap by taking on an SC resilience perspective. Only recently, Naghshineh and Carvalho (2022a) conducted a systematic search of the existing literature followed by a critical review of the gathered evidence to propose how AM adoption affects the state of the SC, thereby influencing the SC capabilities and vulnerabilities that underlie SC resilience. Subsequently, they called for empirical research to extend upon their research and validate their findings. In light of these considerations, we aim to respond to their call for empirical research by finding answers to the following research questions (RQs):

- **RQ1**. To what extent does AM adoption affect the state of the SC?
- **RQ2**. How does AM adoption affect the state of the SC?

To come up with answers to these RQs based on the holistic viewpoint of industry, we conducted an exploratory survey whereby we aimed to collect data from experts working for companies involved in different industries and SCs (e.g., aerospace, automotive, medical, etc.), which had adopted one or more AM processes (e.g., powder bed fusion, material extrusion, directed energy deposition, etc.) for different applications (e.g., direct parts production, rapid prototyping, rapid tooling, etc.). Thereafter, drawing on the collected quantitative data (i.e., Likert scale responses), we identified the extent to which AM adoption affects the state of the SC, thereby addressing RQ1. We also gathered qualitative data (i.e., explanations) from the respondents aimed at supporting their quantitative answers and compared them with the existing evidence in the literature to explain how AM adoption affects the state of the SC, thereby addressing RQ2.

The rest of this paper is organized in the following manner. Section two presents the related theoretical background of this research. In section three, the conducted exploratory survey is described. In section four, the results are discussed and propositions are put forward that reflect the theoretical implications of the research. In section five, the managerial implications are discussed and an empirical framework is put forward. Finally, in section six, conclusions are drawn and future research directions are suggested.

2. Theoretical background

AM is an advanced computer technology that digitalizes SCs (Verboeket & Krikke, 2019; Seyedghorban et al. 2020), creating objects in a layer-by-layer fashion via computer-aided design (CAD) models and special machines commonly referred to as 3D printers (ISO/ASTM 52900, 2021). As noted in section one, the adoption of this digital technology gives rise to SC structural dynamics (Dolgui & Ivanov, 2020), which signify the transition of the SC from one state to another. In more specific terms, this transition entails changes taking place in the main SC dimensions, i.e., SC entities (aka nodes), relational links (between the SC entities/nodes), material flows, information flows, lead times, and management policies (Carvalho et al., 2012). For instance, Durach et al. (2017) point out that AM adoption impacts the “structure of supply chains (i.e., the location of the manufacturing facilities)” as well as “supply chain logistics (i.e., transportation and warehousing)”, leading to changes in the arrangement of the SC entities across the SC, their relational links, material flows, information flows, and lead times. Consequently, these changes will affect the SC management policies as well. Hence, to be able to project these changes and their implications for SC resilience, SC state variables are defined and used (Carvalho et al., 2012; 2022). For instance, as shown in Table 1, “Production lead time” and “Delivery lead time” are two SC state variables that reflect the changes that take place in the SC dimension “Lead times”. It is worth noting that the SC state variables (and their designated metrics) in Table 1 were primarily defined by Carvalho et al. (2012) and later developed by Carvalho et al. (2022) to assess SC resilience. Moreover, these SC state variables are used by Naghshineh and Carvalho (2022a) to conceptually appraise the implications of AM adoption for SC resilience; hence, they serve the objective of this research as well. Apart from this, after reviewing the literature, we could not find other sources that put forward a comprehensive list of SC state variables (and their designated metrics) aimed at representing the state of the SC while taking on an SC resilience perspective.

From an SC resilience perspective, understanding the changes that take place in the state of the SC (i.e., SC structural dynamics) due to AM technology adoption is important (Dolgui & Ivanov, 2020), since they, in turn, affect the underlying SC capabilities that are used to mitigate SC vulnerabilities (Pettit et al., 2019; Naghshineh & Carvalho, 2022a). For instance, based on the following piece of supporting 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 affects the SC state variable "Delivery lead time", which can be measured by the designated metric "Ease (in terms of cost) of reducing delivery lead time", consequently affecting the capability of the SC to quickly adapt itself (i.e., SC adaptability) to SC vulnerabilities caused by the unpredictability in customer demands (Naghshineh & Carvalho, 2022a). In view of 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."

Table 1. SC state variables and their related SC dimensions and metrics (adapted from Carvalho et al. 2012, 2022)

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

Note: *"Operations versatility" refers to the capability of a production system to perform various operations (Tsourveloudis and Valavanis, 2002).

Throughout recent years there has been a fair share of empirical research that has investigated the SC effects of AM technology adoption. However, to the best of our knowledge, to date, no empirical research has tried to comprehensively understand to what extent and how AM adoption affects the state of the SC so as to lay out a foundation for future research to investigate the potential SC resilience outcomes of AM adoption. That is to say, the empirical evidence regarding the effects of AM adoption on the state of the SC is fragmented throughout the existing literature, especially when considering the subject matter from an SC resilience perspective. Naghshineh and Carvalho (2022a) highlighted this empirical research gap by performing a systematic search and review of the existing literature. Subsequently, they put forward a Additive Manufacturing-Supply Chain Resilience (AM-SCR) framework, in which they made use of the aforementioned SC state variables (see Table 1) to critically review the effects of AM adoption on the state of the SC, which in turn affect the SC capabilities and vulnerabilities that underlie SC resilience. More specifically, they proposed that certain features of AM adoption affect the state of the SC, while certain barriers inhibit the effects of AM adoption on the state of the SC. In line with the existing literature (e.g., Durach et al. 2017; Verboeket & Krikke 2019), they proposed that such barriers, otherwise known as limitations or bottlenecks (Thomas-Seale et al., 2018; Verboeket & Krikke 2019), play an important role in determining the extent to which AM adoption affects the state of the SC. Thereafter, they called for empirical research to validate their findings, and therefore we aim to address their call in this study. Hence, we adapt part of their conceptual research model that fits the scope of our study, presenting the main research variables. As shown in Figure 1, "Additive manufacturing adoption" is represented by two main variables, i.e., "Additive manufacturing features" and "Additive manufacturing barriers". When considering the subject matter from an SC resilience perspective, AM features tend to motivate the state of the SC to transition to a more favorable state, i.e., positive triggers of SC structural dynamics (Dolgui & Ivanov, 2020), whereas AM barriers tend to inhibit this effect (Naghshineh & Carvalho, 2022a). For instance, while distributed manufacturing (i.e., AM feature) reduces the delivery lead time (i.e., SC state variable) and related logistics costs such as transportation and warehousing (Durão et al., 2017), the excessive need for post-processing (i.e., AM barrier) inhibits this enhancing effect (Dwivedi et al., 2017). Subsequently, the overall effect of AM adoption on the delivery lead time would, in turn, affect the capability of the SC to adapt itself (i.e., SC capability) to the unpredictability in customer demands (i.e., SC vulnerability), thus influencing SC resilience (Naghshineh & Carvalho, 2022a). The latter explanation is only used to illustrate one of the potential outcomes of AM adoption in terms of SC resilience. However, it falls out of the scope of this study, and therefore the variables that represent "Supply chain resilience" in Figure 1 (i.e., "Supply chain capabilities" and “Supply chain vulnerabilities”) are grayed out. We only drew on these variables to stress the importance of AM-driven changes that take place in the state of the SC with regard to SC resilience.

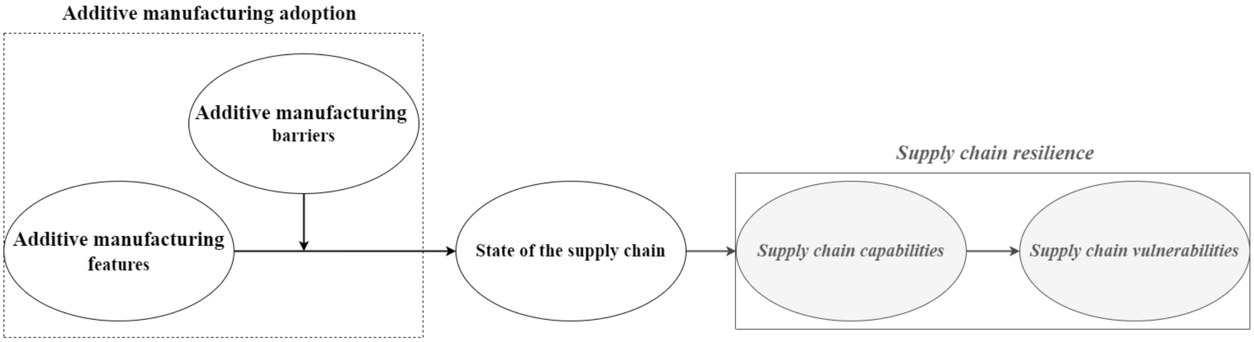


Figure 1. Conceptual research model adapted from Naghshineh and Carvalho (2022a)

In order to be in line with Naghshineh and Carvalho (2022a), we used the same SC state variables and metrics that they used to forecast the effects of AM adoption on the state of the SC (see Table 1). It is worth noting that we excluded “Production capacity scalability” from the list of SC state variables used by Naghshineh and Carvalho (2022a), since it is similar to the SC state variable “Production capacity slack”. While “Production capacity slack” indicates the ease (in terms of cost and time) with which the production capacity can be adjusted, “Production capacity scalability” only indicates the ease (in terms of cost and time) with which the production capacity can be increased. Therefore, we find “Production capacity slack” to be a more comprehensive SC state variable that reflects “Production capacity scalability” as well. Also, it should be noted that the SC state variable “Available alternatives for production processes” is measured by three different metrics (as shown in Table 1), i.e., possibility to outsource production processes, operations versatility, and redundancy in production processes; hence, for brevity, from this point forward we will only mention these metrics when referring to this SC state variable.

3. Research methodology

3.1 Research design

Considering the lack of empirical research regarding the subject matter, we performed an exploratory survey research to investigate to what extent and how AM technology adoption affects the state of the SC. 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. Subsequently, we gathered both quantitative and qualitative data to address RQ1 and RQ2 respectively. We used the collected quantitative data (i.e., Likert scale responses) to estimate the extent to which AM adoption affects the state of the SC (RQ1), while concurrently analyzing the qualitative data (i.e., respondents' explanations justifying their Likert scale responses) to understand how AM adoption affects the state of the SC (RQ2). Hence, this exploratory research method enabled us to gather qualitative data to explain and lend support to the credibility of the quantitative data, thereby establishing methodological triangulation (Jack & Raturi, 2006).

3.2 Sampling and data collection

According to Wohlers et al. (2021), AM is mainly used by companies involved in aerospace, automotive, medical, and energy among other industries. Therefore, to gain the holistic viewpoint of industry on the subject matter, we used the LinkedIn professional network platform to find and inquire experts who were working in such companies around the world (i.e., expert sampling). As a purposive sampling technique (Sharma, 2017), expert sampling allowed us to focus on including professionals with expertise in the field of AM technology. It is worth noting that the LinkedIn platform has already been used for sampling and data collection purposes in notable research. For instance, Kurpjuweit et al. (2021) have used this professional network platform to find experts in the field of AM technology. Hence, we used several different search strings (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 field to participate in the survey. Our search resulted in 417 professional profiles. Subsequently, 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 brief description of the survey along with a weblink to an online questionnaire, which was accompanied by a cover letter explaining the purpose of the survey in more detail and ensured respondent/company anonymity. We started receiving responses from mid-December 2021 until the end of January 2022. The total number of questionnaires we received (after sending follow-up reminders to late responders) was 69, corresponding to a response rate of 17.3%. However, we discarded 9 questionnaires due to incomplete answers (i.e., too many missing values and/or unfilled text fields), which left us with 60 usable questionnaires.

3.3 Survey instrument

We designed the survey instrument in a way to collect both quantitative and qualitative data concurrently. Likert scale questions were used to collect quantitative data regarding the respondent's perception of the extent to which AM technology adoption affects the state of the SC (where 1 indicated "Very low effect" and 5 indicated "Very high effect"), which were captured by the metrics representing the SC state variables. It is worth noting that the SC state variables and their metrics used to form the Likert scale questions were adapted from successful empirical research by Carvalho et al. (2022) aimed at assessing SC resilience, which are also used by Naghshineh and Carvalho (2022a) to propose the effects of AM adoption on the state of the SC and its implications for SC resilience. Subsequent to each Likert scale question, open text fields were provided for the respondents to explain and support their quantitative answers, allowing us to extract meaningful insights regarding how different AM features and barriers affect each SC state variable. The questionnaire also contained general questions regarding the company size, the country, the industry sector, the SC tier, and the respondent's position in the company, as well as the adopted AM processes and their different applications in the company. To ensure anonymity, questions that inquired about the respondents' names as well as their companies' names were presented as optional questions. Prior to dispatch, the questionnaire was first reviewed by an academic and expert in the field and then pilot-tested in several companies that had adopted AM technology. Based on the feedback we received in the pilot testing phase, the questionnaire was first fine-tuned and then administered online via Google forms.

3.4 Data analysis

The descriptive analysis of the companies that the respondents work for is presented in Table 2. The average years of respondent experience in the sample is approximately 9 years (mainly in managerial positions), implying an ideal level of experience and knowledge for answering the survey questions. Also, it is worth highlighting the sample's "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 is presented in Table 3. Comparatively, these descriptive analyses are in line with the report by Wohlers et al. (2021) regarding the "3D Printing and Additive Manufacturing Global State of the Industry", confirming that the derived sample possesses the required characteristics for manifesting the holistic viewpoint of industry on the subject matter. In other words, through this comparison, we could ensure "the representativeness of the sample", which becomes prone to researcher bias in purposive sampling techniques such as expert sampling (Sharma, 2017).

Before proceeding with the statistical analysis of the quantitative data to estimate the extent to which AM adoption affects the state of the SC (RQ1), we evaluated the reliability of the scales using Cronbach's α (Cronbach, 1951). The result for Cronbach's α turned out to be 0.86, which exceeds the commonly accepted value of 0.70 (O'Leary-Kelly & Vokurka 1998), thereby confirming the reliability of the scales. Thereafter, similar to Durach et al. (2017), Jiang et al. (2017), and Ukobitz and Faullant (2021) 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 in the responses. Since this type of statistical analysis 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, to tackle generalizability issues, we put forward propositions based on our findings that are open to further investigation by future research using larger sample sizes and inferential statistics methods.

In conjunction with the statistical analysis of the quantitative data, we also analyzed the respondents’ explanations throughout the open text fields to understand how AM adoption affects the state of the SC (RQ2). To do this, we used the comprehensive list of AM adoption features and barriers put forward by Naghshineh and Carvalho (2022a) as our main reference for coding criteria (aka research dimensions). This way, we made sure that we analyzed each explanation based on the same underlying research dimensions (Miles & Huberman, 1994). Thereafter, we coded the respondents’ explanations for each SC state variable. For instance, “*Producing on site and on demand means no transportation costs and shorter delivery lead times.*”, which is an explanation provided by a respondent for the SC state variable “Delivery lead time”, was coded as the AM feature “On-demand manufacturing”, whereas “*There is a lot of post additive work involved, therefore it is not very easy to reduce delivery lead time.*” was coded as the AM barrier “Excessive post-processing requirements” based on the mentioned coding criteria. In some cases where it was not possible to meaningfully summarize an explanation with the existing coding criteria, we generated new codes. For example, “*With AM lead times for products can be reduced due to fewer parts and elimination of many assembly processes*” (industry expert) was coded as “Part consolidation” since via this AM feature it is possible to reduce the number of parts to manufacture a final part, which in turn reduces the assembly steps and delivery lead time (Ghadge et al., 2018; Knofius et al. 2019). Also, in some cases, more than one code was used to summarize an explanation. For example, “Design freedom” was another code used to summarize the latter explanation, since through this AM feature it is possible to design and manufacture complex products in one step (Holmström et al., 2016), thereby eliminating many assembly steps, which contributes to reducing the delivery lead time. This way, we managed to reduce the respondents’ explanations into manageable units (Miles & Huberman, 1994), which helped us to identify the AM features and barriers that affect each SC state variable. Subsequently, we compared the extracted insights from the respondents’ explanations with the existing evidence in the literature to further ensure the veracity of our findings and triangulate the results (Jack & Raturi, 2006).

Table 2. 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%	*Total*	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%	*Total*	60	100%
Sweden	1	2%	**Respondents' positions**		
Switzerland	1	2%	AM engineer	12	20%
United Kingdom	10	16%	AM manager	14	24%
United States	15	25%	Managing director	10	17%
Total	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%	*Total*	60	100%
> 250 employees	28	47%			
Total	60	100%			

Table 3. Descriptive analysis of the AM processes and their applications in the sample

AM processes	Frequency	Percent	AM applications	Frequency	Percent
Powder bed fusion	50	32%	Direct part manufacturing	56	39%
Sheet lamination	4	3%	Rapid prototyping	52	36%
Directed energy deposition	12	8%	Rapid tooling	24	17%
Vat photopolymerization	24	16%	Maintenance, repair, and overhaul	12	8%
Material extrusion	34	23%	*Total*	144	100%
Material jetting	10	7%			
Binder jetting	16	11%			
Total	150	100%			

4. Results and discussion

Table 4 presents the derived scores for the mean and standard deviation (SD) of the answers to the Likert scale questions, which are ranked from the highest to the lowest mean scores, displaying the results aimed at addressing RQ1. The extent to which AM adoption affects each SC state variable is approximated based on the mean scores. It should be noted that since the mean scores are not whole numbers, we approximated the AM adoption effects by rounding the scores up/down to the closest whole number. For instance, in the case of “Production schedule adaptability”, rounding 4.04 down to 4 represents a high AM effect based on the applied Likert scale. Moreover, the overall effect of AM adoption on the state of the SC is estimated by averaging the mean scores of all the SC state variables.

Table 4. Statistical analysis results

SC state variable	**Mean**	**SD**	**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
The state of the SC	3.13	1.29	Moderate	-

Note: Cronbach’s $\alpha = 0.86$

In the following subsections, we overview the results of the statistical analysis at the beginning of each subsection (RQ1), followed by the findings of the qualitative data analysis (RQ2). As mentioned earlier, we also consider the related literature to compare the findings and discuss the theoretical implications of this research, which are concluded in the form of propositions at the end of each subsection. In section five, we will discuss the managerial implications of the research and put forward an empirical framework accordingly.

4.1 Production schedule adaptability

The Likert scale responses yielded the highest mean score for production schedule adaptability. Also, the dispersion in the answers was at its lowest, indicating the highest level of consensus in the answers compared to other SC state variables. In terms of frequency, this SC state variable received the maximum number of “Very high effect” answers. This result is in line with Naghshineh and Carvalho (2022a) who proposed that AM adoption has the highest effect on production schedule adaptability.

It was noted that in AM "*BOM* [bill of materials] *is first level (raw materials only)*" (industry expert), whereas in conventional manufacturing methods, BOM is normally multi-level. One reason for this is that in AM there is not much need for subcomponents and sub-assemblies to build a final part (Knofius et al., 2019). This is also in line with Ford and Despeisse (2016) and Chan et al. (2018) who state that in AM fewer basic materials are kept as inventory, which in turn facilitates the adaptability of production schedules due to reduced material handling and packaging, storage and warehousing, and transportation (Liu et al., 2014; Waller & Fawcett, 2014). Moreover, different explanations by the respondents 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.*" imply that production setup in AM is relatively fast and easy. This AM feature makes production planning easier, especially when considering the time and cost factors (Weller et al., 2015; Kunovjanek et al. 2020). The use of digital files (e.g., digital inventory) was also associated with the ease in changing the production schedules. As one respondent noted, "*AM is flexible in this respect since you're working with digital files.*" Similarly, in their review, Naghshineh and Carvalho (2022a) identified digital inventory and the distribution of digital files as important AM adoption features that affect production schedule adaptability. Also, tool-less manufacturing plays an important role in facilitating changes in production schedules. Considering different explanations such as "*Quite easy and happening nearly every 2-3 days.*" or "*the ability to change to a new part type can be done quicker than traditional methods.*" by the industry experts, which are in line with Holmström et al. (2016) and Sgarbossa et al. (2021), it can be inferred that the tool-less nature of AM mitigates the need for laborious setups and specific production tools, adding to the flexibility of changing the production schedules. Overall, the explanations were on par with each other, stating that production planning is relatively easy with AM, especially when compared to conventional manufacturing methods.

On the downside, though, the present instability in AM processes was considered to be a barrier. One respondent 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 explanation 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 potential quality issues or scrap and rework. These issues require time to be resolved, which takes away from the flexibility to make changes to the production plans. This is especially true for orders that are already postponed. Thus, such issues can lead to backorders or even customer loss (Naghshineh & Carvalho, 2022a). According to the following explanation: "*Depends on the volumes*" (industry expert), production volume is also a determining factor. In other words, adjusting production plans with ease in cases where AM is not used for low production volumes may not be feasible (Khajavi et al., 2014; 2015), implying AM's low throughput rate (Weller et al., 2015; Dwivedi et al., 2017). Moreover, slow production speed exacerbates this situation. As noted by a respondent, "*Builds can take multiple days to finish, so it is not easy to change once the plan is in place.*" Another mentioned barrier is the need for excessive post-processing in many AM parts, which is reiterated by scholars such as Achillas et al., (2017) and Chekurov et al. (2018) among others. In other words, this barrier reduces AM's agility in changing or modifying the production schedules, which according to Naghshineh and Carvalho (2022b) leads to reduced adaptability of the SC against erratic customer demands. An interesting insight derived from the respondents' explanations: "*It lends itself well to CAD/CAM* [Computer-aided Design/Computer-aided Manufacturing] *software, slicing software and MES* [Manufacturing Execution Systems] *software.*" and "*There is no good MES solution quite yet in the market*" is that although AM is compatible with MES, currently there are not many suitable MES solutions available for this technology, which inhibits its capability in terms of production planning. MES provides "a common user interface and data management system" (Saenz de Ugarte & Artiba, 2009), supporting intelligent manufacturing and decision-making in AM (d'Antonio et al. 2017). This corroborates the findings of Durão et al. (2017) and Chekurov et al. (2018) who state that information and communication technology (ICT) inadequacies limit information exchange, communication, and control in AM. In view of the foregoing, we put forward the following proposition:

Proposition 1. AM adoption has a high effect on production schedule adaptability due to fewer materials and inventory, fast production setup, digital inventory, and tool-less manufacturing. However, this effect is inhibited by the existing unstable AM processes, low throughput rate, slow production speed, excessive post-processing requirements, and ICT inadequacies.

4.2 Delivery lead time

When considering the importance of mean scores, delivery lead time takes second place with the third lowest level of dispersion in the answers, implying general agreement by most of the respondents regarding the high effect of AM adoption on this SC state variable. This was evident from the low frequency of "Low effect" and "Very low effect" answers, while the majority of the answers were alternating between "High effect" and "Very high effect". This result is also very similar to that of Naghshineh and Carvalho (2022a) who ranked delivery lead time as the third most affected SC state variable by AM adoption.

According to the following explanation: "*Producing on site and on demand means no transportation costs and shorter delivery lead times*" (industry expert), two important features of AM adoption are the distributed manufacturing and on-demand manufacturing of parts. Through these AM features, production can be relocated closer to customers, which significantly contributes to reducing delivery lead times as well as transportation costs. As one respondent noted, “*Lead times can be a matter of hours.*” This is also in line with the research findings by Ghadge et al., (2018) who propose that by installing AM machines on-site, parts can be produced on-demand, thus reducing the delivery lead time to nearly zero. Also, another respondent pointed out that 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). This explanation is also in line with Waller and Fawcett (2014) who state that “3D printing allows for rapid prototyping, reducing the product development process cycle time.” Apart from rapid prototyping, which was mentioned as a contributing factor towards reducing the product development cycle time and consequently delivery lead time, some respondents also mentioned the importance of high design freedom in this regard. For instance, “*Some highly complex and time-consuming parts can be produced with AM.”* is an explanation by one respondent that highlights this AM feature, which is also referred to as “new design possibilities” (Wagner & Walton, 2016) or “Design Capabilities” (Naghshineh et al., 2021) in the existing literature. Also, the high degree of design freedom and design capabilities in AM facilitate the consolidation of many parts into one complex part, thus leading to fewer parts and the elimination of many assembly steps, which in turn expedites the 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).

Once again, excessive post-processing requirements were remarked as 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). Also, an outlier answer drew attention to the influence that third-party logistics (3PL) providers can have on the delivery lead time of AM parts. “*Production lead time can be reduced by additive manufacturing, however the delivery itself is dominated by logistics companies*” (industry expert). While this explanation may be true, it mainly depends on the location where AM is being used to produce the parts (Braziotis et al., 2019; Ghobadian et al., 2020). For instance, if the AM plant is located far from the point of use, then the additively manufactured parts may be transported by 3PL providers. In this scenario, the 3PL providers can influence the delivery lead time of the parts. However, as AM is normally used to take production closer to the point of use via different methods of distributed manufacturing, e.g., on-site manufacturing or mobile manufacturing (Rodríguez-Espíndola et al., 2020; Kenger et al., 2021), this scenario is rather unlikely.

Proposition 2. AM adoption has a high effect on delivery lead time due to on-demand manufacturing, distributed manufacturing, rapid prototyping, design freedom, and part consolidation. However, this effect is inhibited by the excessive post-processing requirements.

4.3 Operations versatility

Operations versatility takes third place on the list of the SC state variables affected by AM adoption. Most answers were "High effect", with the distribution of answers being more dispersed compared to the first two discussed SC state variables. Contrary to our findings, operations versatility is ranked seventh by Naghshineh and Carvalho (2022a), implying that the existing evidence in the literature regarding the enhancing effects of AM adoption on operations versatility is not as pronounced as the empirical results of this study.

Interesting insights were extracted from the respondents' explanations. To begin with, the flexibility in AM design was regarded as an enhancer of operations versatility by multiple respondents, who commonly referred to high flexibility in altering part designs aimed at improving functionality and performance (e.g., design/part optimization), corroborating the findings by Huang et al. (2013) and Weller et al. (2015) among other scholars. "*High flexibility and freedom in design provided by AM production.*"; "*AM machines can nearly make any chosen part.*"; "*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 among such illustrative explanations by the respondents that highlight the high design freedom in AM technology. Automated manufacturing as well as tool-less manufacturing via AM were also mentioned as two interrelated 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 the respondents in this regard, which are in line with Holmström and Partanen (2014) who state that "Digital manufacturing technologies allow for the automatic production of objects from CAD design files without shape-defining tooling." Also, it was noted that automation in AM reduces the need for manual operations and labor, lending support to the findings by Gebler et al. (2014) and Tziantopoulos et al. (2019) among other scholars. Furthermore, as is evident in the following explanation: "*We are also able to rapidly produce variable tools on site*" (industry expert), the AM-enabled opportunity to quickly produce the necessary tools on-site and on-demand (i.e., rapid tooling) adds to the versatility of operations. This would also reduce the need for large investments in retooling the production system for each production cycle as already noted in the previous explanations; hence reducing the overall production costs, which is also mentioned by scholars such as Chan et al. (2018) and Kleer and Piller (2019).

Respondents also explained that through rapid prototyping and manufacturing of parts, temporary solutions can be improvised that allow the production system to reduce downtimes. This is in accord with scholars such as Ghadge et al. (2018) and Sgarbossa et al. (2021) noting that with AM it is possible to reach the required service levels while avoiding high downtime costs. "*In some cases, it 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.*"; "*It allows us to quickly make design changes and prove out concepts before outsourcing.*"; 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 by the respondents in this respect. Moreover, "the theoretical ability that products can be made directly in one manufacturing step through the application of AM" (Kunovjanek & Reiner, 2020) was supported by some explanations. For instance, one respondent 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).*"; which is indicative of the possibility to integrate many production processes into one process through AM. In this case, the number of production steps for most parts is reduced to one (Holmström et al., 2016), thereby reducing the complexity of process operations and making production planning much easier (Chiu & Lin, 2016; Oettmeier & Hofmann, 2017). Along the same lines, part consolidation was also noted in an explanation, in the sense that with "*direct manufacturing of parts*" (industry expert), it is possible to reduce the number of parts necessary to build a final part. According to one respondent, "*there is some interest from clients in reducing the number of parts of certain components using AM.*" Another implication raised by some respondents was that not many different types of raw materials and inventory are needed to produce an additively manufactured part, which in return increases the versatility of operations. As one respondent noted, "*several AM parts are based on the same raw material, so an SLM* [Selective Laser Melting] *machine could be used for various parts.*" This finding is also supported by Li et al. (2017) and Chan et al. (2018) who mention the use of fewer raw materials and inventory in AM.

Despite all the mentioned AM features, some barriers also emerged from the explanations, most of which are in line with Naghshineh and Carvalho (2022a; 2022b). Firstly, it was noted that it is "*not easy to change materials*" (industry expert). This barrier is primarily caused by the inability to simultaneously process multiple materials (Rayna et al., 2015; Chiu & Lin, 2016), which in turn requires the deep cleaning of the printers before a new build can be started using different materials. This is also mentioned in research 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 as well as slow production speed were remarked as two other barriers that inhibit the enhancing effect of AM adoption on operations versatility. "*The versatility of standard AM systems is still the same since previous years. 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 the latter explanation, "*Quality measurement systems*" that can mitigate the instability of AM processes, as well as "*fast production updates*" are available in newer systems, however, their high acquisition cost may prevent many firms from (re)investing in them.

Proposition 3. AM adoption has a high effect on operations versatility due to design freedom, automated manufacturing, tool-less manufacturing, rapid tooling, rapid prototyping, temporary solutions, process integration, part consolidation, and fewer materials and inventory. However, this effect is inhibited by the lack of multi-material printing, unstable AM processes, and slow production speed.

4.4 Production capacity slack

Production capacity slack takes fourth place among the most affected SC state variables by AM adoption. However, production capacity slack is ranked 13th by Naghshineh and Carvalho (2022a), indicating a noticeable difference. Most of the answers were marked as "High effect", followed by "Very high effect" and "Moderate effect" respectively. Considering the respondents' explanations, some mentioned 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 respondents. 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 also 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 other explanations referred to the reduced number of operators using AM (due to automated manufacturing) compared to conventional methods, which implies more flexibility in terms of labor when adjusting the production capacity. This AM-enabled automation, in turn, promotes the notion of economies of technology, whereby it is possible to significantly reduce labor (Tuck et al., 2007; Naghshineh et al., 2021). For instance, two respondents respectively explained that there is "*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*". Also, in case of production failure, AM was noted to be a flexible method for readjusting the production capacity compared to conventional methods.

However, some constraints were pointed out as well. For instance, one respondent noted that it "*Depends on whether changing materials is involved or not.*", implying the difficulty in cleaning out the machines and changing the raw materials before starting a new job, which inhibits the ease with which production capacity can be adjusted. This barrier is mainly caused by the lack of multi-material printing in AM (Rayna et al., 2015; Rayna & Striukova, 2016), which may explain why some manufacturers prefer to dedicate each 3D printer to building a specific set of parts that do not require different raw materials and material changeovers. Accordingly, another respondent noted that there are "*Dedicated machines for dedicated products.*" Another related adoption barrier is the limited capacity of the build volumes, which in turn limits the number of parts that can be printed before having to proceed with recycling the material and restarting the job, resulting in a low throughput rate. The following explanation is indicative of these interrelated barriers: "*Scalability depends on the number of machines installed*" (industry expert), implying the limited capacity of the build volumes, and that the number of installed 3D printers should be increased to compensate for the resultant low throughput rate. Alternatively, another solution is to increase the utilization rate of the 3D printers by adding extra work shifts, which may lead to faster depreciation of the machinery as well as incurring more 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, this barrier will inhibit the possibility of easily adjusting the production capacity for batch production (Baumers et al., 2017), which can be elucidated based on the following explanations by the respondents: "*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 according to one respondent makes it difficult to justify increasing production capacity for short-run projects. This is in line with Afshari et al. (2020) among others, who state that the cost of AM processes is generally higher than conventional methods, making the economic use of this technology in some cases infeasible, and that improvements are necessary in this regard (Ryan et al., 2017). One reason for this economic infeasibility is the high cost of industrial-grade AM machines (Kietzmann et al., 2015; Schniederjans, 2017), especially when manufacturers are forced to upgrade to newer systems. This was pointed out by one respondent noting that "*New machines allow for a linear growth but are expensive*".

Proposition 4. AM adoption has a high effect on production capacity slack due to on-demand manufacturing, small batch production, automated manufacturing, and economies of technology. However, this effect is inhibited by the lack of multi-material printing, limited build volumes, low throughput rate, high cost of AM processes, and high cost of industrial-grade AM machines.

4.5 Production lead time

While according to Naghshineh and Carvalho (2022a), the existing literature seems to place a lot of importance on the effects of AM adoption on production lead time, this SC state variable is ranked fifth in this study. Nevertheless, the answers still indicate a relatively high effect of AM on this SC state variable. In line with the existing literature, some of the respondents believed that tool-less manufacturing via AM considerably contributes to reducing production lead time. One respondent even attributed the fast production turnaround in AM (i.e., the time to print and post-process a part) to tool-less manufacturing. This is in accord with Sasson and Johnson (2016) and Sgarbossa et al. (2021) among others, who unanimously state that AM is a tool-less manufacturing method that significantly reduces changeover and setup times, thus reducing production lead time. Along the same lines, fast production setup was mentioned multiple times, which is augmented by the tool-less nature of AM technology. Two respondents' explanations in this case were: "*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 reduce production lead time, which is especially true for parts that possess complex geometries (Petrovic et al., 2011; Bogers et al., 2016). According to a respondent, "*Rapid design iteration with additive gets to functional components faster*." This is the case since through rapid prototyping and rapid manufacturing (Kietzmann et al., 2015; Niaki & Nonino, 2017), the required time for the design and manufacture stages of a functional part can be reduced considerably (Holmström et al., 2017; Ma et al. 2018). "*Production time is reduced drastically.*" and "*The big benefit for prototypes, however, is mainly the lower production time.*" are explanations by the respondents that reflect the reduction in production lead time as a positive outcome of such AM features. Also, it was noted that the reduction in the number of required components to produce a final part, i.e., part consolidation (Knofius et al. 2019; Luomaranta & Martinsuo, 2020), streamlines the whole production process, resulting in faster production lead times. For instance, "*Simplified and faster production process due to reduction of parts in subassemblies*" is an explanation by a respondent referring to part consolidation. This AM feature in turn simplifies the SC (Chiu & Lin, 2016; Ghobadian et al., 2020), especially in the case of parts and products that possess complex geometries and are burdensome to produce via conventional methods (Chen et al., 2015; Nascimento et al., 2019).

However, several respondents also noted that reducing the production lead time via AM is dependent on different variables, e.g., AM process, part complexity, 3D printer model, and the load of post-processing. For instance, the AM processes used for printing parts made of plastic possess shorter production lead times compared to those used for printing metal parts, which need to undergo more stringent post-processing steps such as machining and thermal treatment (Colosimo et al. 2020). One respondent explained that "*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*." Nonetheless, AM is generally criticized because of its slow production speed (Thomas-Seale et al., 2018; Verboeket & Krikke, 2019). For instance, Baumers et al. (2016) report the processing speed of direct metal laser sintering (DMLS) as well as electron beam melting (EBM) processes to be significantly lower than conventional methods. This issue is likely to improve in newer 3D printer models; however, according to some respondents, the high cost of frequent upgrades to faster industrial-grade AM machines can become a problem. Lastly, the present instability in AM processes was considered by some respondents to be a determining factor as to whether or not AM is capable of reducing the production lead time in an efficient manner, providing empirical evidence for the proposition set forth by Naghshineh and Carvalho (2022a) that unstable AM processes "can offset the contributions of AM towards reducing production lead times."

Proposition 5. AM adoption has a high effect on production lead time due to tool-less manufacturing, fast production setup, rapid prototyping, rapid manufacturing, and part consolidation. However, this effect is inhibited by the excessive post-processing requirements, slow production speed, high cost of industrial-grade AM machines, and unstable AM processes.

4.6 Relationship type

Relationship type was ranked sixth on the list of SC state variables affected by AM adoption. This ranking is similar to that of Naghshineh and Carvalho (2022a), who ranked relationship type as the fifth most affected SC state variable based on the existing evidence in the literature. The Likert scale responses were dispersed rather evenly among different choices with "Moderate effect" being the most frequent response. Insightful explanations were given by the respondents, which are in line with the extant literature. It was noted that customer involvement and cooperation in the design and manufacture stages of a product is possible via AM technology, e.g., consumer-centric production or co-creation/co-design (Postada & Zybura, 2014; Bogers et al., 2016; Rylands et al., 2016), which is necessary for manufacturing complex parts in order to avoid potential failures. For instance, one respondent noted that "*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, ...).*" Furthermore, close collaboration with suppliers and customers was mentioned multiple times, corroborating the findings by Oettmeier and Hofmann (2016) who state that a cooperative approach among the members of an AM SC (e.g., AM machine suppliers and raw AM material suppliers) 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 explanations by the respondents highlighting the importance of close collaboration. Another explanation referred to the high level of competition in the AM markets (Weller et al., 2015; Beltagui et al., 2020), which also requires a high degree of cooperation between SC members for success. “*There's a lot of competition in the AM market. In order to survive, cooperation is needed*” (industry expert). This was further explained by some respondents 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 adoption barriers (Dwivedi et al., 2017; Durach 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.*” are two explanations by the respondents that support the latter statement. Apart from these barriers, another inhibiting factor in AM SCs is the potential intellectual property (IP) rights complications (Petrick & Simpson, 2013; Steenhuis & Pretorius, 2017) that may arise due to issues concerning proprietary knowledge, licensing, copyrights, patents, or counterfeiting (Gebler et al., 2014; Chan et al., 2018). For instance, according to some respondents, the effect of AM adoption on the degree of cooperation with other firms in the SC can be “*Low due to IP/technology*” (industry expert); and “*Proprietary techniques and knowledge reduce some communication within the supply chain*” (industry expert).

Proposition 6. AM adoption has a moderate effect on the relationship type between SC members due to consumer-centric production, co-creation/co-design, and close collaboration. This effect is inhibited by the lack of trust, lack of consumer awareness and acceptance, and IP rights complications.

4.7 Redundancy in production processes

With most answers marked as “Moderate effect”, the effect of AM on redundancy in production processes was estimated as moderate, placing it midway on the list of SC state variables. While the consensus according to the respondents’ explanations was that AM has an enhancing effect on redundancy in production processes, some adoption barriers were also mentioned that inhibit this enhancing effect. To begin with, many respondents believed that AM is a suitable method for low volume production (aka, small batch production), given that it does not require different production tools (Tuck et al., 2007; Weller et al., 2015). Hence, it can readily be used to complement the conventional manufacturing methods (i.e., hybrid manufacturing model), providing extra production capacity (Khajavi et al., 2015; Verboeket & Krikke, 2019). “*We often produce small series of parts that would otherwise require tooling.*” and “*Allows us to utilize additive for extra capacity*.” are two explanations by the respondents in this regard. This way it would be possible to provide the necessary redundancy in production processes to deal with variability in demand (e.g., parts with low and sporadic demand), and as a result reduce forecasting efforts (Waller & Fawcett, 2014; Sasson & Johnson, 2016). Moreover, another option for providing redundancy is to use the extra AM capacity available at external sources (i.e., capacity pooling). As one respondent noted, "*High flexibility to increase/decrease production by external suppliers.*"

However, concerns were also expressed regarding the financial viability of AM as an asset aimed at providing redundancy. Some respondents stated that AM machines need to be working at full capacity to justify the financial investments made in them while some others noted that investing in AM requires a lot of capital, mainly due to the high cost of industrial-grade AM machines (Kietzmann et al., 2015; Schniederjans, 2017). "*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 two relevant explanations provided by the respondents that illustrate this barrier. Apart from cost issues, technological barriers were also mentioned. AM's low throughput rate was mentioned by multiple respondents. For instance, "*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 given by different respondents that imply the limited rate at which parts can be printed. Therefore, AM's low throughput rate limits the availability of adequate redundancy in production processes in a timely fashion. Moreover, other interrelated barriers that exacerbate this situation were mentioned. For example, one respondent mentioned that "*AM is still too slow to produce at high numbers.*", pointing out the reason why AM may not be a suitable option for providing redundancy in a mass production setting. Also, it was noted that "*switching between materials can be time consuming, especially in metal processes*" (industry expert); implying the lack of multi-material printing as a barrier (Rayna et al., 2015; Eyers et al., 2018), which further inhibits AM's throughout. Nevertheless, it was also noted that in the foreseeable future, many of these barriers will be overcome as AM technology advances.

Proposition 7. AM adoption has a moderate effect on redundancy in production processes due to small batch production, tool-less manufacturing, hybrid manufacturing, and capacity pooling. This effect is inhibited by the high cost of industrial-grade AM machines, low throughput rate, slow production speed, and lack of multi-material printing.

4.8 Information sharing

Information sharing was ranked eighth with a rather high SD, indicating different opinions among the respondents. In line with scholars such as Tuck et al. (2007) and Ford and Despeisse (2016), some explanations corroborated the notion that the digital nature of AM technology contributes towards information sharing among SC partners, e.g., "*AM is digital so it can facilitate the exchange of information*" (industry expert). For instance, it was explained that the easy and inexpensive transmission of designs in the form of digital files (i.e., digital file distribution) empowers the real-time distributed manufacturing of parts in different locations (Eyers & Potter, 2015; Durão et al. 2017). It was also noted that the storage of many parts in the form of finished goods inventory is overcome by the capability to instead store them as digital inventory (Chekurov et al. 2018; Verboeket & Krikke 2019). One respondent explained that "*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.*" Furthermore, it was noted that as a digital technology, AM is compatible with different types of information systems such as MES, Material Requirement Planning (MRP), and Enterprise Resource Planning (ERP). Lastly, close collaboration and networking between SC partners were considered necessary for information sharing. For instance, "*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 explanations by the respondents in this regard.

On the other hand, it was noted that improvements are necessary to streamline the information flow between different production sites, which is in line with the findings of Durão et al. (2017), Chekurov et al. (2018), and Naghshineh and Carvalho (2022b) who draw attention to the importance of establishing a reliable ICT infrastructure when using AM. Moreover, potential IP rights complications were mentioned multiple times, indicating the concerns that many companies have over exchanging data with other SC entities via unreliable ICT infrastructure (Chan et al., 2018; Verboeket & Krikke 2019). For example, a respondent noted that "*Too much is at stake in terms of IP*". Lastly, a few respondents mentioned that AM is no different from other production methods when it comes to information sharing and that they have to cope with commonplace issues. "*Same as conventional manufacture. Never overrate 'Digital production'. In day-to-day business, many things have to be discussed the old-fashioned way with the supplier of a part, even if it is AM*" (industry expert).

Proposition 8. AM adoption has a moderate effect on information sharing due to digital file distribution, distributed manufacturing, digital inventory, and close collaboration. This effect is inhibited by ICT inadequacies and IP rights complications.

4.9 Possibility to outsource production processes

The mean score for this SC state variable corresponds to a moderate effect, while the dispersion in the answers is relatively high due to contrasting opinions between the respondents. Some respondents explained that AM grants their companies the opportunity to outsource production (Ford & Despeisse, 2016;

Rogers et al., 2016) and gain access to extra production capacity, for instance via capacity pooling (Holmström et al., 2010; Verboeket & Krikke, 2019), hence avoiding the high costs of procuring AM machinery and the need to learn how to use the technology. "*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 three explanations by different respondents that illustrate the AM-enabled possibilities for outsourcing production and capacity pooling. This way, it is possible to focus on activities (other than production) that bring more value to the firm.

Despite these advantages, some respondents noted that the high cost of AM processes can make outsourcing production economically unviable. As one respondent elaborated, "*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 respondents stated that outsourcing production is not an easy task as it can lead to quality issues, while some others noted that in order to avoid quality issues and preserve consistency, they would rather produce the 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 provided by the respondents in this regard. These explanations correspond to the findings by Dwivedi et al. (2017) regarding the present lack of consistency in AM processes, which according to Naghshineh and Carvalho (2022a; 2022b) is more likely to take place when production is outsourced. This issue is exacerbated by the lack of standardization in AM processes and materials. As Thomas-Seale et al. (2018) state, "There is a well acknowledged deficit in the number of standards governing AM processes." Similarly, Chekurov et al. (2018) point out that there is a "Lack of standardization of AM material production processes". All this may as well explain why some respondents mentioned that they would rather keep the AM processes in-house than have them outsourced, e.g., "*Additive is a core in-house process for us, rarely outsourced to maintain consistency and quality*" (industry expert) and "*We keep our core manufacturing processes in-house*" (industry expert). Moreover, it was noted that by insourcing the 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, corroborating the findings by Naghshineh and Carvalho (2022b) in this case.

Proposition 9. AM adoption has a moderate effect on the possibility to outsource production processes. This effect is inhibited by the high cost of AM processes, lack of AM process standards, lack of AM materials standardization, and IP rights complications.

4.10 Available alternatives for sources of supply

Considering its mean score, available alternatives for sources of supply is the tenth affected SC state variable. Many respondents explained that there are still not a lot of AM material and machine suppliers in the market, which forces them to single-source their material and equipment. "*There is only a couple of sources of raw material and a few for additive equipment.*" and "*There are several suppliers of machines and dozens of suppliers of material. However, we still have a limited supply of material.*" are two such explanations by the respondents. However, it was also noted that this issue differs between the AM processes. For instance, one respondent mentioned 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 respondents mentioned that there is a lack of proven machine suppliers in the AM industry space. "*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 two illustrative explanations by the respondents in this case. 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, which is mainly due to 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 respondents, this problem is expected to improve over time as the AM market matures. For instance, it was noted that there are now more open-source systems that allow manufacturers to use different types of materials (e.g., plastic resin pellets instead of just extruded filament), and therefore avoid being fully dependent on only one specific supplier (aka vendor lock-in). Last but not least, the high cost of AM materials as well as industrial-grade AM machines were mentioned as two other barriers that would further limit the number of available alternatives for sources of supply.

Proposition 10. AM adoption has a moderate effect on available alternatives for sources of supply. This effect is inhibited by the limited supply of AM materials and industrial-grade AM machines, the lack of standards for AM materials and processes, and the high cost of AM materials and industrial-grade AM machines.

4.11 Available alternatives for production sites

Most answers regarding this SC state variable were either “Low effect” or “Very low effect”, averaging to relatively “Low effect”. Considering the proposition rankings by Naghshineh and Carvalho (2022a), “Available alternatives for production sites” is ranked eighth on their list, whereas in this study, this SC state variable is ranked 11th. Respondents’ explanations were somewhat controversial. Some respondents believed that distributed AM is groundbreaking as it grants producers access to backup production sites and facilities at different locations, especially close to the point of use, corroborating the findings by scholars such as Durão et al. (2017) and Zanoni et al. (2019) among others. For instance, one respondent noted that “*Having a backup plant for additional capacity is fairly easy to setup.*” Along the same lines, the concept of mobile manufacturing was implied. Mobility in the context of manufacturing is defined as “the ability to change between geographically different places with little penalty in time, effort, cost, or performance.” (Stillström & Jackson, 2007). According to a respondent, “*At the cost of a printer and few other ancillary equipment, production can be set up almost anywhere*.”; which is in accord with the aforementioned definition of mobile manufacturing. Also, it was noted that local/regional production via AM helps to reduce the negative effects of disruptions (e.g., delays in shipment), which is closely in line with the findings of Wagner and Walton (2016). Additionally, attention was drawn to the possibility of outsourcing production, as well as pooling the available AM capacity at other production sites. Accordingly, one respondent noted that “*AM is becoming more mainstream and there is a good chance a company can have alternative production options.*”

Conversely, some respondents mentioned that distributed manufacturing via AM is not as simple as it sounds, especially in cases where the production system is also dependent on conventional methods, e.g., hybrid manufacturing model (Holmström & Partanen, 2014; Khajavi et al., 2015). According to a respondent, “*The additive portion of the manufacturing process is somewhat simple to move, the rest of the operations are not so easily transferable though*.” Moreover, it was noted that a specialized production infrastructure is required for adopting AM technology, the lack of which can significantly reduce the enhancing effects of AM adoption on available alternatives for production sites. For instance, having access to a reliable ICT or utility infrastructure (since AM is energy-intensive) can be challenging, which is also mentioned in the existing literature by scholars such as Chekurov et al. (2018), Boer et al. (2020), and Naghshineh and Carvalho (2022b).

Proposition 11. AM adoption has a low effect on available alternatives for production sites due to distributed manufacturing, outsourcing production, and capacity pooling. This effect is inhibited by the lack of specialized production infrastructure.

4.12 Transport mode

The mean score for transport mode was relatively low with the maximum dispersion in the answers, implying controversial opinions among the respondents. However, the ranking for this SC state variable is similar to Naghshineh and Carvalho (2022a), i.e., 12th, indicating that the empirical results for this SC state variable are on par with the existing evidence in the literature. Regarding explanations, some respondents noted that in AM SCs, the transportation of parts is normally last mile, hinting at close distances between the distribution centers and customers. This was mainly attributed to the AM-enabled distributed configurations where production takes place close to the point of use, e.g., at the distribution centers, therefore reducing the need for long-haul transportation, which is also mentioned by scholars such as Jiang et al. (2017) and Hopkins (2021) among others. According to the respondents, another relevant AM feature is the capability to digitally store and distribute files to produce the necessary parts on-site and on-demand instead of having to physically warehouse and transport them, which is also mentioned by Eyers and Potter (2015) as well as Chekurov et al. (2018) among others. As one respondent briefly noted, "*The supply chain is digital*", enabling the storage and distribution of digital files instead of the storage and transportation of physical parts. Moreover, "this shift towards the delivery of digital files and basic material rather than complex assembled products" (Ford & Despeisse, 2016), which in turn leads to fewer materials and inventory in the SC (Li et al., 2017; Chan et al., 2018), makes it easier to use "different transportation modalities" (Verboeket and Krikke, 2019). Thus, as noted by a respondent, "*Many alternatives for transportation are available*". Furthermore, it was noted that by using vehicles that are equipped with 3D printers, it is possible to print the necessary parts en route to the point of use, corroborating the notion of AM-enabled mobile manufacturing (Pérès & Noyes, 2006; Kenger et al., 2021). Another interesting explanation was that since AM is normally used for low volume production (i.e., small batch production), many of the produced parts can be shipped via usual 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 explains why some answers were marked as "Very high effect" accompanied by explanations such as "*Easy to use multiple transportation methods*" (industry expert). At the same time, some explanations did not concur with the idea that AM is any different from the conventional methods when it came to transport modes. Only in one case, it was mentioned that the transportation of hazardous powders is slower. However, this issue not only applies to AM but also to other production methods. As for other potential AM barriers, we did not identify any mentions.

Proposition 12. AM adoption has a low effect on transport mode due to distributed manufacturing, digital file distribution and digital inventory, fewer materials and inventory, mobile manufacturing, and small batch production.

4.13 Distribution channels

According to the Likert scale responses, the least affected SC state variable is the distribution channels. It is also the only SC state variable that received the maximum number of "Very low effect" and the minimum number of "Very high effect" responses. While Naghshineh and Carvalho (2022a) managed to put forward seemingly coherent propositions based on their literature review regarding the effects of AM adoption on distribution channels, the respondents' explanations did not reveal coherent insights. Some respondents explained that in AM, parts are normally produced in small batches (i.e., small batch production), leading to fewer materials and inventory in the SC, which in turn facilitates distribution. On the contrary, some respondents mentioned that it is expensive and difficult to switch the distribution channels. The reason for this was mainly attributed to the high cost of AM processes, as well as the lack of AM process standards. For instance, one respondent 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 respondent 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 adoption was not considered to bear a considerable effect on the ease to switch distribution channels; and even some respondents believed that the same distribution principles that apply to other manufacturing methods apply to AM technology as well.

Proposition 13. AM adoption has a low effect on distribution channels due to small batch production as well as fewer materials and inventory. This effect is inhibited by the high cost of AM processes and the lack of AM process standards.

4.14 The state of the supply chain

After averaging the derived mean scores of the discussed SC state variables, the overall effect of AM adoption on the state of the SC turned out to be moderate (see Table 4), which in turn is expected to moderately affect the resilience of the SC. We find this estimation to be in accord with the findings of Durach et al. (2017), who state that some of the SC impacts of AM adoption are unlikely to 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 technology advances over time, we expect to see the inhibiting effects of the identified barriers decrease, and therefore the enhancing effect of AM adoption on the state of the SC (and consequently SC resilience) would increase.

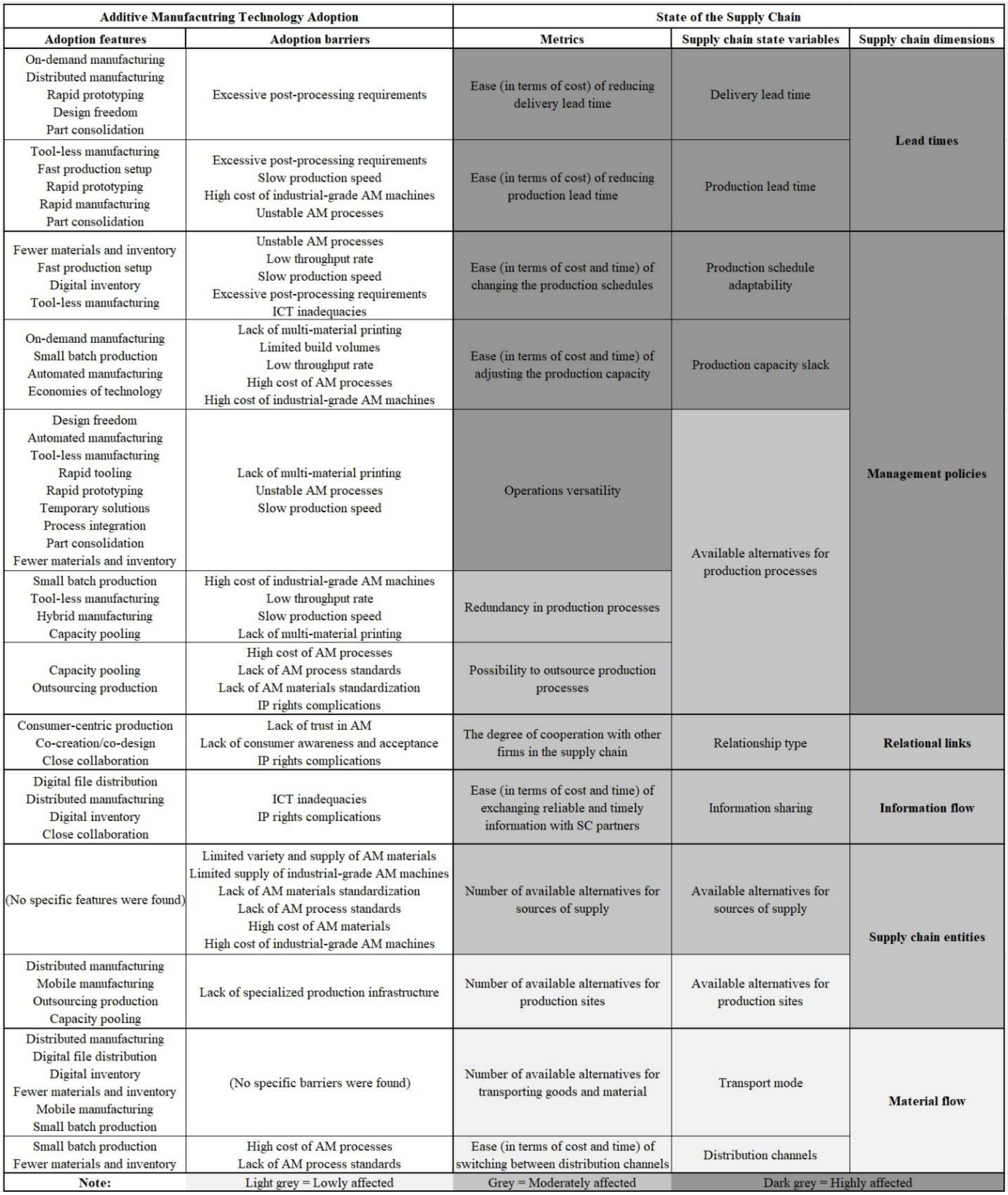
Proposition 14. Overall, AM adoption has a moderate effect on the state of the SC, which in turn is expected to affect the resilience of the SC to a moderate extent. However, over time, the intensity of this effect is likely to increase as the barriers to AM adoption gradually dissipate.

5. Managerial implications

Drawing on the findings of the conducted exploratory survey, an empirical framework is put forward (Figure 2), which indicates to what extent and how AM technology adoption affects different SC state variables. It is worth noting that the AM adoption features and barriers that are noted in the framework have already been discussed in section 4. This empirical framework can be used by practitioners as well as scholars who aim to further analyze the SC effects of AM adoption. In particular, this framework will help those who aim to investigate the SC resilience outcomes of AM adoption, since the SC state variables used to model the framework were primarily defined for assessing SC resilience (Carvalho et al., 2012; 2022). Using empirical evidence from different industries, this framework partly validates the conceptual AM-SCR framework put forward by Naghshineh and Carvalho (2022a). Since this framework is based on findings from different industries as well as the most frequent AM processes used by them (see Tables 2 and 3), it represents a holistic viewpoint of industry on the subject matter.

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 state of the SC and consequently SC resilience due to AM adoption, these AM features are likely to be more influential than others. Likewise, slow production speed, and the 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 are the most frequently noted AM adoption barriers in the framework. Moreover, as noted throughout section 4, there seem to be existing interrelations between these AM features/barriers that may considerably increase/decrease the extent to which AM adoption affects the state of the SC. For instance, design freedom in AM enables the consolidation of many parts into one part, leading to fewer materials and inventory across the SC. This, in turn, will decrease the complexity of the SC by reducing the number of SC layers (Ivanov et al., 2019; Rodríguez-

Espíndola et al., 2020), hence simplifying the state and structural dynamics of the SC (i.e., positive trigger of SC structural dynamics (Dolgui & Ivanov, 2020)), which as a result positively affects SC resilience. As for AM barriers, an illustrative example in this regard is the lack of multi-material printing, which necessitates material changeovers to produce parts that require different materials, therefore reducing the throughput rate (i.e., the rate at which parts can be printed and move through the production process from start to finish). This, in turn, negatively affects the ease (in terms of time and cost) with which production capacity can be adjusted (i.e., production capacity slack), thus making it more difficult to respond to customer demands in a timely fashion (i.e., increased SC vulnerability to unpredictability in customer demand), which as a result negatively affects the resilience of the SC (Naghshineh & Carvalho, 2022a; 2022b). Therefore, gaining detailed knowledge of the AM features and barriers in the proposed framework can assist the managers and policymakers in the decision-making process regarding AM technology adoption and its ensuing effects on the state of the SC, which in turn affect SC resilience.



Additive Manufacutring Technology Adoption		**State of the Supply Chain**		
Adoption features	**Adoption barriers**	**Metrics**	**Supply chain state variables**	**Supply chain dimensions**
On-demand manufacturing Distributed manufacturing Rapid prototyping Design freedom Part consolidation	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	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	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	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	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	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	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	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	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)	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	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	(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	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:	Light grey = Lowly affected	Grey = Moderately affected	Dark grey = Highly affected	

Figure 2. Empirical framework for the effects of AM adoption on the state of the SC

6. Conclusions

Viewing the subject matter from an SC resilience perspective, in this research we aimed to understand to what extent and how AM technology adoption affects the state of the SC. To this end, we conducted an exploratory survey among experts who worked for companies that were using various AM processes aimed at different applications. Through this survey, we inquired the experts about their perception regarding the extent to which AM adoption affects the state of the SC (based on a five-point Likert scale) using different SC state variables, which had already been used in related research by Carvalho et al. (2022) and Naghshineh and Carvalho (2022a). The overall results indicated that AM adoption has a rather moderate effect on the state of the SC, hence addressing RQ1. Also, we asked the respondents to provide explanations for their Likert scale responses, thereby validating the credibility of the results. In doing so, we managed to extract meaningful insights from the respondents' explanations and compare them with the existing literature to clarify how AM adoption affects each SC state variable. More specifically, we identified and explained the AM features and barriers that together define the effects of AM adoption on the state of the SC, thereby addressing RQ2. Subsequently, we discussed our findings and put forward propositions that reflect the theoretical implications of this research. Given the scarcity of empirical research at the intersection of AM technology adoption and SC resilience (Ali & Gölgeci, 2019), we believe that by putting forward propositions that are informed by empirical evidence, we managed to provide a comprehensive research agenda for future research to further investigate the potential SC resilience outcomes of AM technology adoption. Additionally, we put forward an empirical framework by drawing on the research findings (Figure 2), which partly validates the conceptual AM-SCR framework by Naghshineh and Carvalho (2022a). This empirical framework can be used as a point of reference for both practitioners and scholars in the field who intend to further investigate the SC effects of AM adoption and its implications for SC resilience. In summary, in this study, we managed to bridge an important empirical research gap in the body of literature regarding the effects of AM adoption on the state of the SC, which in turn contributes to a better understanding of the implications of AM technology adoption for SC resilience. Although primarily, Naghshineh and Carvalho (2020, 2022a) drew attention to this knowledge gap, to the best of our knowledge, no research had to date provided comprehensive empirical results aimed at overcoming it.

Regarding limitations, in this study, we aimed to inquire experts with first-hand experience in the field of AM technology who were working for companies from around the world that were mainly involved in the aerospace, automotive, medical, and energy industries. Our main motive for doing this was to address the RQs using input data that were primarily informed by experts who work in the aforementioned industries as they are at the forefront of AM technology adoption (Wohlers et al., 2021).

Hence, to obtain a research sample comprised of such experts, who are not easy to find, especially through probability sampling techniques, we resorted to expert sampling via the LinkedIn professional network platform, and by doing so, the following limitations may have been imposed. First, expert sampling is a non-probability sampling technique that is prone to researcher bias in the expert selection phase, thus making it "difficult to defend the representativeness of the sample" (Sharma, 2017); and second, the sample may not be representative of the entire population as there may be experts who are not registered on the LinkedIn platform. Therefore, to ensure that the obtained sample was representative of the aforementioned industries, we benchmarked the descriptive analyses of the sample (presented in Tables 2 and 3) against the report by Wohlers et al. (2021), which as noted earlier showed a high level of similarity. Also, to avoid generalizability issues due to sample size, i.e., 60, which may not be considered large enough for statistical generalizability, we chose descriptive statistics over inferential statistics to analyze the quantitative data. It should be noted that in descriptive statistics, the sample size is not of great importance, since generalizations are not to be extended to the entire population (Israel, 1992). Likewise, statistical generalizability was not our goal with respect to qualitative data analysis (Stuart et al., 2002). Nevertheless, the qualitative techniques that we used in this research (e.g., using a predetermined questionnaire for data collection, ensuring a specific procedure for coding and analyzing the data, developing a database, and comparing respondents' answers to find similarities and differences) improve the external validity of the findings (Riege, 2003). It is also worth noting that the "diverse range of participants and companies" in the sample should have helped with yielding "more robust findings and a more in-depth understanding of the subject" (Belhadi et al., 2022). Moreover, as the companies in the sample mainly belonged to developed countries, we answered the call for research by Belhadi et al. (2022) regarding the "exploration of AM technology adoption in developed nations", especially when considering the subject matter from an SC resilience perspective.

In view of the aforementioned limitations, we put forward propositions that are open to further investigation. Hence, to validate the generalizability of these propositions, we recommend future research to conduct large-scale surveys and analyze the gathered data by means of different inferential statistics methods. Alternatively, case studies may be carried out that focus on certain industry sectors with specific AM processes and applications to compare the results and refine the propositions contextually. While we drew on the SC state variables used by Naghshineh and Carvalho (2022a) to examine the effects of AM adoption on the state of the SC, future research can extend upon our findings by drawing on other SC state variables. Also, future research can examine the importance of the SC state variables within certain SCs and assign relative weights to them accordingly, which may yield different estimations of the AM adoption effects on the state of the SC. Last but not least, longitudinal research can be performed to confirm the veracity of the findings over time, especially as AM technology advances and the barriers to its adoption gradually disappear.

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4

Towards a Practice-based Framework for Supply Chain Resilience in the Context of Additive Manufacturing Technology Adoption

This chapter consists of the following paper:

Naghshineh, B. & Carvalho, H.
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Towards a Practice-based Framework for Supply Chain Resilience in the Context of Additive Manufacturing Technology Adoption

Abstract

Since the importance of adopting additive manufacturing technology for enhancing supply chain resilience has become evident to industry and the research community now more than ever, empirical frameworks that can provide directions for practitioners and scholars in this regard are necessary. Therefore, in this research, we employ an exploratory approach towards developing an empirical framework informed by experts with practice-based knowledge in industries that are at the forefront of additive manufacturing technology adoption. While viewing the subject matter from the dynamic capabilities perspective, we made it our objective to devise a framework that can guide supply chain management through choosing the effective additive manufacturing-enabled resilience practices geared towards developing supply chain resilience. Our findings suggest that additive manufacturing adoption affects each resilience practice to a different extent, consequently affecting different supply chain capabilities aimed at mitigating supply chain vulnerabilities, and therefore influencing supply chain resilience.

Keywords: Additive manufacturing; 3D printing; Resilience practices; Supply chain capabilities; Supply chain vulnerabilities; Practice-based framework

1. Introduction

With the outbreak of the COVID-19 pandemic, different industries as well as the research community have focused on evaluating the opportunities that arise from the adoption of digital technologies to enhance supply chain resilience (SCR) (Ivanov et al., 2021; Belhadi et al., 2021). While the importance of adopting such digital technologies as a means to enhance SCR is elaborated in recent empirical research by scholars such as Zouari et al. (2020) and Balakrishnan and Ramanathan (2021) among others, the existing literature falls short of presenting adequate empirical results that specifically focuses on the opportunities that arise from adopting additive manufacturing (AM) technology to enhance SCR (Ali and Gölgeci, 2019; Iftikhar et al., 2022). This knowledge shortfall is highlighted by Naghshineh and Carvalho (2022a), who performed a systematic search and review of the literature to propose the potential implications of AM technology adoption for SCR. They posit that adopting AM technology affects the state of the SC in ways that influence important SC capabilities and vulnerabilities that underlie SCR. There are dispersed pieces of evidence in extant literature that support their proposition. For example, Durão et al. (2017) state that AM enables the distributed manufacturing of products in locations closer to consumers (e.g., localized manufacturing/on-site manufacturing), thus allowing the firm to reduce its delivery lead times. From an SCR perspective, reducing the delivery lead times, i.e., resilience practice, improves the responsiveness of the SC, i.e., SC capability (Carvalho et al., 2022), which in turn helps the firm to deal with SC vulnerabilities such as unpredictability in customer demand, therefore enhancing SCR (Naghshineh & Carvalho, 2022a).

Given the opportunity to deploy such resilience practices in an SC context where AM technology is used, it is sound to reason (from a resource-based view) that supply chain management (SCM) would be willing to invest the firm's limited resources in the most effective AM-enabled resilience practices that help the firm to build the right SC capabilities against SC vulnerabilities, and therefore enhance SCR (Mellor et al., 2014; Pettit et al., 2019). This reasoning is in accord with Balakrishnan and Ramanathan (2021) who posit that the use of digital technologies such as AM "influences the resilience practices in a firm's supply chain operations", as well as Zouari et al. (2020) who posit that adopting digital technologies such as AM improves the SC capabilities necessary to enhance SCR. Thus, in line with the dynamic capabilities view (which extends upon the resource-based view of the firm), understanding to what extent AM technology affects the resilience practices in the firm's SC operations is valuable to SCM so as to build the SC capabilities that the firm needs to deal with SC vulnerabilities (Pettit et al., 2019; Naghshineh & Carvalho, 2022a), and consequently enhance SCR in the face of constant SC changes that may lead to SC disruption vulnerabilities (Ponomarov and Holcomb, 2009; Chowdhury and Quaddus, 2017). However, to the best of our knowledge, to date, no empirical study has focused on investigating the effects of AM on SC capabilities and vulnerabilities that underlie SCR, while considering the role of resilience practices. Hence, we aim to overcome this knowledge gap and put forward an empirical framework by addressing the following research questions (RQs):

RQ1. To what extent does AM technology adoption affect the resilience practices?

RQ2. How does AM technology adoption affect the SC capabilities and vulnerabilities that underlie SCR via the resilience practices?

The rest of this paper is organized in the following manner. In section two, the theoretical background regarding the main research variables is presented, leading to the conception of the research model. Also, the employed theoretical perspective is discussed in more detail. In section three, the exploratory research approach that was employed is elaborated. Subsequently, in section four, the results are discussed and compared with the existing AM and SCM literature to derive the theoretical implications of the study, which are summarized in the form of propositions at the end of respective subsections. In section five, an empirical framework is put forward that outlines the managerial implications of the study. Lastly, in section six, conclusions are drawn and directions for future research are suggested.

2. Theoretical background

The adoption of digital technologies brings about fundamental changes in the SC (Dolgui & Ivanov 2020), "SCR in particular" (Ivanov et al. 2021). Among such technologies, AM (empowered by computer-aided design (CAD) software and 3D models) produces objects layer upon layer by depositing materials on the build platform (ISO/ASTM 52900, 2021), and is believed to be capable of digitalizing the SCs (Verboeket & Krikke, 2019; Seyedghorban et al. 2020). Recently, AM has received considerable attention from the industry as well as the research community, mainly due to its capability in enabling SCM practices aimed at solving SC problems. For instance, with the outbreak of the COVID-19 pandemic, AM has been used globally in response to the ongoing shortages in the medical SC, relieving the strained healthcare systems around the world (Kunovjanek & Wankmüller, 2020). One of the main features of AM that has contributed to its success in this regard is the distributed manufacturing of medical parts close to their point of use, which leads to significant reductions in delivery lead times and costs (Durão et al., 2017), hence improving the resilience of the medical SC (Verboeket et al., 2021). Generally, reducing the delivery lead times is regarded as a resilience practice that improves the SC's responsiveness (Carvalho et al., 2022). In other words, according to Verboeket et al. (2021), in the case of the medical SC, the use of AM technology has proved to reduce the delivery lead times of medical items via distributed manufacturing (aka localized manufacturing/on-site manufacturing), thus improving the SC's responsiveness (aka adaptability), which represents the capability of the SC in promptly adapting its operations to respond to arising SC vulnerabilities (Pettit et al., 2013; Naghshineh & Carvalho, 2022a). Evidently, this is an instance where the use of AM technology enables the firm to exercise a resilience practice (e.g., reduce delivery lead time), which in turn enhances a specific SC capability (i.e., responsiveness/adaptability), therefore reducing the vulnerability of the SC to disruptions (Carvalho et al., 2022; Naghshineh & Carvalho, 2022a). In summary, this translates into improved SCR, which is regarded as a higher-order construct comprised of a set of SC capabilities that help the SC to deal with disruption vulnerabilities (Ponomarov & Holcomb, 2009; Pettit et al., 2019). According to Pettit et al. (2010), "Supply chain resilience increases as capabilities increase and vulnerabilities decrease.". Also, they state that "linkages exist between each vulnerability and a specific set of capabilities", which can be controlled to improve SCR. Considering that digital technologies such as AM contribute “to improving SCM practices” (Zouari et al., 2020), or more specifically “encourage the firm’s supply chain resilience practices” (Balakrishnan & Ramanathan, 2021), and that “resilience practices are a means of achieving SC capabilities” (Carvalho et al., 2022), in this study we aim to understand to what extent AM technology affects the resilience practices (RQ1), and how this in turn affects the SC capabilities and vulnerabilities that underlie SCR (RQ2). In view of these considerations, we put forward the conceptual model for this study as depicted in Figure 1.

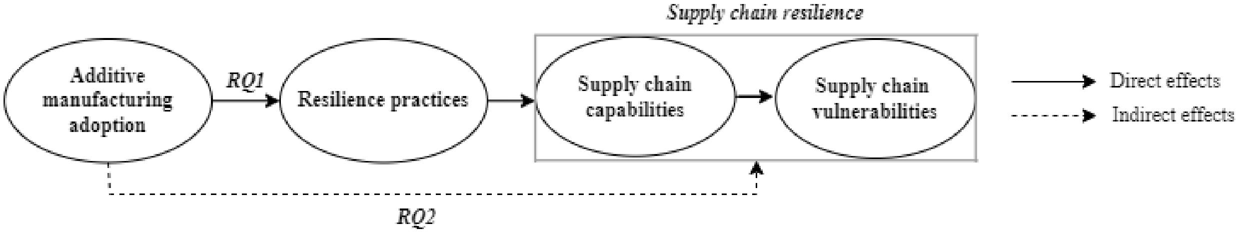


Figure 1. Conceptual research model adapted from Naghshineh and Carvalho (2022a)

While there are some empirical studies similar to Verboeket et al. (2021) in extant literature that indicate how the use of AM technology enables certain resilience practices, which in turn improve certain SC capabilities, thus enhancing SCR, to the best of our knowledge, no single empirical research has by far attempted to investigate the subject matter in a comprehensive manner. In other words, we could not find any empirical research that considers the effects of AM technology adoption on different resilience practices, explaining how various SC capabilities and vulnerabilities that underlie SCR would get affected in the process. After reviewing the literature at the intersection of AM and SCM, however, we came across the research by Naghshineh and Carvalho (2022a) who performed a systematic search and critical review of the existing evidence in the literature to propose the implications of AM technology adoption for SCR. More specifically, they propose how different features and barriers of AM technology adoption affect the state of the SC, thus influencing the SC capabilities and vulnerabilities that underlie SCR. To do this, they make use of different metrics to capture the effects of AM adoption features and barriers on different SC state variables, which they associate with different SC capabilities and vulnerabilities, and subsequently put forward the Additive Manufacturing-Supply Chain Resilience (AM-SCR) framework. The metrics that Naghshineh and Carvalho (2022a) have used to form the AM-SCR framework also represent some of the resilience practices discussed by Carvalho et al. (2022), which are geared towards improving different SC capabilities. Thus, in order to control the scope of this study, we selected nine resilience practices from Carvalho et al. (2022) (see Table 1), the metrics of which are already used in the AM-SCR framework. Moreover, these resilience practices and their metrics proved to be relevant to the purpose of our study as they are already mentioned in the existing empirical AM and SCM literature. Hence, as the selected resilience practices are directly associated with improving SC capabilities (Carvalho et al., 2022), we could use their metrics as observable items to empirically examine the extent to which AM adoption affects the resilience practices aimed at improving different SC capabilities (RQ1). Additionally, as the aforementioned metrics are already associated with different SC capabilities and vulnerabilities in the AM-SCR framework, we used this framework to explicate how AM technology adoption affects different SC capabilities and vulnerabilities that underlie SCR via the resilience practices (RQ2). It is worth noting that to the best of our knowledge, the AM-SCR framework is by far the only framework that uses the most comprehensive classification of SC capabilities and vulnerabilities proposed by Pettit et al. (2010, 2013) to evaluate the implications of AM technology adoption for SCR. This claim is further supported by Zouari et al. (2020) who state that "Pettit et al.'s (2010, 2013) classification of capabilities and sub-capabilities offers the most exhaustive assessment of SCR in empirical studies compared to others". The definitions for the identified SC capabilities and vulnerabilities in this study along with their subfactors that define each SC capability/vulnerability in more detail are presented in Appendix A.

Table 1. Resilience practices and metrics selected from Carvalho et al. (2022)

Resilience practices	**Metrics**
Change the production schedule	Ease (cost and time) of changing the production schedules
Reduce delivery lead time	Ease (cost) of reducing delivery lead time
Use maximum capacity	Ease (cost and time) of adjusting the production capacity
Reduce response time	Ease (cost) of reducing production lead time
SC common response	The degree of cooperation with other firms in the supply chain
Align SC information systems	Ease (cost and time) of exchanging reliable and timely information with SC partners
Use alternative suppliers	Number of available alternatives for sources of supply
Use alternative production sites	Number of available alternatives for production sites
Use alternative transport modes	Number of available alternatives for transporting goods and material

***Note:** "Operations versatility" refers to the capability of a production system to perform various operations.

From a theoretical perspective, we draw on the dynamic capabilities view to investigate the subject matter. The use of established theoretical perspectives not only helps to identify the underlying relationships between the research variables but also contributes to the generalizability of the findings (Walker et al., 2015). According to the existing literature, the most established theoretical perspectives/lenses to view SCR are the resource-based view as well as the dynamic capabilities view (Tukamuhabwa et al., 2015; Kochan & Nowicki, 2018). While the resource-based view regards technology adoption as a resource to improve the firm's performance (Wernerfelt, 1984), it fails to consider the dynamic nature of the SC as a determining factor (Cavusgil et al., 2007), which is particularly important in the SCR context (Ponomarov & Holcomb, 2009). This shortcoming, however, is addressed by the dynamic capabilities view, whereby investing in resources (e.g., technology adoption) as well as deploying the necessary management practices are considered in conjunction with the dynamic nature of the SC in order to achieve distinctive capabilities that aid the firm in gaining a sustainable competitive advantage (Teece et al., 1997; Ponomarov & Holcomb, 2009). In other words, from the dynamic capabilities perspective, investing in technology adoption (e.g., AM adoption) as a resource is an SCM strategy to gain a competitive advantage over other players in the market, especially in dynamic SC environments that are constantly under resource pressures due to impending disruption vulnerabilities (Teece, 2014; Kalaitzi et al., 2019).

At the intersection of AM technology adoption and SCR, to the best of our knowledge, the first studies to draw on the dynamic capabilities are Naghshineh and Carvalho (2020; 2022a; 2022b), followed by Belhadi et al. (2022). Similarly, in this study, we employ this theoretical perspective while investigating the subject matter. However, unlike studies using the resource-based view and dynamic capabilities view that "fall short of identifying processes, resources and paths that increase competencies during environmental uncertainties along the supply chain." (Chowdhury & Quaddus, 2017), in this study we put forward an additive manufacturing-supply chain resilience practices (AM-SCR*P*) framework that allows SCM to identify suitable paths to building SC capabilities and mitigating SC vulnerabilities via deploying AM-enabled resilience practices aimed at enhancing SCR.

3. Methodology

3.1 Research design and instrumentation

In this study, we took advantage of an exploratory survey research whereby we targeted experts with experience in the field of AM and SCM to collect both quantitative and qualitative data to address RQ1 and RQ2 respectively. More specifically, we collected quantitative data using Likert scale questions aimed at capturing the respondents' perceptions regarding the extent to which AM technology adoption affects the resilience practices (RQ1), while we analyzed the qualitative data that were provided in the form of explanations by the respondents to justify their Likert scale responses, thereby explicating how AM technology adoption affects different SC capabilities and vulnerabilities that underlie SCR via the resilience practices (RQ2). In an attempt to further triangulate our findings, we also compared the results of the qualitative data analysis with evidence from the AM and SCM literature (i.e., secondary data). It is worth noting that our research design is similar to successful research designs implemented by Durach et al. (2017) and Ukobitz and Faullant (2021), who investigated the impacts of AM technology adoption on different SCs. While Durach et al. (2017) conducted a multi-stage survey study where they used a combination of Likert scale questions and free text fields to collect expert responses, Ukobitz and Faullant (2021) conducted a Likert scale-based survey together with semi-structured interviews, followed by secondary research.

Accordingly, the survey questionnaire was designed in a way that enabled us to collect the required quantitative and qualitative data in one phase. This way, apart from asking the respondents to answer the specified Likert scale questions, we also managed to ask them to concurrently provide explanations that justified their answers to the Likert scale questions, hence increasing the reliability of the survey results. To form the Likert scale questions, we used the same metrics representing the resilience practices that are used by Carvalho et al. (2022) (see Appendix B), hence avoiding the need to define new scales. It should be noted that these metrics have also been used to form the AM-SCR framework by Naghshineh and Carvalho (2022a), which is in line with the objective of our research and helped us in answering the RQs. The questions were based on a five-point scale (where 1 signified very low effect and 5 signified very high effect) and were aimed at assessing the respondents' perceptions regarding the extent to which the use of AM technology affects different resilience practices in their SC operations (aimed at answering RQ1). Open text fields were provided right after each Likert scale question, allowing the respondents to explain the reasons for their Likert scale responses (aimed at answering RQ2). These explanations in conjunction with the AM-SCR framework enabled us to explicate how various features and barriers of AM technology adoption affect different SC capabilities and vulnerabilities that underlie SCR via the resilience practices (explained in detail in subsection 3.3). Apart from the Likert scale questions, there were also general questions regarding the country, industry sector, SC tier, etc., as well as the AM processes and applications that the companies had developed. The questionnaire was then reviewed by an expert and academic in the field and pilot-tested in multiple companies that were using AM technology. After making improvements based on the feedback, we administered the questionnaire online using Google forms, which was accompanied by a cover letter that described the purpose of the survey and ensured anonymity of the respondents and their companies.

3.2 Sampling and data collection

In order to investigate the subject matter from the industry's viewpoint, we conducted our survey among experts that were involved in industries with more experience in using AM technology. According to the report by Wohlers et al. (2021) regarding the "3D Printing and Additive Manufacturing Global State of the Industry", AM is widely adopted by the automotive, aerospace, energy, and medical industries, among others. Thus, to be able to find experts that worked for companies involved in such industries, we resorted to expert sampling, which is a non-probability sampling technique (Sharma, 2017), using the LinkedIn professional network platform. It should be noted that the LinkedIn platform is already used for expert sampling by other scholars, e.g., Kurpjuweit et al. (2021). Hence, through expert sampling via the LinkedIn platform, we managed to find professionals with expertise in the field of AM and SCM from around the globe that were involved in the aforementioned industries, who otherwise would have been very difficult to find via the probability sampling techniques. We made use of different search keywords (e.g., “Production manager”, “Operations manager”, “Managing director”, “Supply chain manager”, etc., together with “Additive manufacturing” and “3D printing”) to look for registered professionals on the LinkedIn platform. The search returned 417 profiles, out of which we selected 400 expert profiles after reviewing the accuracy of the search results. Subsequently, we sent out 400 invitations accompanied by a brief description of the survey and a weblink to the online questionnaire over the course of December 2021. Thereafter, we started receiving responses from mid-December 2021 until the end of January 2022. After sending reminders to late responders during the mentioned period, we received 69 completed questionnaires, corresponding to a response rate of 17.3%. However, we had to discard 9 questionnaires as they contained multiple unanswered questions/unfilled text fields, leaving us with 60 usable questionnaires.

To ensure that the derived sample possessed the characteristics of the intended target population, we compared its descriptive analyses with the report by Wohlers et al. (2021), indicating a high level of similarity. For instance, we found the reported percentages in Table 2 regarding the industry sector of the companies to conform with the distribution of AM technology adoption among different industries reported by Wohlers et al. (2021). We also benchmarked the derived percentages in Table 3 regarding the adopted AM processes and their applications in the sample against the report by Wohlers et al. (2021), which resulted in a high level of similarity as well. Hence, this comparison helped us to validate the representativeness of the derived sample, which is prone to researcher bias when using the expert sampling technique (Sharma, 2017). Moreover, as it can be seen in Table 2, the 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). Along the same lines, as the sample is comprised of companies operating in rather developed economies, the findings are likely to be more robust since Industry 4.0 technologies such as AM are more mature in developed economies (Dalenogare et al., 2018; Wagire et al., 2021). This is also in line with Belhadi et al. (2022) who suggest that the “exploration of AM technology adoption in developed nations” is an important avenue for research. Lastly, the experts in the sample had an average working experience of 9 years (mainly in managerial positions), which implied an appropriate level of experience for taking part in the survey.

Table 2. Descriptive analysis of the companies in 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%	*Total*	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%	*Total*	60	100%
Sweden	1	2%	**Respondents' positions**		
Switzerland	1	2%	AM engineer	12	20%
United Kingdom	10	16%	AM manager	14	24%
United States	15	25%	Managing director	10	17%
Total	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%	*Total*	60	100%
> 250 employees	28	47%			
Total	60	100%			

Table 3. Descriptive analysis of the AM processes and their applications adopted by the companies in the sample

AM processes	**Frequency**	**Percent**	**AM applications**	**Frequency**	**Percent**
Powder bed fusion	50	32%	Direct part manufacturing	56	39%
Sheet lamination	4	3%	Rapid prototyping	52	36%
Directed energy deposition	12	8%	Rapid tooling	24	17%
Vat photopolymerization	24	16%	Maintenance, repair, and overhaul	12	8%
Material extrusion	34	23%	*Total*	144	100%
Material jetting	10	7%			
Binder jetting	16	11%			
Total	150	100%			

3.3 Data analysis methods

To estimate to what extent AM adoption affects the resilience practices (RQ1), we drew on the average scores of the respondents' answers to the Likert scale questions. Similar to Durach et al. (2017) and Ukobitz and Faullant (2021), we found this descriptive statistical analysis method to be capable of yielding an overall estimate of the respondents' perceptions regarding the subject matter. Also, to estimate to what degree the respondents agreed on the subject matter, we considered the level of dispersion in their answers by calculating the standard deviation (SD). It is worth noting that before proceeding with the analysis of the Likert scale responses, we used Cronbach's α to assess the reliability of the scales (Cronbach, 1951). The score for Cronbach's α was 0.89, surpassing the widely accepted value of 0.70, hence confirming the reliability of the scales (O'Leary-Kelly & Vokurka 1998).

To explicate how AM adoption affects the SC capabilities and vulnerabilities that underlie SCR via resilience practices (RQ2), we needed specific research dimensions (aka coding criteria) that would help us analyze the respondents' explanations (i.e., qualitative data analysis) based on the same underlying criteria (Miles & Huberman,1994). Therefore, we took advantage of the work by Naghshineh and Carvalho (2022a) as it provides a comprehensive list of AM features and barriers that affect the metrics representing the resilience practices in our study. Also, we drew on the AM-SCR framework in their work to identify the SC capabilities and vulnerabilities that would be affected, since each metric in the AM-SCR framework is already associated with relevant SC capabilities, which in turn are linked to SC vulnerabilities. For example, after analyzing the respondent's explanation "*Producing on site and on demand means no transportation costs and shorter delivery lead times.*", which meant to elaborate on the effect of AM on the metric "Ease (cost) of reducing delivery lead time", we inferred that the AM feature "Distributed manufacturing" would promote the on-site and on-demand production of parts, thus facilitating the resilience practice "Reduce delivery lead time". According to the AM-SCR framework, this effect in turn enhances the "Adaptability" of the SC (i.e., SC capability), which mitigates the vulnerability of the SC to "Turbulence" (i.e., SC vulnerability) caused by the "Unpredictability in customer demand". This example (depicted in Figure 2) clarifies how the mentioned research dimensions enabled us to analyze the respondents' explanations in order to explicate how AM adoption affects the SC capabilities and vulnerabilities that underlie SCR via the resilience practices, therefore addressing RQ2. Additionally, we sought supporting evidence from the literature (i.e., secondary data) to triangulate our findings. For instance, the excerpt shown in Figure 3 lends support to the validity of the mentioned example:

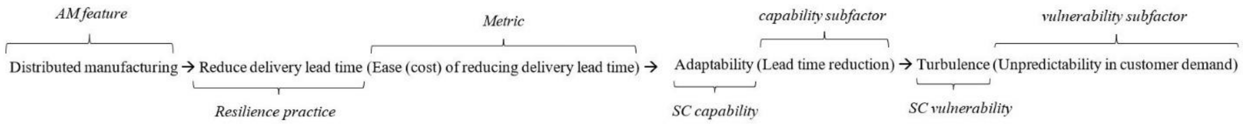
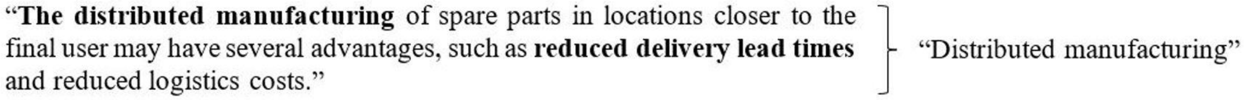


Figure 2. An example of how AM can affect SCR via resilience practices



"**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."

"Distributed manufacturing"

Figure 3. Text segment from Durão et al. (2017)

Overall, we analyzed the gathered data in the following manner. After deriving the average and SD scores using the quantitative Likert scale responses, we followed the process of reducing, displaying, and drawing conclusions using the respondents' explanations (Miles & Huberman, 1994). To reduce the data, we coded the respondents' explanations based on the mentioned comprehensive list of AM features and barriers by Naghshineh and Carvalho (2022a). In a few cases where the list did not contain relevant AM features or barriers that would properly summarize and describe the respondents' explanations, we generated new codes. For instance, in the case of the explanation "*With AM lead times for products can be reduced due to fewer parts and elimination of many assembly processes.*", which was regarding the AM's effect on the "Ease (cost) of reducing delivery lead time", we generated the code "Part consolidation" as an AM feature, which was not available on the aforementioned list. Also, it is worth noting that in some cases, more than one code was used to describe and summarize an explanation. For instance, in the case of the latter explanation, apart from "Part consolidation", we also used the code "Design freedom" from the list of AM features and barriers. We considered this code to be relevant since the high degree of "Design freedom" in AM allows for the consolidation of many parts into one part (Ford & Despeisse, 2016; Knofius et al., 2019).

An interesting theme that emerged while analyzing the respondents' explanations was related to the existing AM barriers that inhibit the effects of AM adoption on resilience practices. For instance, while analyzing the respondent's explanation "*Production planning is relatively easy with 3d printing compared to injection molding or CNC, but unsteady processes may cause problems*.", which was regarding the effect of AM on the "Ease (cost and time) of changing the production schedules", we identified and coded "Unstable AM processes" as an AM barrier that inhibits the resilience practice "Change the production schedule". Next, to explicate the effects of the identified AM features and barriers on the resilience practices and subsequently the SC capabilities and vulnerabilities, we grouped and arranged the codes according to the AM-SCR framework as explained earlier (see Figure 2). Performing this step allowed us to display the qualitative data in a structured manner and draw conclusions accordingly (Appendix C presents some illustrative examples). It should be noted that we went over this process multiple times to ensure relevance and transparency in our findings (Miles & Huberman; 1994). Also, as mentioned earlier, we used evidence from the existing literature to support and triangulate our findings (Jack & Raturi, 2006).

4. Results and discussion

The quantitative data analysis results, which indicate the extent to which AM adoption affects the resilience practices, are presented in Table 4. In the subsections that follow, the effects of AM adoption on each resilience practice as well as the ensuing implications for SC capabilities and vulnerabilities that underlie SCR are discussed respectively, while considering the existing literature. In addition, propositions are put forward at the end of each subsection that summarize the theoretical implications of the study.

Table 4. Quantitative data analysis results

Resilience practices	Mean	SD	Effect	Rank
Change the production schedule	4.04	1.01	High	1st
Reduce delivery lead time	3.78	1.18	High	2nd
Use maximum capacity	3.56	1.21	High	3rd
Reduce response time	3.52	1.28	High	4th
Supply chain common response	3.38	1.22	Moderate	5th
Align supply chain information systems	3.25	1.47	Moderate	6th
Use alternative suppliers	2.69	1.28	Moderate	7th
Use alternative production sites	2.48	1.34	Low	8th
Use alternative transport modes	2.18	1.63	Low	9th

Note: The score for Cronbach's α is **0.89** indicating the reliability of the scales.

4.1 Change the production schedule

The respondents' answers revealed that AM adoption has the highest effect on the ease (in terms of cost and time) to change the production schedules compared to the other resilience practices. Also, the dispersion in the quantitative answers was at its lowest, indicating consensus among the respondents regarding the enhancing effect of AM on this resilience practice. This effect was attributed to different AM features, among which fast production setup and tool-less manufacturing were the most pronounced ones. Some respondents explained that production setup is rather fast and easy, providing the flexibility to quickly change the production plans to meet erratic customer demands without incurring noticeable costs. "*Highly agile, fast to program and start a job*" was among such explanations. Also, it was noted that the tool-less nature of AM further enhances this flexibility and allows the manufacturers to quickly switch the printers to different products in order to manage sudden changes in customer demands. "*We commonly switch the machines to different products to manage changes in demand.*" is an illustrative explanation in this regard. Overall, we found these explanations to be in line with scholars such as Ding et al. (2021) who state that "AM enables the production of a variety of products and batch sizes without incurring sunk costs of tools or moulds and without changeover costs." or Sgarbossa et al. (2021) who state that "AM is a tool-less manufacturing approach, with no or very limited setup times." Another mentioned AM feature was the need for fewer materials and inventory compared to conventional manufacturing methods (CM), which makes it easier to change the production schedule, thus enhancing the flexibility to fulfill erratic customer orders. According to one respondent, the bill of materials (BOM) is single level in AM, which means that there are fewer materials and inventory. This is because only raw materials and 3D models (in the form of digital files, i.e., digital inventory) are required as input to print a complex part (Liu et al., 2014; Zanoni et al., 2019), whereas in CM, the BOM is normally comprised of different components and subassemblies (i.e., multi-level BOM). An interesting observation is that these AM features seem to be interrelated. For instance, the need for fewer materials and inventory leads to reductions in setup and changeover times (i.e., fast production setup) as well as the number of subassemblies (Liu et al., 2014; Durach et al., 2017), all of which facilitate the ease (in terms of cost and time) to change the production schedules. Given these AM features, a demand-pull SCM strategy can be deployed (Christopher & Ryals, 2014; Delic and Eyers, 2020), where production is postponed until demand is materialized (i.e., Flexibility (Production postponement)). This way, it will be easier to deal with erratic customer demands (i.e., Turbulence (Unpredictability in customer demand)) as well as possible customer disruptions (i.e., Supplier/Customer Disruptions (Customer disruptions)) by being able to change the production schedules swiftly.

However, certain barriers were also pointed out that inhibit the enhancing effect of AM adoption in this regard. To begin with, slow production speed and low throughput rate were noted to hinder the timely changing of production plans by eroding the processing times, thus making it difficult to respond to sudden changes in customer demands. Excessive post-processing was also mentioned as another barrier that takes away from AM's agility to quickly fulfill customer orders, especially when the printed parts require complex machining among other post-processing steps. For instance, a respondent noted: "*overall is less agile if the part requires complex machining and other post processes*." Moreover, another remarked barrier was the present instability in AM processes that can hinder the timely completion of the production plans, which is in line with the findings by Naghshineh and Carvalho (2022b). One of the respondents explained that production planning is rather easy with AM, especially when compared to CM; however, unsteady AM processes may cause problems. Lastly, we spotted information and communication technology (ICT) inadequacies as another barrier. For instance, one respondent noted that "*there is no good MES* [Manufacturing Execution Systems] *solution quite yet in the market.*" MES provides "a common user interface and data management system" (Saenz de Ugarte & Artiba, 2009), helping to establish good data management, thus facilitating AM operations (Chan et al., 2018).

Proposition 1. AM adoption has a high effect on changing the production schedules, affecting the flexibility in order fulfillment, which in turn affects the vulnerability of the SC to unpredictability in customer demands as well as customer disruptions.

4.2 Reduce delivery lead time

According to the respondents' answers, reducing delivery lead time is the second resilience practice that is rather highly affected by AM adoption. The dispersion in the quantitative answers was relatively low, implying general agreement among the respondents. Primarily, the emphasis regarding the enhancing effect of AM on reducing delivery lead time was attributed to distributed manufacturing as well as on-demand manufacturing of parts. As two of the respondents explained respectively, "*Producing on site and on demand means no transportation costs and shorter delivery lead times.*" and "*AM is much cheaper and faster than traditional methods, especially as it cuts transportation costs and times.*" We found these explanations to be in line with Ghadge et al. (2018) who state that as "parts are manufactured on demand near the consumption locations, the delivery time is zero as no movement of parts is involved between other SC echelons." or Durão et al. (2017) who state that 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." Since the need for the distribution and delivery of parts is reduced via these AM features, SC adaptability (i.e., Adaptability (Lead time reduction)) will be increased against shortages in distribution capacity (i.e., Resource limits (Distribution capacity)) as well as sudden changes in customer demands, which may necessitate faster delivery lead times.

Furthermore, design freedom and part consolidation were two other interrelated AM features that were pointed out by the respondents. One respondent explained that "*Delivery lead time is reduced not just due to reduced manufacturing lead time, but also due to reduced part development lead time powered by the high degree of additive manufacturing design freedom.*", whereas another respondent explained that "*With AM lead times for products can be reduced due to fewer parts and elimination of many assembly processes.*". These explanations are supported by evidence from the existing literature. For instance, Kunovjanek et al. (2020) state that "Due to the manufacturing freedom of AM, the consolidation of separate parts into one more complex part becomes possible which eliminates certain assembly needs.", reiterating the notion that through the high level of AM design freedom, many parts can be consolidated into one part (Ford & Despeisse, 2016; Knofius et al., 2019). Therefore, as there will be fewer parts to distribute, not only SC adaptability will be increased against possible distribution capacity shortages and erratic customer demands, but also there will be fewer cases of inventory theft and damage (i.e., Deliberate Threats (Piracy and theft)). Also, rapid prototyping of some parts with AM was noted to reduce the delivery lead times. For instance, one respondent explained that AM is a "*Good option to reduce the lead time for prototype components (i.e. 3D printed samples can simulate airbags, sub-components or vehicle parts and be used for testing purposes).*", corroborating the example by Luomaranta and Martinsuo (2020) that AM provides the "Possibility to manufacture working prototype components for testing a complex product or assembly". This way, the firm can go through multiple iterations during the product development process (Fawcett & Waller, 2014; Zanoni et al., 2019), thus allowing it to quickly develop and deliver complex products that conform with customer demands, hence increasing the adaptability of the SC in this regard.

Despite all the mentioned advantages that AM adoption presents for reducing delivery lead time, excessive post-processing requirements can act as a barrier. For instance, a respondent noted that "*Lead time is longer if machining is required.*" Under this circumstance, adaptability to changes in customer demands becomes rather difficult (Naghshineh & Carvalho, 2022b), since post-processing steps can be costly and time-consuming (Achillas et al., 2017; Kunovjanek et al., 2020).

Proposition 2. AM adoption has a high effect on reducing delivery lead time, affecting SC adaptability, which in turn affects the vulnerability of the SC to limited distribution capacity, unpredictability in customer demands, and piracy and theft.

4.3 Use maximum capacity

The respondents' answers to the Likert questions indicated that AM adoption has a relatively high effect on the ease (in terms of cost and time) with which a firm can adjust its production capacity. Also, the derived SD score indicates that there was consensus among the respondents regarding the enhancing effect of AM adoption on this resilience practice. This effect was mainly attributed to the possibility of manufacturing the parts/products on demand in small batches. Multiple respondents mentioned that it is easy for their firms to change the production capacity when needed, e.g., "*It is not a problem to adjust production to closely match demand.*" or "*We can scale up production capacity very quickly when needed.*", especially in the case of small-batch production, lending support to the findings of Delic and Eyers (2020) who state that AM provides the flexibility to quickly respond to unpredictable customer orders by manufacturing the requested parts on demand and in low-volumes. Along the same lines, it was noted that as an automated manufacturing method, AM can bring about efficiency, e.g., "*Automated system. The same number of operators can operate more machines.*", supporting the notion of economies of technology whereby it is possible to operate multiple machines by a single operator (Tuck et al., 2007; Naghshineh et al., 2021), thus generating outputs with minimal resource requirements (i.e., Efficiency (Asset utilization)).

Nevertheless, low throughput rate and limited build volumes were pointed out as two interrelated barriers that inhibit the enhancing effect of AM adoption on utilizing maximum production capacity. One respondent explained that "*The change of the production capacity is only easy up to the maximum building chamber volume. If more parts are needed, the job preparation and the post material recycling steps make it difficult*.", drawing attention to AM's low throughput rate as a barrier, which is mainly caused by the limited build volumes of 3D printers (Baumers et al., 2016; Dwivedi et al., 2017). Also, it was noted that the current lack of multi-material printing (Rayna et al., 2015; Chiu and Lin, 2016) makes the job preparation somewhat challenging. "*If machines are dedicated to a particular material but are flexible in processing other materials, time and labor must be spent to clean out the old material, change machine parameters, run tests, etc. before capacity can be modified using the new desired material.*" This AM barrier has also been mentioned by Eyers et al. (2018), where all the cases in their study considered material loading as a labor-intensive task, which is exacerbated by material changeovers since extensive cleaning of the 3D printer would be necessary before the new material can be loaded into the 3D printer. Lastly, it was noted that the high cost of AM processes, especially in Metal AM, makes it difficult to cost-efficiently scale up the production capacity to fulfill customer orders that are placed at short notice, corroborating the findings of Naghshineh and Carvalho (2022b) in this regard. According to a respondent, "*Metal AM technology is still very expensive, and it's difficult to justify increasing capacity for short run projects and demand variability*." Another reason for this issue was mentioned to be the high cost of industrial-grade AM machines (Kietzmann et al., 2015; Schniederjans, 2017). As one respondent explained, "*Industrial machines are expensive. So it is not easy to scale up and not cheap either. Making a decision to install new machines can take time.*"

Proposition 3. AM adoption has a high effect on using maximum capacity, affecting SC efficiency, which in turn affects the vulnerability of the SC to unpredictability in customer demands.

4.4 Reduce response time

The respondents' quantitative answers indicated that AM adoption has a relatively high effect on the ease with which production lead time can be reduced. Also, the derived score for SD indicates consensus among the respondents. Rapid prototyping as well as rapid manufacturing of parts were highlighted as prominent AM features that help reduce production lead time. One respondent noted that "*Rapid design iteration with additive gets to functional components faster*.", which is in line with Fawcett and Waller (2014) stating that "By reducing leadtimes, rapid prototyping allows multiple iterations in the development process, which yields more innovative, higher-quality products." Also, as Candi and Beltagui (2019) point out, "3DP can be useful in the early stages of innovation for prototyping and testing designs". Apparently, this possibility not only enables the firm to quickly develop new products in response to unpredictable customer demands but also helps it to deal with competitive innovations that stem from fierce competition in the market (i.e., External pressures (Competitive innovation)). This is especially true when viewed from the dynamic capabilities perspective where the firm needs to constantly adapt itself to the rapidly changing markets by developing new products to gain a competitive advantage (Leonard-Barton, 1992; Teece et al., 1997). Furthermore, it was noted that AM-enabled tool-less manufacturing leads to fast production turnaround time, which is the time to design, print and post-process a part. "*No tooling means fast production turnaround.*" We find this explanation to be in accord with Berman (2012) stating that "Prototype development costs and time requirements are also significantly reduced since no tools and dyes are required in 3-D printing." Apart from these AM features, attention was also drawn to fast production setup and part consolidation, both of which contribute to reducing response time. "*Faster and cheaper to build and install new AM production line*." as well as "*Simplified and faster production process due to reduction of parts in subassemblies.*" were among the explanations by respondents that imply these AM features respectively. Interestingly enough, fast production setup can also be attributed to tool-less manufacturing. According to Liu et al. (2014), "Because AM only requires 3D data and raw material in order to produce a complex part, it will reduce setup and changeover time, and the number of assemblies." This statement implies that fast production setup in AM is due to tool-less manufacturing. By reducing response time, these AM features boost the adaptability of the SC to develop new customized products that comply with erratic customer demands. Also, the findings suggest that there are potential synergies between different AM features, e.g., tool-less manufacturing empowering fast production setup.

Nevertheless, some barriers do exist that take away from AM's enhancing effect on reducing response time. To begin with, excessive post-processing was pointed out by some respondents, which can take away from the capability of the firm's SC to quickly adapt and respond to unpredictable customer demands (Naghshineh & Carvalho, 2022b). One respondent explained that "*the production time is rather comparable to conventional manufacturing, since AM also includes significant post-processing.*"; which is also in accord with Achillas et al. (2017) stating that the final production cost of AM processes such as fused deposition modeling (FDM) remain rather high due to "very slow processing speeds and the requirement for significant post-processing." This statement also raises the issue of slow production speed, which was implicitly mentioned by a respondent in the following explanation: "*New machines are especially much more performant and quicker.*" Also, unstable processes can inhibit the enhancing effect of AM on reducing response time (Naghshineh & Carvalho, 2022a; 2022b). For instance, as it can be explicated from the following explanation: "*AM may or may not save production time. It depends on the process, the materials, postprocessing steps, etc.*", some AM processes are more susceptible to instability issues, which can negatively affect production lead time. In other words, such instability issues can undermine the reliability and repeatability of the processes (Durach et al., 2017; Ding et al., 2021), which may lead to unforeseen failures that disrupt the firm's production operations (i.e., Turbulence (Unforeseen technology failures)), and as a consequence prolong the production lead time. Lastly, the high cost of industrial-grade AM machines was mentioned. For instance, one respondent noted that "*The lower production time is offset by the higher machine costs.*" In summary, the aforementioned barriers undermine AM's ability in reducing response time to deal with the unpredictability in customer demands.

Proposition 4. AM adoption has a high effect on reducing response time, affecting SC adaptability, which in turn affects the vulnerability of the SC to unpredictability in customer demands as well as competitive innovations. However, unforeseen technology failures may take place more often due to the present instability in AM processes.

4.5 Supply chain common response

Overall, the respondents perceived the effect of AM adoption on the degree of cooperation with other firms throughout the SC as relatively moderate. Close collaboration was mentioned in the respondents' explanations multiple times. There were several explanations similar to "*We cooperate very frequently and at a high level with both customers and suppliers.*", lending support to the proposition by Mellor et al. (2014) that the implementation of AM requires increased collaboration with suppliers as well as customers throughout the SC. Apart from raising "new ideas for production to the customer" (Luomaranta & Martinsuo, 2020) that helps the firm to maintain its market position (i.e., Market position (Customer relationships)) against external pressures stemming from competitive innovations, close collaboration with partners in an AM SC can also help the firm to deal with other SC vulnerabilities such as unpredictability in customer demands as well as supplier disruptions (i.e., Supplier/Customer Disruptions (Supplier disruptions)), especially through postponement of orders (Holmström & Partanen, 2014; Delic & Eyers, 2020), i.e., Collaboration (Postponement of orders). This is also in accord with Naghshineh and Carvalho (2022b) who identify close collaboration with SC partners as a practice aimed at mitigating different SC vulnerabilities, e.g., supplier capacity limitations. Moreover, it was noted that close collaboration aimed at technology development can help to avoid quality problems that may give rise to SC vulnerabilities such as customer disruptions. "*We are collaborating on technology development to ensure we are getting the right quality.*" Likewise, Oettmeier and Hofmann (2016) point out that close collaboration is necessary between AM material and machine suppliers, since incompatibilities between materials and machines may cause issues that can undermine the expected performance outcomes. Similarly, a respondent had explained that "*Cooperation with business partners is very important. Especially before and after every transaction (raw material* *acquisition and post processing).*" Along the same lines, consumer-centric production as well as co-design/co-creation were two other explicated AM features based on the respondents' explanations, both of which are likely to have similar effects in terms of SC capabilities and vulnerabilities. Co-design/co-creation with users is an important AM feature that drives the "shift from manufacturer-centric to consumer-centric business models" (Bogers et al., 2016). Through a consumer-centric business model based on co-design/co-creation, the firm has better prospects of maintaining a stronger and longer-term relationship with its customers, especially as these AM-enabled features can help the firm to better deal with erratic customer demands and provide products that properly fit the customer needs, thus avoiding potential customer disruptions. For instance, in a business model where the production of the final products is postponed to later stages by passing the printing phase to the consumers, i.e., consumer-centric production (Steenhuis and Pretorius, 2016, 2017), the firm can focus on customizing the product designs based on customer feedback (i.e., co-design/co-creation) to better meet the unpredictability in their demands (Waller & Fawcett, 2014; Rayna & Striukova, 2016) and avoid potential customer disruptions.

As for the existing barriers, complications regarding intellectual property (IP) rights were mentioned several times by the respondents. For instance, "*Could be higher. but there are constraints about IP.*" was among common explanations that reflects the existing concerns regarding the protection of IP rights in both "business-to-business and business-to-consumer contexts" (Verboeket & Krikke, 2019). This is the case since many firms are concerned with infringements that may take place after communicating information (e.g., sharing 3D models) with other SC members (Jiang et al., 2017; Naghshineh et al., 2021). The lack of methods and regulatory frameworks (e.g., copyright frameworks, patents, trademarks, and licensing) for dealing with potential infringements exacerbates this situation as 3D scanning together with 3D printing make the counterfeiting of ideas and products quite easy (Gebler et al., 2014; Chan et al., 2018). Moreover, lack of trust in AM is another barrier that hinders the practicing of SC common response in the context of AM. As one respondent noted, "*There are still some doubts regarding AM in many industries that require more cooperation*.", corroborating the findings of Dwivedi et al. (2017) and Verboeket and Krikke (2019) in this regard. Lastly, lack of consumer awareness and acceptance was another mentioned barrier by the respondents, which is also pointed out by Durach et al. (2017). Clearly, these barriers negatively affect the level of cooperation among the SC members, thus reducing the capability of the firm's SC in providing timely responses to customer demands.

Proposition 5. AM adoption has a moderate effect on practicing SC common response, affecting the firm's market position as well as collaboration with other firms in the SC, which in turn affects the vulnerability of the SC to competitive innovations, unpredictability in customer demands, supplier disruptions, and customer disruptions.

4.6 Align supply chain information systems

The respondents' answers indicated that AM has a relatively moderate effect on the ease with which SC partners can exchange reliable and timely information. The dispersion in the quantitative answers was rather high, implying different opinions among the respondents. Many drew attention to the possibility of sharing information using digital files (i.e., digital file distribution), which can be easily stored (i.e., digital inventory) when compared to physical inventory (Holmström et al., 2016; Chekurov et al., 2018). Apparently, these AM features improve the visibility of the SC as they facilitate the exchange of information (i.e., Visibility (Information exchange)). Therefore, through improved SC visibility, it would be easier to interact with other SC members, e.g., outsourcing production (i.e., Connectivity (Degree of outsourcing)). Moreover, such improvement in SC visibility would also help to deal with supply disruptions as well as unpredictability in customer demands with more ease. Along the same lines, AM facilitates inventory management due to its compatibility with different information systems. According to a respondent, "*Since AM is a digital process, it is amenable and compatible with other digital technologies for sharing information: MES* [Manufacturing Execution System], *MRP* [Material Requirement Planning], *ERP* [Enterprise Resource Planning], *etc.*" This flexibility in inventory management (i.e., Flexibility (Inventory management)) also contributes to more flexibility in demand forecasting (i.e., Anticipation (Demand forecasting)), especially when dealing with the unpredictability in customer demands that can lead to production capacity shortages (i.e., Resource limits (Production capacity)). Also, some respondents considered the digital nature of AM as a facilitator of information exchange. Therefore, by taking advantage of AM's digital nature together with close collaboration with other SC members, it would be easier to exchange information for collaborative decision-making (i.e., Collaboration (Collaborative information sharing)) and collaborative forecasting (i.e., Collaboration (Collaborative forecasting) to deal with the unpredictability in customer demands and disruptions. This is also in line with Belhadi et al. (2022) who suggest that AM together with other digital technologies such as sensors and data analytics can lead to enhanced sensing capabilities, "therefore enhancing information sharing and collaboration." Lastly, distributed manufacturing via AM may as well act as an incentive for SC members to align their information systems (Durão et al., 2017). This is the case since any node along the SC that is equipped with compatible AM machinery can act as a production site (Zanoni et al., 2019). As one respondent noted, "*One design already produced in the US can be replicated in Europe in real time, if the same equipment is available, or in a few days with different equipment.*" In such a scenario, aligning SC information systems boosts information sharing, thus enhancing SCR (Naghshineh & Lotfi, 2019).

However, despite all the mentioned advantages, some respondents expressed their concerns about potential IP rights complications. Two respondents mentioned that "*Too much is at stake in terms of IP*" and that there are "*IP restrictions*", lending support to the statement by Dwivedi et al. (2017) that the concept of digital inventory in the context of AM poses challenges for the protection of IP rights, as well as the statement by Schniederjans (2017) that legislation should improve to protect the manufacturers' IP rights against black-market copies. Such an impediment negatively affects the capability of the firm to collaboratively share information with other SC members and perform tasks such as collaborative forecasting (Naghshineh & Carvalho, 2022b), turning continuous information flow for everyday operations into an SC vulnerability (i.e., Connectivity (Reliance upon information flow)). Also, such a situation leaves the firm's technology and products vulnerable to industrial espionage (i.e., Deliberate threats (Industrial espionage)). Another relevant barrier in many AM SCs is the inadequate means of ICT (Chekurov et al., 2018). "*We still have to work on streamlining the information flow between the sites.*" is an explanation given by a respondent that draws attention to this barrier. Furthermore, ICT inadequacies can lead to cybersecurity issues, increasing the risk of data breaches (Zanoni et al. 2019). Along the same lines, Chan et al. (2018) state that "good data management can facilitate 3DP, and vice versa.", especially in the context of AM-enabled distributed manufacturing where "information exchange, communication, and control between the production sites" become challenging tasks (Durão et al., 2017). Thus, in the absence of adequate ICT, connectivity issues may arise that undermine the capability of the firm to exchange reliable and timely information with its SC partners, therefore causing SC vulnerability to reliance on information flow (Naghshineh & Carvalho, 2022b).

Proposition 6. AM adoption has a moderate effect on aligning SC information systems, affecting SC visibility, anticipation, flexibility in order fulfillment, and collaboration, which in turn affects the vulnerability of the SC to the degree of outsourcing, supplier disruptions, customer disruptions, unpredictability in customer demands, and production capacity shortages. However, SC vulnerability to reliance on information flow and industrial espionage may deteriorate due to ICT inadequacies and potential IP rights complications.

4.7 Use alternative suppliers

The answers to the Likert scale questions indicated that the respondents perceived the effect of AM on practicing multiple sourcing as moderate, with no considerable dispersion in the answers, implying general agreement. While the respondents did not point out any particular AM feature in their explanations, they mentioned multiple barriers that inhibit the number of available alternatives for sources of supply. The most pronounced barrier that emerged from their explanations was the limited variety and supply of AM materials. "*There is a high dependency on a small number of suppliers in the industry, which means we are single sourcing materials and machines. This is something we are working to change, as it means high risk of supply.*" and "*A stable delivery network (every time more than one supplier for each material) is necessary for additive manufacturing.* " are two such explanations. These explanations are in line with Niaki and Nonino (2017) who state that the "limited range of available raw material and a shortage of suppliers lead to a high negotiating power for AM material suppliers". According to one respondent, this situation is exacerbated when AM machines are supplied as closed source systems (vs. open-source systems), which only work with specific materials. "*Too many closed systems do not allow for a variety of feedstock suppliers.*" In the case of closed source systems, as Kunovjanek et al. (2020) state, "AM machine producers can potentially restrict the supply of AM raw materials concerning type and purchasing channel". Also, as one respondent noted, the AM market is still young and there are many patents that protect the suppliers by locking customers into only buying from them. "*In my opinion, same as other technologies/fields. Even less I might say as the market is young and still many patents protect suppliers and force you to work with them.*" Altogether, the limited variety and supply of AM materials reduces sourcing flexibility as there are not many alternative suppliers available (i.e., Flexibility (Alternate suppliers)). According to Naghshineh and Carvalho (2022b), this situation can also give rise to interrelated SC vulnerabilities such as shortage of production capacity at the manufacturing firm due to shortage of raw materials (i.e., Resource limits (Raw material availability)) caused by the limited number of suppliers and supply of AM materials (i.e., Resource limits (Supplier capacity)). In other words, this situation creates a high degree of dependence on the capacity of a limited number of suppliers to provide the necessary input materials for production to take place at the manufacturing firm (i.e., Connectivity (Reliance upon specialty sources).

The second most pronounced barrier was the lack of regulation and standardization of AM materials, which is also mentioned by scholars such as Chekurov et al. (2018) and Verboeket and Krikke (2019). "*Raw material supply is maturing but qualification presents a barrier to switching suppliers quickly.*" is a respondent explanation that illustrates this barrier. Since the quality of the AM raw materials is an important factor, the present lack of regulation and standardization necessitates extensive quality assurance (QA) and quality control (QC) to be carried out by the manufacturers in-house, which is considered to be "an additional burden" (Kunovjanek et al., 2020). This is mainly due to the lack of "unified guidelines/regulations and established standards" (Zanoni et al., 2019), which turns the QA/QC of AM materials into a process that is "predominately dictated by in-house specifications" (Thomas-Seale et al., 2018). According to the explanations, the lack of regulation and standardization makes the traceability of AM materials difficult as well. This issue has been raised in the existing literature by scholars such as Chan et al. (2018) who state that there are difficulties in tracing the origins of AM materials. Thus, the traceability of AM materials should be ensured by the manufacturers (Petrovic et al., 2011), which according to a respondent compels them to "*audit and validate the suppliers in more detail*". The high cost of AM materials was another mentioned barrier, which is in line with the existing literature, e.g., Dwivedi et al. (2017) and Durach et al. (2017). All these barriers may as well reduce the sourcing flexibility of raw materials, causing the same SC vulnerabilities that were discussed earlier in this subsection. For instance, the lack of regulation and standardization of AM materials coupled with their limited traceability can make multiple sourcing difficult and lead to dependency on a limited number of suppliers whose materials meet the quality standards of the manufacturing firm, while the high cost of AM materials can limit the production capacity of the manufacturing firm (Naghshineh & Carvalho, 2022b). Apart from issues related to AM materials, some respondents remarked the high cost and limited supply of industrial-grade AM machines as other barriers that make multiple sourcing even more difficult. Furthermore, it was noted that the lack of AM process standards turns the qualification of new machine suppliers into a rigorous task, which is in accord with the findings of Wagner and Walton (2016). These barriers may as well cause vulnerability to production capacity as well as reliance on a limited number of qualified machine suppliers (Naghshineh & Carvalho, 2022b).

Proposition 7. AM adoption has a moderate effect on multiple sourcing, which negatively affects sourcing flexibility, making the SC more vulnerable to raw materials availability, production capacity, supplier capacity, and reliance on specialty sources.

4.8 Use alternative production sites

The effect of AM on using alternative production sites was perceived as relatively low by the respondents, with moderate dispersion in their quantitative answers compared to other resilience practices. Distributed manufacturing turned out to be the most pronounced AM feature enabling the use of alternative production sites. It was noted that "*At the cost of a printer and few other ancillary equipment, production can be set up almost anywhere*.", supporting the notion of local manufacturing whereby "manufacturing is distributed with many production facilities." (Ryan et al., 2017) as well as distributed manufacturing configurations enabled by AM (Durach et al., 2017; Braziotis et al., 2019). An important implication of this AM-enabled resilience practice is the capability to distribute production facilities at different locations (i.e., Dispersion (Distributed capacity)), thus avoiding the concentration of production capacity in one location (i.e., Sensitivity (Concentration of capacity)), which mitigates the risk of deliberate misconducts such as terrorism and sabotage (i.e., Deliberate threats (Terrorism and sabotage)) or piracy and theft. According to one respondent, "*If one production site is down, we are able to divert production to another site.*" In other words, the firm will have the flexibility (i.e., Flexibility (Reallocation of production)) as well as the adaptability (i.e., Adaptability (Rerouting of requirements)) to promptly adjust its operations and gain access to adequate production and distribution capacity to fulfill and deliver customer orders in the face of disruptions. For instance, mobile manufacturing via AM as a distributed manufacturing method can improve SCR in the aforementioned ways. According to Stillström and Jackson (2007), mobility in manufacturing is "the ability to change between geographically different places with little penalty in time, effort, cost, or performance.", which was evident in the respondents' explanations. Moreover, it was noted that "*AM can enable local or regional production reducing the effects of delays in shipping and other disruptions.*", which allows the firm to protect itself against potential supplier/customer disruptions that may take place in certain nodes across the SC. It was also mentioned that "*Having a backup plant for additional capacity is fairly easy to setup.*", alluding to the possibility of pooling production capacity (Holmström et al., 2016; Verboeket and Krikke, 2019), which helps to buffer the negative effects of disruptions (e.g., ripple effect), thus increasing the manufacturing flexibility of the firm against unexpended surges in demand (Khajavi et al., 2014; Ivanov et al., 2019). As Ivanov et al. (2019) state "The core of additive manufacturing applications to SCM is the usage of 3D printers at different stages in the SC to increase manufacturing flexibility".

However, explanations such as "*More specialized production infrastructure is required for additive compared to subtractive.*" or "*Harder to invest due to higher infrastructure cost and capital cost.*" revealed the lack of specialized production infrastructure as a big obstacle that can significantly impede this resilience practice, thus limiting production and distribution capacities. An instance of this issue has been mentioned by Chekurov et al. (2018) regarding the underdeveloped ICT infrastructure of many companies for handling AM digital file transfers. Also, as Eyers et al. (2018) point out, the high cost of machine infrastructure for industrial AM inhibits the production capacity flexibility. In case the firm does not possess a specialized AM infrastructure itself, another option is to temporarily outsource the production operations to service providers (Ford & Despeisse, 2016; Rogers et al., 2016) until its production capacity is stabilized. As one respondent explained, "*AM is becoming more mainstream and there is a good chance a company can have alternative production options*.", which implies the possibility of outsourcing production to service providers in different locations (Eyers & Potter, 2015). This practice opens up opportunities to gain access to markets that are geographically dispersed (i.e., Dispersion (Dispersion of markets)), thus expanding the scale and extent of the firm's supply network (i.e., Connectivity (Scale and extent of supply network)) and establishing a globally distributed SC (i.e., Connectivity (Import/export channels)). Despite increased dependence on external entities, outsourcing production can also help the firm to mitigate possible supplier/customer disruptions.

Proposition 8. AM adoption has a low effect on using alternative production sites, affecting dispersion, flexibility in order fulfillment, and adaptability, which in turn affects the vulnerability of the SC to the concentration of capacity, terrorism and sabotage, piracy and theft, distribution capacity, production capacity, scale and extent of supply network, import/export channels, supplier disruptions, and customer disruptions. However, in the case of outsourcing production, SC vulnerability may increase due to increased dependence on external entities.

4.9 Use alternative transport modes

AM was perceived to have a relatively low effect on using different modes of transport, with the highest dispersion in the answers. The most noticeable interrelated AM features in the respondents' explanations were digital inventory and digital file distribution, both of which were considered to be enablers of distributed manufacturing. As one respondent explained, "*AM can eliminate the transportation of goods and materials since production could theoretically be located as close as possible to the point of use.*" He continued, "*AM parts are represented by digital files so inventory can be digital too and production can take place on demand.*" This explanation emphasizes the benefits of AM-enabled distributed manufacturing, i.e., reducing transportation by manufacturing on demand close to the point of use (Holmström et al., 2010; Ryan et al., 2017). Also, the capability to store parts in digital format and distribute them digitally can further reduce the need for physical storage and transportation throughout the SC (Ford & Despeisse, 2016; Ghobadian et al., 2020), which is referred to as the "digital transportation of products" by Verboeket and Krikke (2019). As noted by a respondent, "*With AM, we will move from transcontinental transport problem (container, packaging, inventory redundancies) to last mile transport.*" Moreover, another respondent explained that it is "*Easy to use multiple transportation methods*". This is especially true as AM materials normally come in fewer types and basic forms (Durach et al., 2017; Li et al., 2017), therefore it is easier to move them around with "different transportation modalities" (Verboeket & Krikke, 2019). As Ford and Despeisse (2016) state "Logistics are simplified as fewer, more basic material inputs are needed." Also, it was noted that parts can be printed in transit using a transport vehicle that is equipped with 3D printers, i.e., mobile manufacturing (Pérès & Noyes, 2006; Kenger et al., 2021), reducing the lead time and improving manufacturing capacity flexibility (Ryan et al., 2017). This production method is especially feasible for low-volume batches (Kunovjanek & Reiner, 2020), i.e., small batch production, as there is no need for product-specific tools and complex machine setups (Shukla et al., 2018), making it possible to equip the transport vehicles with 3D printers (Kenger et al., 2021). Lastly, according to a respondent, it is possible to use typical courier services to ship the parts, since they are normally printed in small batches. All these AM features add to the flexibility of the SC in order fulfillment by allowing the produced parts to be delivered via different transport modes and routing options (i.e., Flexibility (Alternate distribution channels)), thus mitigating potential shortages in production and distribution capacities. Also, such AM-enabled freedom in transportation and distribution helps to deal with possible geopolitical disruptions (Iftikhar et al., 2022), which can cause suppliers disruptions and negatively affect the import/export of products in over-extended SCs (i.e., Turbulence (Exposure to geopolitical disruptions)).

However, despite all the mentioned AM features, the average score of the quantitative answers still indicated a low effect of AM on using alternative transport modes. With reference to potential barriers, it was noted that the "*Transport of hazardous powders is slower*." In the case of hazardous materials, distribution capacity may become limited since their transportation requires special care and conditions, limiting the flexibility to promptly alternate between different transport modes and routing options. However, as this barrier is common among other production methods, we did not consider it as an AM adoption barrier.

Proposition 9. AM adoption has a low effect on using alternative transport modes, affecting flexibility in order fulfillment, which in turn affects the vulnerability of the SC to distribution capacity, production capacity, supplier disruptions, and exposure to geopolitical disruptions.

5. Managerial implications

In this study, we aimed to conceive an empirical framework that can help SC managers and policymakers to make more informed decisions about how to improve the resilience of the SC via different resilience practices in a context where AM technology is used. Thus, to gain the viewpoint of the industry on the subject matter, we conducted a survey whereby we gathered both quantitative and qualitative data from active firms in different industries that use various AM processes (see Tables 2 and 3). Drawing on the gathered data, we could estimate the extent to which AM affects different resilience practices as well as specify how various SC capabilities and vulnerabilities are likely to get affected as a result. We also identified the AM features and barriers that affect each resilience practice by analyzing the respondents' explanations and comparing them with evidence from AM and SCM literature. By doing so, we managed to specify 48 paths that originate from AM adoption features and barriers affecting resilience practices, which subsequently lead to certain SC capabilities and vulnerabilities, thus affecting SCR. These paths are marked by black/red arrows in the AM-SCRP framework (Figure 4), whereby red arrows represent the (10) paths that exclusively lead to deterioration of the SC capabilities and consequently their related SC vulnerabilities. Also, the AM barriers that are highlighted in red are the ones causing these deteriorations as explained throughout section 4. As for the direction of the effects (i.e., positive vs. negative), just in the case of multiple sourcing, we could determine the effect of AM as negative, since only AM barriers that inhibit this resilience practice were pointed out, and no AM features emerged from the respondents' explanations. However, with respect to other resilience practices, as a mix of AM features and barriers emerged from the respondents' explanations, it was not possible to determine the direction of the effects with absolute confidence, thus we only estimated the extent to which (i.e., high/moderate/low) AM is likely to affect these resilience practices based on the quantitative answers to the Likert scale questions. The highly affected resilience practices and their related variables (i.e., AM features, barriers, metrics, SC capabilities and vulnerabilities) are highlighted in color blue in the AM-SCRP framework, whereas colors green and yellow indicate moderate and low effects respectively.

As it can be seen in the AM-SCRP framework (Figure 4), AM adoption affects "Flexibility" via the resilience practices "Change the production schedule", "Align supply chain information systems", "Use alternative production sites", "Use alternative transport modes", and "Use alternative suppliers". Firstly, AM has a relatively high effect on changing the production schedules, which in turn affects the flexibility in order fulfillment by facilitating production postponement. For instance, the storage of digital inventory instead of physical inventory in an AM context makes it easier to change the production schedule by shifting the order penetration point (OPP) upstream SC towards the make-to-order (MTO) policy (Verboeket & Krikke, 2019), thus facilitating production postponement when compared to the make-to-stock (MTS) policy. This flexibility in production postponement in turn allows the firm to better deal with the unpredictability in customer demands as well as possible customer disruptions. However, barriers such as slow production speed, low throughput rate, or excessive post-processing requirements take away from this flexibility as explained in subsection 4.1. Secondly, AM has a relatively moderate effect on aligning SC information systems, which affects the flexibility in order fulfillment by facilitating inventory management (Ghadge et al., 2018; Delic et al., 2019), e.g., digital inventory. This flexibility in inventory management allows the firm to mitigate the unpredictability in customer demands as well as potential shortages in production capacity. Thirdly, AM has a relatively low effect on using alternative production sites, which in turn affects the flexibility in order fulfillment by making it possible to reallocate production to a different site through distributed manufacturing, capacity pooling, or even outsourcing production. This flexibility in turn allows the firm to mitigate possible shortages in production and distribution capacity. However, the lack of specialized production infrastructure inhibits the effect of AM on this resilience practice. Fourthly, AM has a relatively low effect on the use of alternative transport modes, affecting the flexibility in order fulfillment by making it easier to alternate between different distribution channels (i.e., transportation modes and routing options) via AM features such as fewer materials and inventory, digital inventory as well as digital distribution of files, and mobile manufacturing. As explained in subsection 4.9, this flexibility mitigates SC vulnerabilities to shortages in production and distribution capacities, as well as supplier and geopolitical disruptions. For instance, according to a respondent, "*BOM is first level (raw materials only)*" in AM, which facilitates the use of different modes of transport since materials can be more easily adapted to “different transportation modalities” (Verboeket & Krikke, 2019). Nevertheless, in the case of hazardous AM materials, extra caution should be exercised, which may take away from the flexibility to use different modes of transport. Lastly, AM has a rather moderate negative effect on practicing multiple sourcing (i.e., using alternative suppliers) as there are multiple existing barriers to the supply of AM materials (i.e., the limited variety and supply of AM materials, lack of AM materials standardization, high cost of AM materials) as well as the supply of AM machines (i.e., limited supply of industrial-grade AM machines, lack of AM process standards, high cost of industrial-grade AM machines) that reduce the flexibility in sourcing, causing SC vulnerabilities to raw material availability, supplier capacity, production capacity, and reliance on specialty sources, which are also pointed out by Naghshineh and Carvalho (2022b). As noted earlier, in this case, we could determine the direction of this effect as negative, since the majority of the respondents only explained how different AM barriers limit multiple sourcing. Altogether, the findings are in accord with Delic and Eyers (2020) who posit that AM adoption improves SC flexibility and performance. Furthermore, these findings provide empirical evidence for supporting the proposition put forward by Naghshineh and Carvalho (2022a) that “AM adoption has a limiting effect on the available alternatives for sources of supply”, which is mainly caused by the aforementioned barriers, also corroborating the proposition put forward by Naghshineh and Carvalho (2022b) that “SC vulnerabilities caused by AM adoption barriers negatively affect SCR”.

AM adoption affects “Adaptability” via the resilience practices “Reduce response time”, “Reduce delivery lead time”, and “Use alternative production sites”. Firstly, AM has a relatively high effect on reducing response time, affecting the capability of the firm to quickly adjust its operations to respond to challenges. AM features such as rapid prototyping and rapid manufacturing of parts, which are empowered by tool-less manufacturing and fast production setup, help reduce the production lead time, thus increasing the adaptability of the firm to respond to SC vulnerabilities caused by the unpredictability in customer demands as well as competitive innovations in the market. As Niaki and Nonino (2017) state, “AM is most advantageous in market environments characterized by demand for customization and flexible parts”, referring to contemporary market environments where frequent competitive innovations drive the firm to quickly adapt its product portfolio to erratic customer demands for business continuity. In this case, “The shortened development lead times 3DP offers can allow product developers to quickly alter or customize products to meet new market trends faster than competitors.” (Candi & Beltagui, 2019). In other words, “AM provides a significant time-to-market reduction, a key capability for business success.” (Niaki & Nonino, 2017). However, slow production speed and excessive post-processing requirements are among the barriers that inhibit the effect of AM on this resilience practice. Also, the present instability in AM processes can lead to unforeseen failures in production operations. Secondly, AM has a relatively high effect on reducing delivery lead time, which affects SC adaptability as well. For instance, through a high degree of design freedom, AM enables the consolidation of many parts into a one complex part. This not only allows the firm to better respond to unpredictable customer demands for complex products but also reduces the need for warehousing and distribution of many subcomponents along the SC, thus reducing SC vulnerabilities to distribution capacity shortages as well as instances of inventory theft and damage. Another important AM feature that helps to reduce delivery lead time is the on-demand manufacturing of products empowered by distributed manufacturing (aka local manufacturing). "For example, Additive Manufacturing could be used to produce spare-parts on-demand in a location near to the customer" (Delic & Eyers, 2020). Apparently, such "a 'print on demand' approach" (Sgarbossa et al., 2021) via AM can significantly reduce the delivery lead times of parts/products. However, as already explained in subsection 4.2, excessive post-processing inhibits the effectiveness of AM in this regard (Naghshineh & Carvalho, 2022b). Thirdly, AM has a relatively low effect on using alternative production sites. In case of disruptions, AM-enabled distributed manufacturing allows the firm to promptly reroute its production to different facilities (i.e., capacity pooling) or even to other manufacturing firms (i.e., outsourcing production), therefore mitigating vulnerabilities to shortages in production and distribution capacity. As Zanoni et al. (2019) state "Any node on the supply chain that is connected to the web and equipped with an AM-based machine can be considered as a production site along the supply chain.", suggesting the use of alternative production sites through AM-enabled distributed manufacturing. Overall, the results are corroborated by the existing research such as Liu et al. (2014), who show that it is possible to reduce the response times via AM, especially through distributed AM. Nevertheless, provisioning specialized infrastructures at different production sites/locations to ensure consistent AM operations can be difficult, inhibiting AM's effect in this regard.

AM adoption affects "Dispersion" via the resilience practice "Use alternative production sites". According to our findings, AM has a relatively low effect on using alternative production sites, influencing distributed capacity as well as dispersion of markets. While AM features such as distributed manufacturing would enable a firm to distribute its production facilities at various locations and avoid SC vulnerabilities to geographic co-dependence on production facilities and suppliers, deliberate threats such as terrorism and sabotage, or even piracy and theft in certain areas, they would also allow the firm to expand the scale and extent of its supply network by gaining access to international markets. As many studies suggest (e.g., Weller et al., 2015; Hartl & Kort, 2017), AM facilitates entering new markets, "leading to more local production" (Kleer & Piller, 2019). However, despite all the AM features that contribute towards using alternative production sites and enhance "Dispersion", the lack of specialized production infrastructure acts as a barrier that inhibits the enhancing effect of AM on this resilience practice. Issues such as "the fixed and expensive nature of the machine infrastructure" (Eyers et al., 2018), or "creating a secure IT infrastructure"

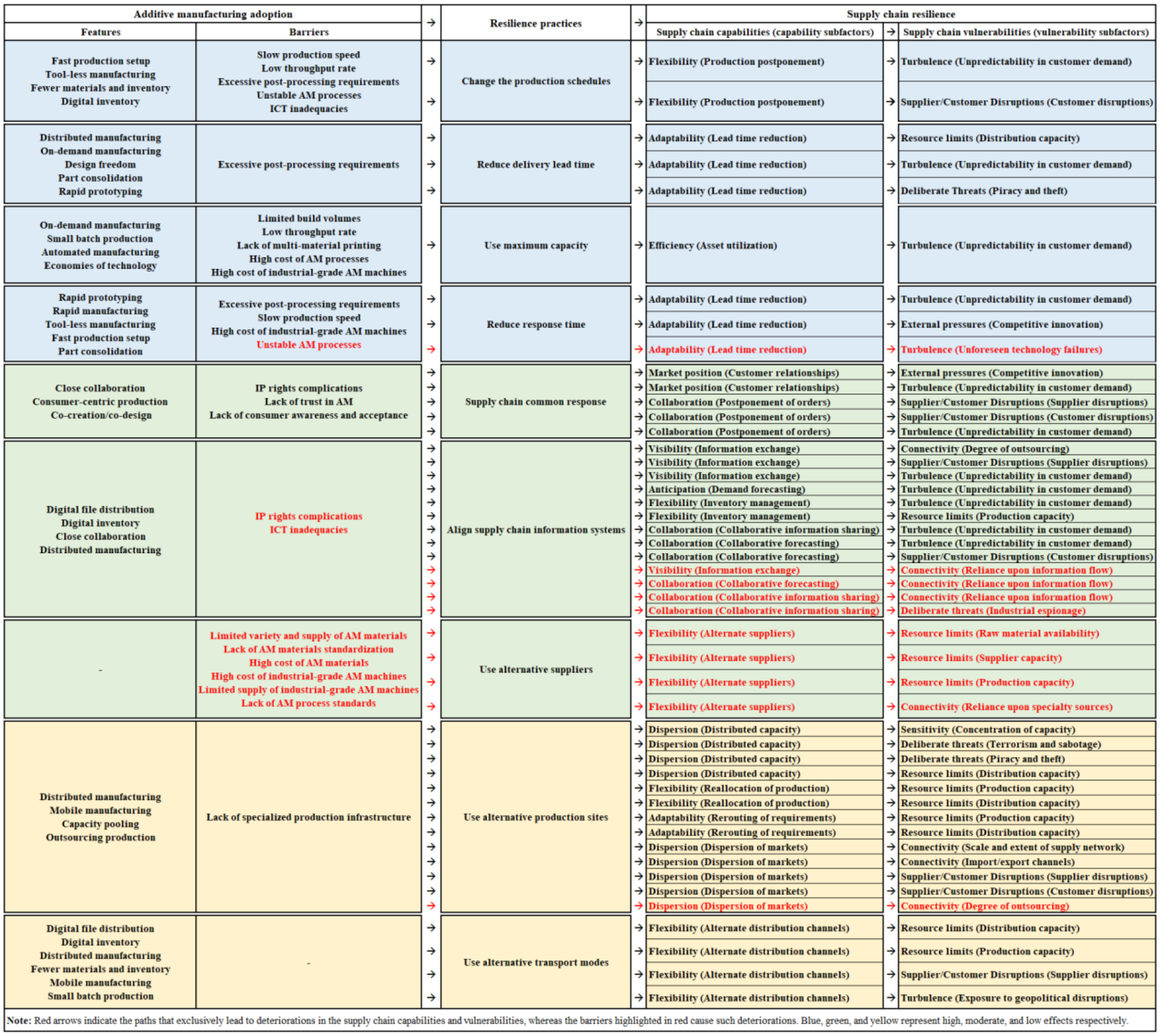
(Verboeket & Krikke, 2019) are among the reasons that make the provision of specialized production infrastructure for AM difficult. Furthermore, in the case of outsourcing production, SC vulnerability can increase due to the increased degree of interdependence between the firm and external entities (e.g., AM service providers).

AM adoption affects "Collaboration" via the resilience practices "Supply chain common response" and "Align supply chain information systems". Firstly, AM has a relatively moderate effect on SC common response, influencing collaboration through postponement of orders. "For example, a consumer printing final product allows for the ultimate in postponement" (Waller & Fawcett, 2014). As explained in subsection 4.5, this consumer-centric method of production in turn mitigates SC vulnerabilities caused by the unpredictability in customer demands and customer disruptions. However, potential IP rights complications together with the lack of consumer awareness and trust in AM inhibit the effect of this technology on practicing SC common response. Secondly, AM has a relatively moderate effect on aligning SC information systems, which affects collaborative information sharing and related tasks such as demand forecasting with other SC partners (Naghshineh & Lotfi, 2019). For instance, the possibility to implement distributed manufacturing of parts across the SC via AM technology motivates the SC partners to align their information systems in order to enable this manufacturing method (Durão et al., 2017). Such an initiative aimed at collaborative information sharing will reduce the SC vulnerabilities to unpredictability in customer demand and customer disruptions as explained in subsection 4.6. Overall, the findings are in accord with Oettmeier and Hofmann (2016) as well as Luomaranta and Martinsuo (2020) who claim that AM promotes collaboration throughout the SC. However, potential IP rights complications coupled with ICT inadequacies are barriers that not only inhibit collaborative information sharing and forecasting capabilities but also give rise to SC vulnerabilities to reliance on continuous information flow and instances of industrial espionage, which are in accord with the findings of Naghshineh and Carvalho (2022b). This is because digitalizing an SC with a digital technology such as AM creates reliance on real-time communication and coordination of different information systems throughout the SC, and therefore the SC "can be vulnerable to cyberattacks. These attacks can include industrial espionage, IP leakage, or even production sabotage." (Tang & Veelenturf, 2019).

AM adoption affects "Visibility" and "Anticipation" via the resilience practice "Align supply chain information systems" as shown in the AM-SCRP framework. As Weller et al. (2015) state, "With AM, direct digital manufacturing allows for digital information flow along the value chain from product design to production", lending support to the notion that AM adoption promotes aligning information systems throughout the SC, which is also in line with the general postulate by Balakrishnan and Ramanathan (2021) that the use of digital technologies such as AM "will encourage the firm's supply chain resilience practices." More specifically, AM features such as digital inventory and digital file distribution, which empower distributed manufacturing across the SC, incentivize the SC members to align their information systems, hence improving the SC visibility and anticipation capabilities. This improvement in SC visibility not only facilitates related tasks such as production outsourcing but also mitigates the vulnerability to supplier disruptions that originate from upstream SC. Also, by staying aligned and connected, forecasting methods can be used more effectively by the SC members to anticipate the unpredictability in customer demand that originates from downstream SC. Nonetheless, ICT inadequacies followed by concerns for IP rights protection not only inhibit the AM's enhancing effect in this regard but can also cause SC vulnerability to dependence on continuous information flow for everyday operations, which calls for establishing a secure ICT infrastructure throughout the SC (Naghshineh & Carvalho, 2022b).

AM adoption affects "Efficiency" via the resilience practice "Use maximum capacity". AM has a relatively high effect on using maximum capacity due to features such as automated manufacturing and small batch production, supporting the notion of economies of technology and addressing the dilemma concerning the economies of scale. For instance, '"Economies of technology" will be possible through the utilization of multiple AM machines by a single operator' (Naghshineh et al., 2021), leading to reduced labor. Moreover, as products can be produced in small batches or even one by one, "they are not subject to economies of scale" (Hartl & Kort, 2017). Therefore, such features turn AM into an ideal technology that facilitates the adjustment of production capacity, allowing the firm to make the best of resources at its disposal to generate outputs with minimal resource requirements. As explained in subsection 4.3, efficiency in production helps the firm to better deal with the unpredictability of customer demands, especially when considering time and cost factors. These findings are in accord with Belhadi et al. (2022) who report that AM augments efficiency within the SC. However, present AM barriers such as the limited build volumes and lack of multi-material printing undermine the capability to adjust the production capacity, thus reducing the efficiency due to the incurred time and cost penalties.

AM adoption affects "Market position" via the resilience practice "Supply chain common response". AM has a relatively moderate effect on practicing SC chain common response through features such as co-design/co-creation and consumer-centric production, which allow the customer to be involved in the design and production phases of the products. As Oettmeier and Hofmann (2017) state, 'Customers may take the role of "co-producers", e.g., by being integrated in the product design process, because in AM, design and production can easily be separated.' By allowing the customers to co-design and co-create the products, not only the firm can better respond to the unpredictability of their demands but also deal with competitive innovations, thus consolidating its position in the market. However, concerns regarding the protection of IP rights coupled with the lack of consumer awareness and trust in AM inhibit the effect of this technology on cooperating with other firms throughout the SC.



Additive manufacturing adoption		→	Resilience practices	→	Supply chain resilience		
Features	Barriers				Supply chain capabilities (capability subfactors)	→	Supply chain vulnerabilities (vulnerability subfactors)
Fast production setup Tool-less manufacturing Fewer materials and inventory Digital inventory	Slow production speed Low throughput rate Excessive post-processing requirements Unstable AM processes ICT inadequacies	→	Change the production schedules	→	Flexibility (Production postponement)	→	Turbulence (Unpredictability in customer demand)
		→		→	Flexibility (Production postponement)	→	Supplier/Customer Disruptions (Customer disruptions)
Distributed manufacturing On-demand manufacturing Design freedom Part consolidation Rapid prototyping	Excessive post-processing requirements	→	Reduce delivery lead time	→	Adaptability (Lead time reduction)	→	Resource limits (Distribution capacity)
		→		→	Adaptability (Lead time reduction)	→	Turbulence (Unpredictability in customer demand)
		→		→	Adaptability (Lead time reduction)	→	Deliberate Threats (Piracy and theft)
On-demand manufacturing Small batch production Automated manufacturing Economies of technology	Limited build volumes Low throughput rate Lack of multi-material printing High cost of AM processes High cost of industrial-grade AM machines	→	Use maximum capacity	→	Efficiency (Asset utilization)	→	Turbulence (Unpredictability in customer demand)
Rapid prototyping Rapid manufacturing Tool-less manufacturing Fast production setup Part consolidation	Excessive post-processing requirements Slow production speed High cost of industrial-grade AM machines Unstable AM processes	→	Reduce response time	→	Adaptability (Lead time reduction)	→	Turbulence (Unpredictability in customer demand)
		→		→	Adaptability (Lead time reduction)	→	External pressures (Competitive innovation)
		→		→	Adaptability (Lead time reduction)	→	Turbulence (Unforeseen technology failures)
Close collaboration Consumer-centric production Co-creation/co-design	IP rights complications Lack of trust in AM Lack of consumer awareness and acceptance	→	Supply chain common response	→	Market position (Customer relationships)	→	External pressures (Competitive innovation)
		→		→	Market position (Customer relationships)	→	Turbulence (Unpredictability in customer demand)
		→		→	Collaboration (Postponement of orders)	→	Supplier/Customer Disruptions (Supplier disruptions)
		→		→	Collaboration (Postponement of orders)	→	Supplier/Customer Disruptions (Customer disruptions)
		→		→	Collaboration (Postponement of orders)	→	Turbulence (Unpredictability in customer demand)
Digital file distribution Digital inventory Close collaboration Distributed manufacturing	IP rights complications ICT inadequacies	→	Align supply chain information systems	→	Visibility (Information exchange)	→	Connectivity (Degree of outsourcing)
		→		→	Visibility (Information exchange)	→	Supplier/Customer Disruptions (Supplier disruptions)
		→		→	Visibility (Information exchange)	→	Turbulence (Unpredictability in customer demand)
		→		→	Anticipation (Demand forecasting)	→	Turbulence (Unpredictability in customer demand)
		→		→	Flexibility (Inventory management)	→	Turbulence (Unpredictability in customer demand)
		→		→	Flexibility (Inventory management)	→	Resource limits (Production capacity)
		→		→	Collaboration (Collaborative information sharing)	→	Turbulence (Unpredictability in customer demand)
		→		→	Collaboration (Collaborative forecasting)	→	Turbulence (Unpredictability in customer demand)
		→		→	Collaboration (Collaborative forecasting)	→	Supplier/Customer Disruptions (Customer disruptions)
		→		→	Visibility (Information exchange)	→	Connectivity (Reliance upon information flow)
		→		→	Collaboration (Collaborative forecasting)	→	Connectivity (Reliance upon information flow)
		→		→	Collaboration (Collaborative information sharing)	→	Connectivity (Reliance upon information flow)
		→		→	Collaboration (Collaborative information sharing)	→	Deliberate threats (Industrial espionage)
-	Limited variety and supply of AM materials Lack of AM materials standardization High cost of AM materials High cost of industrial-grade AM machines Limited supply of industrial-grade AM machines Lack of AM process standards	→	Use alternative suppliers	→	Flexibility (Alternate suppliers)	→	Resource limits (Raw material availability)
		→		→	Flexibility (Alternate suppliers)	→	Resource limits (Supplier capacity)
		→		→	Flexibility (Alternate suppliers)	→	Resource limits (Production capacity)
		→		→	Flexibility (Alternate suppliers)	→	Connectivity (Reliance upon specialty sources)
Distributed manufacturing Mobile manufacturing Capacity pooling Outsourcing production	Lack of specialized production infrastructure	→	Use alternative production sites	→	Dispersion (Distributed capacity)	→	Sensitivity (Concentration of capacity)
		→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Terrorism and sabotage)
		→		→	Dispersion (Distributed capacity)	→	Deliberate threats (Piracy and theft)
		→		→	Dispersion (Distributed capacity)	→	Resource limits (Distribution capacity)
		→		→	Flexibility (Reallocation of production)	→	Resource limits (Production capacity)
		→		→	Flexibility (Reallocation of production)	→	Resource limits (Distribution capacity)
		→		→	Adaptability (Rerouting of requirements)	→	Resource limits (Production capacity)
		→		→	Adaptability (Rerouting of requirements)	→	Resource limits (Distribution capacity)
		→		→	Dispersion (Dispersion of markets)	→	Connectivity (Scale and extent of supply network)
		→		→	Dispersion (Dispersion of markets)	→	Connectivity (Import/export channels)
		→		→	Dispersion (Dispersion of markets)	→	Supplier/Customer Disruptions (Supplier disruptions)
		→		→	Dispersion (Dispersion of markets)	→	Supplier/Customer Disruptions (Customer disruptions)
		→		→	Dispersion (Dispersion of markets)	→	Connectivity (Degree of outsourcing)
Digital file distribution Digital inventory Distributed manufacturing Fewer materials and inventory Mobile manufacturing Small batch production	-	→	Use alternative transport modes	→	Flexibility (Alternate distribution channels)	→	Resource limits (Distribution capacity)
		→		→	Flexibility (Alternate distribution channels)	→	Resource limits (Production capacity)
		→		→	Flexibility (Alternate distribution channels)	→	Supplier/Customer Disruptions (Supplier disruptions)
		→		→	Flexibility (Alternate distribution channels)	→	Turbulence (Exposure to geopolitical disruptions)

Note: Red arrows indicate the paths that exclusively lead to deteriorations in the supply chain capabilities and vulnerabilities, whereas the barriers highlighted in red cause such deteriorations. Blue, green, and yellow represent high, moderate, and low effects respectively.

Figure 4. The Additive Manufacturing-Supply Chain Resilience Practices (AM-SCR*P*) framework

6. Conclusions

In this study, we drew on the dynamic capabilities view to investigate the effects of AM technology adoption on enhancing SCR while considering the role of resilience practices. More specifically, we aimed at speculating how AM-enabled resilience practices would affect various SC capabilities and vulnerabilities that underlie SCR. Hence, we contributed to overcoming a noticeable knowledge gap in the existing literature at the intersection of AM technology adoption and SCM regarding the effectiveness of resilience practices that SCM can deploy to improve SCR when making use of the AM technology. To investigate the subject matter from the viewpoint of the industry, we took advantage of an exploratory survey research and collected quantitative and qualitative data from companies involved in different industries that had adopted different AM processes for a wide range of applications (e.g., direct part manufacturing, rapid prototyping, rapid tooling, and maintenance, repair, and overhaul). We used the quantitative empirical data to estimate to what extent AM affects the different resilience practices (RQ1), while we used the empirical qualitative data to explicate how such resilience practices in turn affect the SC capabilities and vulnerabilities that underlie SCR (RQ2). Subsequently, we triangulated our findings by comparing them with the existing evidence in the AM and SCM literature. Hence, we managed to put forward an empirical framework (Figure 4), which clarifies the underlying relationships between AM features and barriers, resilience practices, and SC capabilities and vulnerabilities.

The contributions of this study are manyfold. At the intersection of digital technologies and SCR, “many past studies are still conceptual and lack empirical corroboration” (Iftikhar et al., 2022). Therefore, by employing an exploratory survey research, we addressed an unexplored theme in the body of literature. Moreover, as the survey targeted companies operating in relatively developed economies, the findings are likely to be robust for generalization since digital technologies such as AM are more mature in such economies (Belhadi et al., 2022). Also, by drawing on empirical insights from experts involved in different industries and countries, we managed to derive practice-based knowledge that can be applied across international markets (Balakrishnan & Ramanathan, 2021). Furthermore, using this knowledge, we managed to refine and transform the conceptual AM-SCR framework primarily put forward by Naghshineh and Carvalho (2022a) into a practice-based framework, i.e., AM-SCRP, which can be put to test by practitioners and policymakers. One of the main contributions of the AM-SCRP framework is the specification of various resilience practices that are linked to certain SC capabilities and vulnerabilities based on empirical evidence from the industry. Thus, in the face of impending SC vulnerabilities, the AM-SCRP framework allows practitioners and policymakers to examine and choose the most suitable AM-enabled resilience practices in order to build the necessary SC capabilities. Also, the effectiveness of the chosen AM-enabled resilience practices can be estimated via the AM-SCRP framework. In more specific terms, this practice-based framework helps practitioners and policymakers to consider the different features of AM in order to invest the limited resources of the firm in the most effective AM-enabled resilience practices for improving SCR, while paying attention to the potential barriers that not only inhibit the effects of AM in this regard but also can give rise to different SC vulnerabilities (Naghshineh & Carvalho, 2022b). While there are a handful of broad-based conceptual frameworks in the existing literature (e.g., Ivanov et al., 2019, Spieske & Birkel,

2021) that present a general overview of the impacts of different digital technologies on SCR, to the best of our knowledge, to date, no empirical framework other than the AM-SCRP framework has focused on the potential implications of AM technology adoption for SCR while considering the role of resilience practices in such detail. Hence, we managed to address a big gap in the body of literature regarding "Additive Manufacturing Enabled Supply Chain Management" (Sonar et al., 2022), and in particular its implications for SCR management (Ivanov et al. 2021).

Regarding limitations, we had to limit the number of resilience practices to be able to control the scope of the research. Thus, as explained earlier, after considering their relevance based on the existing empirical AM and SCM literature, we selected nine resilience practices from Carvalho et al. (2022), the metrics of which are also used in the AM-SCR framework by Naghshineh and Carvalho (2022a). This way, we managed to stay in line with the AM-SCR framework since it is the main reference providing the research dimensions (aka coding criteria) for this study. However, future research may extend upon the findings of this study by exploring other potential AM features/barriers, resilience practices, and SC capabilities and vulnerabilities. Moreover, as we aimed to collect the data from experts with first-hand experience in the automotive, aerospace, energy, and medical industries that are at the forefront of AM technology adoption (Wohlers et al., 2021), we made use of expert sampling via the LinkedIn professional network platform, which as a non-probability sampling technique can impose the following limitations. First, researcher bias may have been introduced in the expert selection phase; and second, there may have been experts who were not registered on the LinkedIn platform. Such issues may affect the representativeness of the sample. Therefore, in an attempt to validate the representativeness of the derived sample, we benchmarked its descriptive analyses against the characteristics of the target population available in the report by Wohlers et al. (2021), which as explained earlier showed a high level of similarity. Also, as the sample size (i.e., 60) may not be large enough for performing inferential statistics, instead, we made use of descriptive statistics, for which "nearly any sample size will suffice." (Israel, 1992). Similarly, we performed the qualitative data analysis with no intention of statistical generalizability (Stuart et al., 2002). However, the qualitative techniques that we used (i.e., using a predetermined questionnaire for collecting the data; taking on a certain procedure for coding the collected data; developing a database for keeping track of the data; and comparing the findings with the existing AM and SCM literature) tend to enhance the transferability of the results (Riege, 2003). Nevertheless, as our study is the first to empirically investigate the implications of AM adoption for resilience practices and SCR, instead of generalizing the results, we put forward propositions. Therefore, we recommend future research to test the generalizability of these propositions via extensive surveys with larger sample sizes using inferential statistics methods. Furthermore, we urge future research to conduct single or multiple case studies in order to test and validate the AM-SCRP framework in certain industries with specific AM processes and SC settings, which may lead to conceiving industry-specific variations of the AM-SCRP framework. Last but not least, as AM technology advances and AM adoption barriers are gradually overcome, longitudinal research can help estimate the effectiveness of AM-enabled resilience practices over time.

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Appendix A – Definitions for the SC capabilities and vulnerabilities as well as their subfactors adapted from Pettit et al. (2013)

SC capability	**Definition**	**SC capability subfactor(s)**	**Definition**
Flexibility (in sourcing)	Capability to promptly adjust inputs or the mode of receiving inputs.	Alternate suppliers	Capability to find alternative sources of supply for key inputs, e.g., raw material.
Flexibility (in order fulfillment)	Capability to promptly adjust outputs or the mode of delivering outputs.	Reallocation of production	Capability to promptly reallocate jobs/orders to different production units or among alternative suppliers.
		Production postponement	Capability to postpone production to better respond to demand.
		Inventory management	Capability to efficiently manage inventory (e.g., cycle stock, safety stock) at different SC nodes (e.g., warehouses, distribution centers, retail locations, etc.).
		Alternate distribution channels	Capability to promptly alter modes of transport as well as the routing options for outbound shipments.
Adaptability	Capability to adjust operations to respond to challenges or opportunities.	Lead time reduction	Capability to further reduce lead times.
		Rerouting of requirements	Capability to promptly reallocate jobs/orders to different production facilities or among alternative suppliers.
Dispersion	Capability to widely distribute or decentralize assets.	Distributed capacity	Capability to distribute the production facilities at various locations.
		Dispersion of markets	Capability to sell products to customers in different geographic locations.
Collaboration	Capability to work effectively with other firms for mutual interest.	Collaborative forecasting	Capability to utilize collaborative demand forecasting techniques through information sharing.
		Collaborative information sharing	Capability to transparently share information among SC members to improve collaborative decision making.
		Postponement of orders	Capability to postpone orders when the production capacity is disrupted.
Visibility	Capability to gain knowledge about the SC environment as well as the status of the operating assets.	Information exchange	Capability to regularly exchange information with other SC members, e.g., customers, suppliers, etc.
Efficiency	Capability to generate outputs with minimal resource requirements.	Asset utilization	Capability to efficiently utilize assets to generate outputs.
Market Position	Capability of a firm in maintaining its position in specific markets.	Customer relationships	Capability to maintain strong, long-term relationships with customers.
Anticipation	Capability to detect impending events.	Demand forecasting	Capability to use forecasting methods effectively.
SC vulnerability	**Definition**	**SC vulnerability subfactor(s)**	**Definition**

Turbulence	Recurrent changes in external factors that are beyond the firm’s control.	Unpredictability in customer demand	Erratic customer demand for products.
		Exposure to geopolitical disruptions	Recurrent disruptions in imports/exports because of geopolitical turmoil.
		Unforeseen technology failures	Frequent unforeseen failures in technology that disrupt operations.
Resource limits	Output constraints caused by the unavailability of production factors.	Distribution capacity	Limited capacity for product distribution.
		Production capacity	Limited production capacity.
		Raw material availability	Limited supply of raw materials for production.
		Supplier capacity	Limited supplier capacity.
Connectivity	Degree of interdependence on external entities.	Scale and extent of supply network	The number of members in the SC.
		Reliance upon specialty sources	Dependence on specialty components or materials for production.
		Import/export channels	Access to globally distributed SCs.
		Reliance upon information flow	Dependence on continuous information flow for everyday operations.
		Degree of outsourcing	The extent to which operations are outsourced to external entities.
Deliberate threats	Deliberate misconducts to cause financial/human harm or disrupt operations.	Industrial espionage	Technologies or products being compromised by industrial espionage.
		Piracy and theft	Vandalism and theft of products.
		Terrorism and sabotage	Acts of terrorism or sabotage that target personnel or facilities.
Supplier/Customer disruptions	Vulnerability of customers and suppliers to outside forces or disruptions.	Supplier disruptions	Suppliers frequently facing serious disruptions.
		Customer disruptions	Customers frequently facing serious disruptions.
Sensitivity	Importance of carefully controlled conditions for process and product integrity.	Concentration of capacity	Geographic concentration and/or co-dependence of production facilities or suppliers.
External pressures	Business constraints or barriers caused by external influences, which do not specifically target the firm.	Competitive innovation	Frequent competitive innovations threatening the firm’s product portfolio.

Appendix B – Questionnaire

The implications of additive manufacturing technology adoption for supply chain resilience

This questionnaire aims to explore how the use of additive manufacturing (also known as 3D-printing) affects the ability of the company's supply chain to become more resilient to disruption vulnerabilities. The estimated time to complete this questionnaire is 20 minutes. The identity of the respondents and their companies will be kept confidential. Your contribution will be of great value to the advancement of this research. As a token of appreciation for your time and effort, the results of this research will be shared with you upon its completion. Thank you.

- Respondent's name (optional):
- Name of the company you currently work at (optional):
- Years of experience in the additive manufacturing field:
- Post/job in the company:
- Company's industry sector:
- Country where the company is located:
- Number of employees in the company:
  - ○ 0 < x < 50
  - ○ 50 < x < 250
  - ○ 250 < x

- What is/are the main use(s) of additive manufacturing in the company?
  - ☐ Rapid prototyping
  - ☐ Rapid tooling (e.g., molds, jigs, and fixtures)
  - ☐ Direct part manufacturing
  - ☐ Maintenance and repair
  - ☐ Other:

- What additive manufacturing technology process(es) is/are used by the company?
  - ☐ Powder Bed Fusion
  - ☐ Sheet Lamination
  - ☐ Directed Energy Deposition
  - ☐ Vat Photopolymerization
  - ☐ Material extrusion
  - ☐ Material Jetting
  - ☐ Binder Jetting
  - ☐ Other:

- How do you position the company in the supply chain?
  - ○ 2nd tier Supplier
  - ○ 1st tier Supplier
  - ○ Focal company
  - ○ 1st tier Customer

- ○ 2nd tier Customer
- ○ Other:

- Please indicate to what extent the use of additive manufacturing technology affects the following variables throughout the company's supply chain operations, followed by your explanation for each answer. Please note that 1) signifies Very low effect, 2) Low effect, 3) Moderate effect, 4) High effect, and 5) Very high effect. In case you are not sure, please refrain from answering and write "not sure" in the explanation section.

1. Ease (in terms of cost and time) of changing production schedules.

1	2	3	4	5
○	○	○	○	○

Explanation:

2. Ease (in terms of cost) of reducing delivery lead time.

1	2	3	4	5
○	○	○	○	○

Explanation:

3. Ease (in terms of cost and time) of adjusting production capacity.

1	2	3	4	5
○	○	○	○	○

Explanation:

4. Ease (in terms of cost) of reducing production lead time.

1	2	3	4	5
○	○	○	○	○

Explanation:

5. The degree of cooperation with other companies in the supply chain.

1	2	3	4	5
○	○	○	○	○

Explanation:

6. Ease (in terms of cost and time) of exchanging reliable and timely information with supply chain partners.

1 2 3 4 5
○ ○ ○ ○ ○

Explanation:

7. Number of available alternatives for sources of supply.

1 2 3 4 5
○ ○ ○ ○ ○

Explanation:

8. Number of available alternatives for production sites.

1 2 3 4 5
○ ○ ○ ○ ○

Explanation:

9. Number of available alternatives for transporting goods and materials.

1 2 3 4 5
○ ○ ○ ○ ○

Explanation:

- Please provide an email address below in case you wish to receive the results of the research when it is concluded:

Appendix C – Illustrative examples of how the respondents' explanations were coded and sorted

Respondents' explanations	**Coded AM feature**	**Coded AM barrier**	**Resilience practice**	**Metric**	**Related SC capability (subfactor)**	**Related SC vulnerability (subfactor)**
"**We commonly switch the machines to different products to manage changes in demand**."	Tool-less manufacturing	-	Change the production schedule	Ease (cost and time) of changing the production schedules	Flexibility (Production postponement)	Supplier/Customer Disruptions (Customer disruptions)
"Production planning is relatively easy with 3d printing compared to injection molding or CNC, **but unsteady processes may cause problems.**"	-	Unstable AM processes	Change the production schedule	Ease (cost and time) of changing the production schedules	Flexibility (Production postponement)	Supplier/Customer Disruptions (Customer disruptions)
"**Producing on site** and **on demand means no transportation costs and shorter delivery lead times."**	Distributed manufacturing	-	Reduce delivery lead time	Ease (cost) of reducing delivery lead time	Adaptability (Lead time reduction)	Resource limits (Distribution capacity)
"Lead time is **longer if machining is required.**"	-	Excessive post-processing requirements	Reduce delivery lead time	Ease (cost) of reducing delivery lead time	Adaptability (Lead time reduction)	Turbulence (Unpredictability in customer demand)
"**It is not a problem to adjust production to closely match demand.**"	On-demand manufacturing	-	Use maximum capacity	Ease (cost and time) of adjusting the production capacity	Efficiency (Asset utilization)	Turbulence (Unpredictability in customer demand)
"If machines are dedicated to a particular material but are flexible in processing other materials, **time and labor must be spent to clean out the old material, change machine parameters, run tests, etc. before capacity can be modified using the new desired material**."	-	Lack of multi-material printing	Use maximum capacity	Ease (cost and time) of adjusting the production capacity	Efficiency (Asset utilization)	Turbulence (Unpredictability in customer demand)
"No tooling means **fast production turnaround**."	Rapid manufacturing	-	Reduce response time	Ease (cost) of reducing production lead time	Adaptability (Lead time reduction)	External pressures (Competitive innovation)
"AM may or may not save production time. **It depends on the process,** the materials, postprocessing steps, etc."	-	Unstable AM processes	Reduce response time	Ease (cost) of reducing production lead time	Adaptability (Lead time reduction)	Turbulence (Unforeseen technology failures)

“**We cooperate very frequently and at a high level with** both customers and **suppliers**.”	Close collaboration	-	Supply chain common response	The degree of cooperation with other firms in the supply chain	Collaboration (Postponement of orders)	Supplier/Customer Disruptions (Supplier disruptions)
“Could be higher. **but there are constraints about IP.”**	-	IP rights complications	Supply chain common response	The degree of cooperation with other firms in the supply chain	Market position (Customer relationships)	Turbulence (Unpredictability in customer demand)
“**Since AM is a digital process**, it is amenable and c**ompatible with other digital technologies for sharing information: MES, MRP, ERP, etc.**”	Digital file distribution	-	Align supply chain information systems	Ease (cost and time) of exchanging reliable and timely information with SC partners	Flexibility (Inventory management)	Resource limits (Production capacity)
“We still have to work **on streamlining the information flow between the sites.**”	-	ICT inadequacies	Align supply chain information systems	Ease (cost and time) of exchanging reliable and timely information with SC partners	Visibility (Information exchange)	Connectivity (Reliance upon information flow)
“**Having a backup plant for additional capacity is fairly easy to setup.**”	Capacity pooling	-	Use alternative production sites	Number of available alternatives for production sites	Dispersion (Distributed capacity)	Sensitivity (Concentration of capacity)
"**Harder to invest due to higher infrastructure cost and capital cost**."	-	Lack of specialized production infrastructure	Use alternative production sites	Number of available alternatives for production sites	Flexibility (Reallocation of production)	Resource limits (Production capacity)
“Raw material supply is maturing **but qualification presents a barrier to switching suppliers quickly**.”	-	Lack of AM materials standardization	Use alternative suppliers/multiple sourcing	Number of available alternatives for sources of supply	Flexibility (Alternate suppliers)	Resource limits (Raw material availability)
“**There is a high dependency on a small number of suppliers in the industry**, **which means we are single sourcing materials** and machines. This is something we are working to	-	Limited variety and supply of AM materials	Use alternative suppliers/multiple sourcing	Number of available alternatives for sources of supply	Flexibility (Alternate suppliers)	Connectivity (Reliance upon specialty sources)

change, **as it means high risk of supply.**”						
"Easy to use multiple transportation methods"	Fewer materials and inventory	-	Use alternative transport modes	Transport mode	Flexibility (Alternate distribution channels)	Turbulence (Exposure to geopolitical disruptions)
“**AM can eliminate the transportation of goods and materials since production could theoretically be located as close as possible to the point of use**. AM parts are represented by digital files so inventory can be digital too and production can take place on demand.”	Distributed manufacturing	-	Use alternative transport modes	Transport mode	Flexibility (Alternate distribution channels)	Resource limits (Distribution capacity)

5

Exploring the interrelations between additive manufacturing adoption barriers and supply chain vulnerabilities: The case of an original equipment manufacturer

This chapter consists of the following paper:

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Exploring the interrelations between additive manufacturing adoption barriers and supply chain vulnerabilities: The case of an original equipment manufacturer

Abstract

Purpose – This study aims to explore how certain adoption barriers of additive manufacturing may lead to supply chain vulnerabilities, which in turn would deteriorate the supply chain resilience of the firm that adopts this technology.

Design/methodology/approach – A case study of a leading original equipment manufacturer that uses additive manufacturing to directly produce end-use metal parts for different industries was performed. Primary data were collected using the in-depth interview method complemented by secondary data from internal and publicly available sources. The findings were compared with the existing literature to triangulate the results.

Findings – The findings indicate that certain adoption barriers of additive manufacturing make the supply chain vulnerable to reliance on specialty sources, supplier capacity, production capacity, utilization of restricted materials, importance of product purity, raw material availability, unpredictability in customer demand, reliability of equipment, unforeseen technology failures, reliance on information flow, industrial espionage, and utilities availability.

Originality – This is the first study to empirically examine and identify supply chain vulnerabilities that are caused by the adoption barriers of additive manufacturing technology.

Research limitations/implications – The supply chain resilience outcomes of the identified supply chain vulnerabilities and their interrelated adoption barriers are proposed.

Practical implications – Drawing on the case study findings and the existing literature, relevant practices are put forward in a framework that management can use to mitigate the identified supply chain vulnerabilities caused by the additive manufacturing adoption barriers.

Keywords Additive manufacturing; 3D printing; Adoption barriers; Supply chain vulnerabilities; Supply chain resilience; Mitigation practices; Case study

Paper type Research paper

1. Introduction

Oftentimes supply chains (SCs) are vulnerable to disruptions. One striking example is the COVID-19 pandemic that has led to serious deficits in supply availability throughout the world. In the hope of avoiding the grueling after-effects of such disruptions, active firms and SCs strive to become more resilient, thus requiring supply chain management (SCM) to develop the means necessary to this end. Lately, an innovative technological solution to improving supply chain resilience (SCR) has been the use of additive manufacturing (AM), especially in response to the COVID-19 pandemic (Kunovjanek & Wankmüller, 2020; Spieske & Birkel, 2021). With the growing adoption rate of AM technology, the state and structural dynamics of the contemporary SCs have been subject to changes (Dolgui & Ivanov, 2020; Naghshineh & Carvalho, 2022). However, these changes are not always in favor of the firms adopting this disruptive technology, since they can give rise to different SC vulnerabilities (Naghshineh & Carvalho, 2022).

From an SCM perspective, SC vulnerabilities reduce the ability of the SC to be resilient against disruptions (Kochan et al., 2018; Pettit et al., 2019). Thus, not only it is important to consider the opportunities that the adoption of industry 4.0 technologies such as AM bring about (Ricci et al., 2021), but also to study the risks and vulnerabilities that they can cause (Naghshineh & Carvalho, 2022). Nevertheless, the existing research at the intersection of AM technology adoption and SCM remains mainly focused on investigating the solutions that this technology has to offer and fails to empirically examine the SC vulnerabilities that it can cause. Only recently, Naghshineh and Carvalho (2022) performed a systematic search and review of the extant literature to investigate the implications of AM technology adoption for SCR by drawing on the SC capabilities and vulnerabilities that underlie SCR. Their research indicates that while AM adoption contributes to improving SC capabilities, which are used to deal with SC vulnerabilities, there are also SC vulnerabilities that may arise. They attributed the increase in several of such SC vulnerabilities to certain AM adoption barriers (aka limitations or bottlenecks) and called for empirical research to validate their proposition.

In view of these considerations, in this work, our main objective is to study the case of an original equipment manufacturer (OEM) to understand how the existing barriers to AM adoption can cause SC vulnerabilities, which would consequently deteriorate SCR. Also, we aim to propose the negative SCR outcomes of the identified SC vulnerabilities and their interrelated AM adoption barriers, and by doing so, provide directions for future research. Finally, we draw on our case study findings in conjunction with the existing literature to put forward practices that SCM can use to mitigate the identified AM adoption barriers and their ensuing SC vulnerabilities. Therefore, we will address the following research questions (RQs):

RQ1. How can AM adoption barriers lead to different SC vulnerabilities?

RQ2. How would the SC vulnerabilities caused by AM adoption barriers affect SCR?

RQ3. What are the possible practices for mitigating the SC vulnerabilities caused by AM barriers?

The rest of this paper is organized as follows. In section two, the related theoretical background is presented. In section three, the chosen methodology is elaborated. In section four, the findings of the case study are discussed. In section five, the theoretical and managerial implications are stated. In section six, concluding remarks as well as directions for future research are noted.

2. Theoretical background

AM is an advanced computer technology capable of digitizing SCs (Verboeket & Krikke, 2019), which produces objects in successive layers using special machines (i.e., 3D printers) and 3D digital design data (ISO/ASTM 52900, 2021). The adoption of AM technology for different applications (e.g., end-use parts production, production tooling, rapid prototyping, and spare parts production) in different industries is not only expected to impact the state of the SCs in ways that improve their capabilities, e.g., flexibility in dealing with time and demand risks (Durach et al., 2017; Ivanov et al., 2019), but also in ways that may lead to increased SC risks and vulnerabilities, e.g., supplier capacity (Naghshineh & Carvalho, 2022). In other words, the use of AM technology may cause SC vulnerabilities, which are regarded as factors that reduce SCR, thus exposing the firm and its SC to disruptions (Blackhurst et al., 2011; Pettit et al., 2010, 2019).

Recently, Naghshineh and Carvalho (2022) proposed that certain adoption barriers of AM technology can give rise to different SC vulnerabilities by inhibiting the impacts of AM adoption on the state of the SC and called for empirical research in this regard. Their proposition is corroborated by Stornelli et al. (2021) who posit that the adoption barriers of advanced manufacturing technologies bear potential outcomes. However, after searching the existing literature, we could not find any related research that provides explicit empirical results in this regard. However, we came across different works that have comprehensively considered the existing adoption barriers of AM. For instance, Thomas-Seale et al. (2018) have conducted a thorough case study research in different industries throughout the UK, identifying eighteen different adoption barriers that hinder AM's progress in producing end-use parts. Nevertheless, despite all the research that has been carried out at the intersection of AM and SCM, to date and to the best of our knowledge, there is still no empirical evidence that explains how the present AM adoption barriers can cause SC vulnerabilities. Thus, bearing in mind the importance of AM adoption barriers, we proceeded by using the additive manufacturing-supply chain resilience (AM-SCR) framework put forward by Naghshineh and Carvalho (2022) to guide our case study and compare our findings with the existing literature.

The AM-SCR framework considers the expected inhibiting effects of a wide range of AM adoption barriers and highlights their possible interrelations with a set of conceptually identified SC vulnerabilities, which are originally part of the comprehensive SC vulnerability taxonomy put forward by Pettit et al. (2010, 2013). To date and to the best of our knowledge, the AM-SCR framework is the only framework in the literature that provides a comprehensive theoretical foundation for conducting empirical research at the intersection of AM technology adoption and SCR. Therefore, we found the AM-SCR framework to be a suitable reference for our research as it enabled us to benchmark our case study findings against relevant AM adoption barriers and SC vulnerabilities. It is worth noting that prior to the conception of the AM-SCR framework, Naghshineh and Carvalho (2020) hypothesized the positive impacts of AM technology adoption on SCR and provided a conceptual model. However, much like the rest of the existing research, they did not consider the potential SC vulnerabilities that the adoption of AM technology can cause.

In Figure 1, we have extended upon the conceptual research model by Naghshineh and Carvalho (2022), drawing attention to the potential implications of AM adoption barriers for the SC vulnerabilities. As it can be seen in Figure 1, it is stipulated that AM adoption impacts the state of the SC, which in turn affects the SC capabilities and vulnerabilities that underlie SCR. However, as the focus of this research is on exploring the potential interrelations between AM adoption barriers and SC vulnerabilities, the other variables are greyed out in the model. Also, in line with Naghshineh and Carvalho (2022), the theoretical lens for this research is based on the dynamic capability view (DCV), which is an extension to the resource-based view (RBV) (Teece et al., 1997). While RBV may suffice to justify adopting AM technology as a resource to obtain competitive advantage, it fails to consider the dynamic state of the SC, making it difficult to justify the obtained competitive advantage as sustainable over time, especially in the fast-paced and highly volatile markets of today (Teece et al., 1997; Eisenhardt & Martin, 2000). Therefore, in the context of SCR, where constant volatilities and uncertainties give rise to SC vulnerabilities, DCV serves as an appropriate theoretical lens to look at the subject matter and try to identify relevant mitigation practices (Ponomarov & Holcomb, 2009; El Baz & Ruel, 2021).

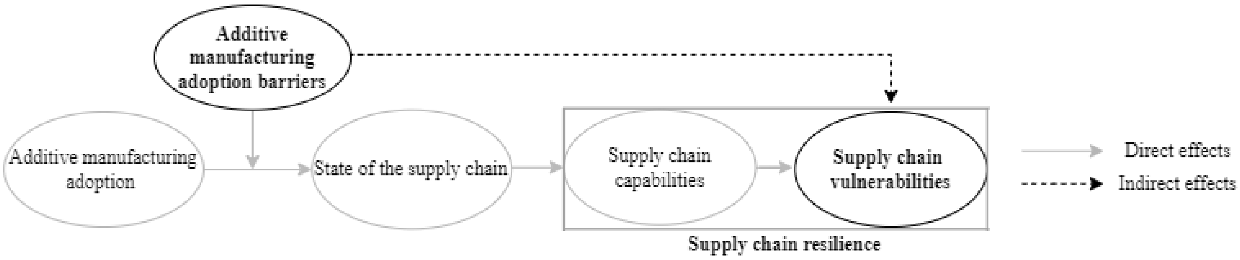

Figure 1. Conceptual research model adapted from Naghshineh and Carvalho (2022)

3. Methodology

Considering the exploratory nature of this research area (i.e., AM technology adoption and its SC implications), case study is often regarded as a suitable research approach (Mellor et al., 2014; Davies et al., 2022). Generally, case studies are suitable for exploratory research in nascent research areas and possess a great potential for uncovering the existing interrelations between different research variables through a real-life context (Yin, 2018). Therefore, similar to successful single case studies performed in this research area by scholars such as Mellor et al. (2014), Chen et al. (2015), Stentoft et al. (2020), and Davies et al. (2022) among others, we also opted for a single case study research approach as it allowed us to gain an in-depth understanding of the subject matter as well as the necessary insights to identify the underlying issues that had not been explored before (Voss et al., 2002; Yin, 2018). According to Chen et al. (2015), a single case study is a suitable approach in this research area, since “this is a complex field with ambivalent results depending on the specific process and conditions”. Moreover, as no prior research had investigated the subject matter before, a single case study was used as a pilot case that can serve as a starting point for future multiple case studies, representing “a significant contribution to knowledge and theory building” (Yin, 2018).

The OEM under study is among the leading firms in Europe that use metal AM to produce high-end thermodynamic equipment, turbomachinery, and fuel delivery systems for various industries such as energy, aerospace, automotive, and motorsport, among others. Recently, metal AM has been expanding at a considerable rate because of its high feature resolution and accuracy as well as the wide range of possibilities that it generates for the manufacture of functional parts (Colosimo et al., 2020), leading to a higher technology readiness level in various industries compared to other AM technologies (Wohlers, 2021). Drawing on its extensive knowledge and experience in design engineering as well as materials development, the OEM under study normally undertakes an end-to-end AM process, which includes the design, prototype, test, and build of final parts. With regard to its SC, the OEM mainly acts as the first-tier supplier of custom-made parts and is in contact with AM materials and machine suppliers as well as customers, exposing it to both upstream and downstream SC activities. In view of these considerations, we found the selected OEM to possess the properties of a suitable representative case for our study (Seuring, 2008; Yin, 2018).

We chose to conduct an in-depth interview as our primary data collection method since it enabled us to gather rich empirical data through an in-depth discussion with the informant to precisely identify the AM adoption barriers and their ensuing SC vulnerabilities at the OEM (Guion et al., 2011; Kahkonen, 2014). At the time of the interview, the informant was in charge of overseeing the AM operations with five years of experience in the field, as well as an academic background at the intersection of AM technology and SCM, making him a suitable key informant for our case study (Yin, 2018). The interview was conducted following a semi-structured format where key questions were preplanned; however, at times follow-up questions were asked to seek clarity and understanding (Guion et al., 2011). The interview was conducted through an online video conferencing platform (due to COVID-19 restrictions) and audio-recorded with the informant's prior consent. We also complemented the interview data with secondary data, using internal as well as publicly available information on the OEM's official website, which included a wide range of archival data about the production processes, products, markets, news reports, and even case studies that the OEM had previously performed.

Afterwards, we analyzed the gathered qualitative data to highlight the key findings (Strauss & Corbin, 1990). In doing so, we used the AM-SCR framework by Naghshineh and Carvalho (2022) that includes a comprehensive list of AM adoption barriers as well as SC vulnerabilities, which were primarily defined by Pettit et al. (2013), so as to code the adoption barriers and their related SC vulnerabilities that emerged from the data analysis. Hence, the AM-SCR framework provided us with the necessary research dimensions (aka coding criteria) to condense the collected data into manageable units (Miles & Huberman, 1994). This in turn helped us to establish clear links between the key findings and the research objective, and subsequently develop an empirical framework (Thomas, 2006).

To improve the quality and rigor of our case study research (Seuring, 2008), we took the necessary measures to ensure construct validity, internal validity, external validity, and reliability (Yin, 2018). To ensure construct validity, we used more than just one source to collect data and made use of secondary data (i.e., data triangulation). Also, subsequent to the interview, we asked the informant to review and confirm the interview report (Miles & Huberman, 1994). Internal validity was established by making sure that the findings were related (Riege, 2003), i.e., understanding the reasons as to why SC vulnerabilities occur due to certain AM adoption barriers and how they are interrelated. External validity was ensured by comparing the findings with extant literature (Riege, 2003; Yin, 2018). Furthermore, to ensure reliability, two researchers were present during the interview to minimize researcher bias (Riege, 2003).

4. Results and discussion

We begin this section by discussing the details of AM at the OEM under study, elaborating on the technology and processes, material type, product characteristics, production policy, reasons and requirements for using AM. We believe that presenting this information is necessary to differentiate our case from the potential future case research. After all, each case is likely to be different in terms of AM specificities and requirements leading to distinctive results. Next, we discuss how certain AM adoption barriers cause SC vulnerabilities at the OEM. Also, we consider the existing literature to compare and highlight our case study findings. The identified SC vulnerabilities and their definitions can be found in Table 1.

Table 1. The identified SC vulnerabilities and their definitions adapted from Pettit et al. (2010, 2013)

SC vulnerabilities	Definitions
Reliance on specialty sources	Dependence on specialty components or materials for production.
Supplier capacity	Limited supplier capacity.
Production capacity	Limited production capacity.
Importance of product purity	High dependence of product quality on the quality of supplies/inputs.
Utilization of restricted materials	Dependence on the use of regulated or restricted materials.
Raw material availability	Limited supply of raw materials for production.
Unpredictability in customer demand	Erratic customer demand for products.
Reliability of equipment	Vulnerability of production equipment to failure.
Unforeseen technology failures	Frequent unforeseen failures in technology that disrupt operations.
Industrial espionage	Technologies or products being compromised by industrial espionage.
Reliance on information flow	Dependence on continuous information flow for everyday operations.
Utilities availability	Limited access to utilities as well as reliable utility infrastructure.

4.1 Additive manufacturing at the original equipment manufacturer

The OEM takes advantage of the powder bed fusion (PBF) technology, which is among the most promising AM technologies for producing metal parts (Thomas-Seale et al., 2018). In PBF processes, thermal energy is used to selectively fuse the feedstock on the build area **(**ASTM International, 2015). The OEM uses two different PBF processes, i.e., selective laser sintering (SLS) and direct metal laser sintering (DMLS), to manufacture intricate end-use parts such as advanced modular heat exchangers, which are later installed in machines and vehicles by the customers. Depending on the application of the final part, the AM material that the OEM uses is either Aluminium or Inconel powder, whereas, according to the informant, some other AM firms use Stainless steel powder. In terms of characteristics, the parts that the OEM produces are rather small-sized, single-material, complex, critical, low-volume, high-demand, and high-cost parts that normally possess long production lead times.

The production policy that the OEM follows is print-to-order, which is synonymous to the make-to-order production policy (Torres et al., 2020). Apart from the fact that some businesses such as motorsport are seasonal, the main reason that the OEM follows a print-to-order policy is that the designs constantly change (even during the projects) due to 1) part design optimization; and 2) building issues, which can be resolved, for instance, by adding/removing supports. Also, the print-to-stock policy is not feasible since it deprives the OEM of production flexibility and spontaneity. However, the informant stated that some firms follow the print-to-stock policy and build many parts to be stored since they do not change their part designs that often.

The main reason that the OEM uses the AM technology for part production is the AM-enabled high level of customization to meet the exact part specifications that customers require, resulting in high performance levels. This is in line with Rogers et al. (2016) and Colosimo et al. (2020), among other authors, who state that AM provides valuable opportunities for customization. There are some alternative solutions via conventional manufacturing (CM) that customers can use, however, they would be outperformed by the OEM's products. Quoting from the informant: "*The main advantage is that you can build exactly what the customer needs with high performance* […] *I would be comparing them* [AM parts] *with the second-best option* [CM]. *So, in this case, outside of AM, you have solutions that can be adapted and applied fairly quickly that are cheaper, but they are often outperformed by our solutions*".

The informant noted that the main requirements for being an AM part producer in their field are (but not limited to): state-of-the-art design as well as information technology (IT) capabilities, e.g., the capability to develop proprietary software for specific solutions in-house; certification of production processes; quality certifications, e.g., quality assurance (QA) and quality control (QC); material management and qualified workers who have experience in handling AM materials mainly due to risk of contamination. Interestingly enough, the lack of many of these requirements is referred to as adoption barriers, limitations or bottlenecks of AM technology throughout the existing literature (e.g., Chekurov et al. 2018; Thomas-Seale et al. 2018; Verboeket & Krikke 2019). For instance, Thomas-Seale et al. (2018) quote from a participant in their case study that "*the majority of the problems associated with AM can be removed or greatly alleviated by informed design for AM*", implying the present lack of AM design capabilities, or Verboeket and Krikke (2019) state that "creating a secure IT infrastructure can be a challenge. Moreover, the IT infrastructure of Original Equipment Manufacturers (OEMs) may currently be unable to support digital spare parts distribution, and upgrading IT may require large investments.", which implies the lack of IT capabilities in many AM SCs.

4.2 Adoption barriers and Supply chain vulnerabilities

The informant believed that apart from product requirements, the main driving factor for the OEM to be deeply invested in SLS and DMLS processes is practicality and convenience due to the long-term ties it has with its supplier of AM machinery and equipment, which specializes in producing PBF 3D printers. In this case, the OEM has become dependent on its machine supplier (Oettmeier & Hofmann, 2016), which is an instance of reliance on specialty sources (Pettit et al., 2013). Moreover, being dependent on the capacity of the machine supplier to deliver the production equipment on time increases exposure to external risks, i.e., higher supply risk in case disruptions take place upstream SC (Ivanov et al., 2019). In such a circumstance, the production capacity of the OEM will also become dependent on the capacity of the supplier to deliver the machines or their spare parts on time as any delay can disrupt the OEM's production operations.

The AM materials that the OEM uses for production are in the form of powder, for which the purity level is a determining quality factor. The powder is prone to contamination (e.g., during transport, oxidation, or even exposure to other materials), which can greatly compromise its purity level, thus negatively affecting the build process and part quality. This high level of sensitivity to powder quality makes the limited traceability of AM materials (or more specifically as Thomas-Seale et al. (2018) phrase it: "difficulties in traceability of powder") a big issue since it can undermine the importance of product purity. Also, it was noted that the lack of regulation and standardization of AM materials makes it very difficult to control the utilization of restricted materials upstream SC. This corroborates the statement by Chan et al. (2018) who claim that "there are difficulties in tracing the origins of source materials".

The availability of AM raw materials is vulnerable to disruptions that either take place upstream SC (external risks), compromising the capacity of the main supplier to deliver on time, or are caused by defaults in the Kanban system of the OEM itself that lead to inaccurate order placements, resulting in stock-outs. In either case, the negative effect of powder shortage on the OEM's performance is a failure to meet the production schedules on time, which may result in lost orders. The SC vulnerability to the availability of raw materials is exacerbated by the limited number of suppliers (Niaki & Nonino, 2017) who can provide the powder according to the quality standards set by the OEM. In case the main supplier fails to deliver on time, the OEM has to source from other suppliers, and as the informant stated, "*the risk is obviously getting lower quality powder*". This instance corroborates the finding by Chekurov et al. (2018) that there is variable quality between different suppliers and shipments of AM materials (i.e., "supplier quality parity"). Thus, in this instance, the OEM's production capacity is also dependent on the capacity of its main qualified powder supplier, which prompts another instance of reliance on specialty materials/components for production. In cases where the OEM has no choice but to source from other suppliers, apart from facing the risk of getting lower-quality powder, normally it has to endure longer delivery lead times that negatively affect its production schedules.

One main disadvantage of AM is the excessive post-processing, which nearly takes up almost 60% of the production lead time at the OEM. All the manufactured parts need to go through the post-processing phase, which considerably adds to the lead time (as well as cost) of production. "*All the parts need to be machined, tested for porosity, leaks and cracks depending on the build material. So, the post-processing actually ends up adding a lot to the lead time of the part, not so much to the building process, so that is a disadvantage*". The informant added, "*AM lags behind the so-called conventional methods, where established and mechanized production processes exist*". Also, one main issue with the post-processing of the parts is the risk of scrap and rework, meaning that the part is prone to defects during the post-processing steps such as machining or heat treatment. For instance, "*if the machining process is not performed as intended, it can ruin a good part*", causing a longer production lead time (as well as higher production costs) since "*the part should be printed from scratch*". Longer production lead times caused by this AM adoption barrier diminish the adaptability (i.e., ability to adjust operations) of the SC to deal with unpredictable customer demands (Naghshineh & Carvalho, 2022).

Another issue that the OEM faces is the present instability in PBF processes. There is a lot of variation in the building process of parts that leads to an approximate failure rate of 40%. In other words, out of every ten additively manufactured parts at the OEM, only about six parts pass the tests, e.g., dimensional inspection, stress relief, etc. The informant asserted that this figure is considerably high and calls for stringent in-process monitoring and certification of production processes. This problem is also mentioned by Colosimo et al. (2020) who look into the quality issues caused by PBF processes. From an SC vulnerability perspective, such instability in AM processes undermines the reliability of equipment (i.e., 3D printers), and may render AM an inefficient means of production.

In addition, the informant emphasized the importance of maintenance to prevent printer malfunction (i.e., unforeseen technology failures). This issue is correlated with the limited long-term usability of AM machines (Durach et al., 2017), which calls for continuous maintenance and upkeep (Meisel et al., 2016). In case there is a printer malfunction or breakdown at the OEM, on-site technicians rectify the issue as fast as possible. In the meantime, the production schedule for that printer is postponed since it has to be shut down until fully repaired. This entails machine downtime that normally leads to longer production lead times and a failure to meet the production schedules on time. Also, at certain points during the build (i.e., printing process), the powder has to be topped up with no possibility for delays. Therefore, the OEM has employed on-site maintenance personnel to ensure close monitoring even during weekends. In case of printer malfunction or breakdown, a solution is to use the external printers that are provided by the OEM's machine supplier (i.e., capacity pooling). However, the informant noted that with the existing variability in AM production processes, building the same design with another printer may lead to inconsistencies in the final part. The issue of "machine-to-machine and part-to-part variation" (Petrick & Simpson, 2013) is a limitation of AM that undermines the importance of product purity and integrity, which can be attributed to the lack of AM process standards (Thomas-Seale et al., 2018).

Moreover, the informant stressed that apart from losing control over the production processes and checks, another implication of outsourcing production is the risk of exposing the design information, which can create IP rights complications (Kunovjanek & Wankmüller, 2020). This situation can create vulnerabilities to industrial espionage since proprietary 3D designs need to be transferred and processed on external printers. Likewise, the freedom to outsource the post-processing steps to external entities is limited because of the need to share critical information. Also, IP rights complications are partly caused by the information and communications technology (ICT) inadequacies in many AM SCs (Chekurov et al., 2018), turning secure information exchange and cyber security into challenging tasks (Durão et al., 2017; Zanoni et al., 2019), especially when continuous information flow is needed for everyday operations (i.e., reliance on information flow).

The issue with AM being an expensive production method was mentioned multiple times during the interview. The informant believed that post-processing is a major driver of cost in AM, considerably adding to the production costs. "*It* [AM] *is very costly when compared to other solutions and one reason for that is the post-processing of the parts*". Other cost factors were also mentioned, e.g., high-quality AM materials (mainly due to their scarcity), high maintenance requirements, and high energy consumption, which are mentioned throughout the literature as well. However, when comparing our study with the existing literature at the intersection of AM and SCM, the cost factors that stand out in our findings are the high production failure rate, machine depreciation, and design costs. The penalty cost caused by the high failure rate in PBF processes is not often mentioned in the AM and SCM literature. We found the work by Colosimo et al. (2020) to be among the few studies evaluating the additional costs incurred by process instability in metal AM.

Regarding machine depreciation, Niaki and Nonino (2017) and Ryan et al. (2017) state that further technological developments are needed to reduce operational costs and increase efficiency. We also noticed that Durach et al. (2017) consider the limited long-term usability of machines as a barrier to the adoption of AM technology, implying a high rate of machine depreciation. Furthermore, product design costs are argued to be reduced through AM. For instance, Weller et al. (2015) state that design freedom as well as reduction in assembly work via AM decrease the design costs. However, higher costs incurred due to the scarcity of design skills, software knowledge, and experience should be considered as well, which can offset the aforementioned cost-saving advantages of AM design. Additionally, the high cost of industrial-grade AM machinery (Baumers et al., 2016) adds to the challenge of sourcing the right equipment (Kunovjanek et al., 2020). With regard to the SC vulnerability implications caused by the high cost of AM technology, limited production capacity can become an issue since scaling up production may no longer be economically feasible (Naghshineh & Carvalho, 2022).

Lastly, the case study findings indicated that due to the high energy consumption of PBF processes during the build process, access to reliable utility infrastructure that can provide abundant energy (e.g., electricity) is necessary. This issue is also brought up in the existing literature. For instance, Chan et al. (2018) report that energy consumption in AM processes can be about one hundred times higher than in CM processes. Under such circumstances, the limited availability of utilities leads to the reduced capacity of the manufacturer to maintain sustained levels of production (Naghshineh and Carvalho, 2022).

5. Research implications

In this section, we reflect on the theoretical implications of our case study research and propose the possible SCR outcomes of the identified SC vulnerabilities and their interrelated AM adoption barriers. As explained earlier, to do this, we make use of the AM-SCR framework by Naghshineh and Carvalho (2022), while considering relevant supporting evidence from other works in the literature. Subsequently, we discuss the managerial implications of our research and put forward an empirical framework that points out potential practices that SCM can utilize to mitigate the identified AM adoption barriers and their ensuing SC vulnerabilities.

5.1 Theoretical implications

As stated earlier, the high dependence of AM firms on machine suppliers creates vulnerability to reliance on specialty sources, which consequently can reduce both the flexibility in sourcing and order fulfilment. For instance, if the supplier decides to lock down some machine parameters (i.e., restrictive practice), it will limit the range of AM materials that the OEM can source and use (Kunovjanek et al., 2020), i.e., reduced sourcing flexibility. This will in turn limit the range of products that the OEM can produce and the markets that it can serve (Mellor, 2014), reducing the OEM's flexibility in order fulfilment as well. In this case, supplier capacity and production capacity are also two other interrelated SC vulnerabilities with reliance on specialty sources that can take place, both of which have similar negative SCR outcomes. Moreover, the limited traceability of AM materials can cause vulnerability to the importance of product purity. Pettit et al. (2013) define the importance of product purity as the high dependence of the product quality on the quality of supplies/inputs, which is linked to flexibility in order fulfilment in the context of AM and SCR (Naghshineh & Carvalho, 2022).

Similarly, another identified SC vulnerability is the utilization of restricted materials due to the lack of regulation and standardization of AM materials (Chekurov et al., 2018). This AM adoption barrier undermines the importance of carefully controlled conditions for process and product integrity (Pettit et al., 2013), reducing the SC's capability to quickly recover from disruptions (Naghshineh & Carvalho, 2022). For instance, according to Kietzmann et al. (2015), in the absence of regulation and standardization, the bioprinting of drugs and vaccines or even food printing can have serious consequences that hamper the ability of the SC to quickly recover from the ensuing disruptions. Additionally, the limited number of qualified AM material suppliers creates vulnerability to raw material availability, supplier capacity, and production capacity shortages as well as reliance on specialty sources, which consequently reduce the flexibility of the AM firms in sourcing and fulfilling orders to a great extent. As Naghshineh and Carvalho (2022) state, "any delay, disruption, or breach of the agreement by the suppliers can result in a shortage of AM input material that can prevent the manufacturers from fulfilling their customers' orders on time". This implication is also supported by Niaki and Nonino (2017) who state that there is a shortage of qualified AM material suppliers, giving them a high negotiating power in the contemporary AM SCs.

With respect to the excessive post-processing requirements, "costly and time-consuming finishing tasks" are currently part of AM (Kunovjanek et al., 2020), which (as stated earlier) prolong production lead times and diminish the SC adaptability. Therefore, the impression that OEMs can utilize AM to swiftly fulfil unpredictable customer demands (Delic & Eyers, 2020) should be carefully reconsidered by bringing into the equation the excessive post-processing steps required. Moreover, the present instability in AM processes undermine the reliability of equipment and may cause capacity shortages (Naghshineh & Carvalho, 2022). According to Pettit et al. (2013), capacity issues arise when there is a lack of reliable assets to enable sustained levels of production. Moreover, the reliability of equipment is correlated with asset utilization, which indicates the efficiency of assets in generating outputs (Pettit et al., 2013). Thus, the present instability in processes may as well render AM an inefficient means of production.

The limited long-term usability of AM machines calls for their continuous maintenance and supervision to avoid machine malfunction and breakdowns that cause downtime (i.e., unforeseen technology failures), negatively affecting the SC adaptability by prolonging production lead times (Naghshineh & Carvalho, 2022). Moreover, if the AM firm decides to temporarily outsource production (until the faulty AM machines/equipment are repaired), the existing machine-to-machine variations due to the current lack of AM process standards undermine the importance of carefully controlled conditions for process and product integrity (Pettit et al., 2013). This can cause problems since the manufactured part may turn out to be erroneous or very different when benchmarked against the part specifications that were primarily required by the customer, negatively affecting the flexibility in order fulfilment (Naghshineh & Carvalho, 2022).

The unceasing concern to protect IP rights (Kurpjuweit et al., 2019; Luomaranta & Martinsuo, 2020) and avoid potential SC vulnerabilities such as industrial espionage negatively affects the possibility to decentralize production and use facilities in different locations (i.e., dispersion) via AM-enabled production methods, e.g., capacity pooling (Naghshineh & Carvalho, 2022). Besides, the present ICT inadequacies in AM SCs exacerbate the problem by causing vulnerability to reliance on information flow, undermining the capability of the firm to effectively collaborate with other firms in the SC, e.g., collaborative information sharing (Pettit et al., 2013; Naghshineh & Lotfi, 2019). This finding complements the idea put forward by scholars such as Berman (2012) and Ford and Despeisse (2016) who posit that information sharing would be facilitated in an AM SC where digital files can be easily distributed throughout the SC. Based on our case study findings, we do not find this idea viable unless adequate means of ICT are in place (Chekurov et al., 2018; Chan et al., 2018).

Limitations regarding production capacity, which are due to the high cost of AM, can negatively affect the financial strength of the firm. This adoption barrier is well-acknowledged in the existing literature. However, not much has been said with respect to its implications for SCR. Moreover, the high energy consumption of AM during the build process necessitates the availability of reliable utility infrastructure, otherwise, the capacity of the firm to maintain sustained levels of production can be compromised (Pettit et al., 2013; Naghshineh & Carvalho, 2022). Similarly, while there are arguments concerning the sustainability aspects of the high energy consumption by AM, e.g., economic sustainability by Sasson and Johnson (2016), environmental sustainability by Ford and Despeisse (2016), and social sustainability by Naghshineh et al. (2021), we could not find evidence in the literature that points out the SCR outcomes of the energy-intensive AM processes.

In view of the foregoing, we put forward the following proposition: SC vulnerabilities caused by AM adoption barriers negatively affect SCR.

5.2 Managerial implications

Drawing on the case study findings and the existing literature, in this section we introduce practices that SCM can utilize to mitigate the identified SC vulnerabilities caused by the AM adoption barriers. The empirical framework in Table 2 contains this information.

We started off by calling attention to the SC vulnerabilities caused by the high dependence on machine suppliers, i.e., reliance on specialty sources, supplier capacity, production capacity. To mitigate these potential SC vulnerabilities, the informant stated that the OEM has built a strong relationship based on trust and close collaboration with its machine supplier over time, which is in line with Dwivedi et al. (2017) and Luomaranta and Martinsuo (2020) who posit that trust and collaboration with partners are key to success in AM SCs. Also, longer-term considerations regarding strategic production plans, e.g., single unit or batch production (Oettmeier and Hofmann, 2016), are important in order to invest in the right equipment and machine suppliers from the start. Currently, the limited traceability of AM materials makes it difficult to ensure material quality (Thomas-Seale et al., 2018), which negatively affects the importance of product purity. For instance, in the case of the OEM under study, if the powder's purity level (which is an indicator of quality) is compromised, it will undermine the build process as well as the quality of the manufactured part. Moreover, in the absence of regulation and standardization to govern the production of AM materials (Chekurov et al., 2018), the utilization of restricted materials becomes an SC vulnerability. To tackle these issues, the OEM sources high-quality powder from a trusted supplier. However, as there are not many suppliers alike, the OEM closely collaborates with its main powder supplier to mitigate the potential SC vulnerabilities, i.e., raw material availability, supplier capacity, production capacity, and reliance on special sources.

With respect to solutions geared toward reducing excessive post-processing requirements, the OEM regularly optimizes the part designs, and by doing so, not only it reduces the need for excessive post-processing but also the risk of scrap and rework, which can be caused by possible defaults in the post-processing tasks such as machining or heat treatment, adding to the cost of production as well as lead times. Design optimization is mainly mentioned throughout the existing literature with respect to enhancing part functionality and performance (Weller et al., 2015). Comparably, reducing post-processing requirements through design optimization can be regarded as enhancing the parts production process. Therefore, by investing in its AM design capabilities and skills, the OEM partly offsets the negative effects of excessive post-processing requirements. As for the present instability in AM processes that undermines the reliability of equipment, the informant's assertion (as stated earlier) corroborates the findings of Thomas-Seale et al. (2018) and Verboeket and Krikke (2019) among others, who state that the lack of in-process monitoring as well as the lack of certification of production processes are barriers that impede the successful deployment of AM. Furthermore, considering the limited long-term usability of 3D printers (Durach et al., 2017) and the need for their close monitoring, management should bear in mind the importance of maintenance for keeping the AM machinery operational (Meisel et al., 2016). Despite the conviction that hiring on-site personnel for round the clock maintenance adds to the production costs (Niaki & Nonino, 2017) and may be financially inconvenient, it significantly helps to avoid frequent unforeseen technology failures that disrupt the AM firms' operations. In regard to the lack of AM process standards that affect the importance of product purity, QA and QC measures are implemented by the OEM to deal with this barrier.

To protect its IP rights and avoid vulnerabilities such as industrial espionage (Kurpjuweit et al., 2019; Kunovjanek & Wankmüller, 2020), the OEM refrains from outsourcing the production and post-processing tasks as much as possible. Therefore, it has obtained the necessary resources and know-how to perform the post-processing tasks in-house (i.e., insourcing). Moreover, the OEM has invested in developing its IT capabilities and personnel. For instance, it has managed to develop its proprietary design software in-house and become less reliant on exchanging information with external sources. The OEM has taken this measure to better protect its IP rights and avoid complications caused by ICT inadequacies (Chekurov et al., 2018). However, as the informant stated, "*the downside to this practice is letting go of many potential opportunities for information sharing with others*". Later, we discussed the high cost of AM technology due to different cost factors that can lead to limited production capacity. To contain the aforementioned costs, the OEM mainly specializes in manufacturing high-end parts and uses specific selection criteria to prioritize the production of parts that yield relatively high-profit margins. We found this practice to be in line with Knofius et al. (2016) and Oettmeier and Hofmann (2016) who recommend developing methods and selection criteria for the production of AM parts. Finally, utilities availability due to the high energy consumption of AM (mainly during the build process) was identified as an SC vulnerability. Thus, ensuring access to reliable utility infrastructure before proceeding with AM acquisition and implementation is important. The informant mentioned that the OEM had paid close attention to having access to reliable utility infrastructure before establishing its manufacturing plant in the region.

Table 2. Empirical framework outlining the case study findings

AM adoption barriers	**SC vulnerabilities**	**SCR outcomes**	**Mitigation practices**
High dependence on AM machine suppliers	Reliance on specialty sources	Reduced flexibility (in sourcing and order fulfilment)	Close collaboration with SC partners Source from trusted suppliers
	Supplier capacity		
	Production capacity		
Limited traceability of AM materials	Importance of product purity	Reduced flexibility (in order fulfilment)	Source from trusted suppliers
Lack of regulation and standardization of AM materials	Utilization of restricted materials	Reduced recovery	
Limited number of qualified AM material suppliers	Raw material availability	Reduced flexibility (in sourcing and order fulfilment)	Close collaboration with SC partners
	Supplier capacity		
	Production capacity		
	Reliance on specialty sources		
Excessive post-processing requirements	Unpredictability in customer demand	Reduced adaptability	Design optimization
Instability in AM processes	Reliability of equipment	Reduced capacity	In-process monitoring Certification of the production processes
		Reduced efficiency	
Limited long-term usability of AM machines	Unforeseen technology failures	Reduced adaptability	Continuous maintenance and supervision
Lack of AM process standards	Importance of product purity	Reduced flexibility (in order fulfilment)	QA/QC certifications
IP rights complications	Industrial espionage	Reduced dispersion	Insourcing
ICT inadequacies	Reliance on information flow	Reduced collaboration	Developing IT capabilities
High cost of AM	Production capacity	Reduced financial strength	Developing methods and selection criteria for producing AM parts
High energy consumption during the build process	Utilities availability	Reduced capacity	Ensuring access to reliable utility infrastructure

6. Conclusions

In this research, our main objective was to understand how the present barriers to the adoption of AM technology can cause SC vulnerabilities, which would consequently deteriorate SCR. Therefore, we chose to study the case of an OEM who specializes in manufacturing high-end metal parts for various industries using two PBF processes, i.e., SLS and DMLS. Throughout the case study, we identified twelve different AM adoption barriers that would give rise to twelve distinct SC vulnerabilities. Subsequently, using the case study findings in conjunction with the AM-SCR framework put forward by

Naghshineh and Carvalho (2022) and relevant supporting evidence from the literature, we elaborated on the theoretical implications of our research and proposed the potential SCR outcomes of the identified SC vulnerabilities and their interrelated AM adoption barriers. In doing so, we provided a research agenda for scholars who may be interested in investigating this understudied research topic further. Finally, we discussed the managerial implications of the research and suggested possible mitigation practices (see Table 2).

Our research, like many others, faces some limitations. Besides validating the generalizability of the results, we recommend multiple case studies to consider different industries and AM processes for the manufacture of parts that possess similar or different characteristics, and in doing so, consolidate and extend upon the results of our single case study. Moreover, other SC vulnerabilities and their possible interrelations with AM adoption barriers may be discovered. Last but not least, there is room for improvement with respect to the mitigation practices. Future research may focus on developing the proposed practices in this study or even come up with a new set of practices and strategies that SCM can use to mitigate the SC vulnerabilities caused by AM adoption barriers. All in all, apart from considering the SC vulnerabilities that AM helps to mitigate, future research may as well consider the potential SC vulnerabilities that can be caused by the adoption barriers of this technology. This should facilitate the firm’s decision-making process regarding AM technology adoption and help overcome potential SC vulnerabilities.

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6

CONCLUSION

6.1 Thesis overview

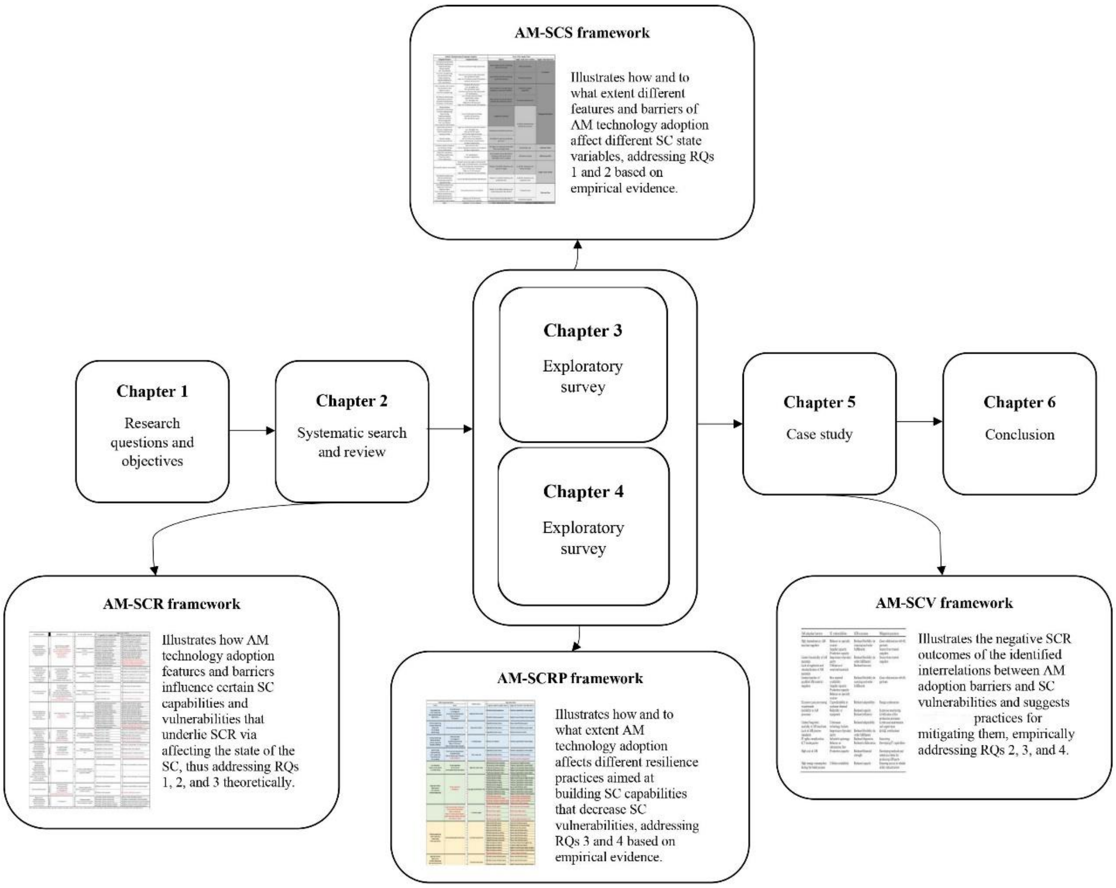
In this study, we drew on the DCV as our theoretical lens, aiming to contribute to the state of the art by understanding and conceptualizing how the adoption of AM technology affects the state of the SC, which would consequently influence the SC capabilities and vulnerabilities that underlie SCR (i.e., RG1). We also made it our goal to empirically explore the affected SC state variables representing the state of the SC (i.e., RG2), as well as resilience practices in the context of AM technology adoption that would help build the necessary SC capabilities required to deal with SC vulnerabilities, thus enhancing SCR (i.e., RG3). To this end, we commenced our research by a systematic search and critical review of the existing literature, hence putting forward relevant propositions and developing a comprehensive conceptual framework (i.e., AM-SCR, Chapter 2, Figure 6). The propositions together with the conceptual framework outline how different features and barriers of AM technology adoption affect different SC state variables that represent the state of the SC. The representative SC state variables in the AM-SCR framework are each linked to different SC capabilities, which in turn are linked to relevant SC vulnerabilities. Hence, this framework conceptually illustrates how AM technology adoption influences certain SC capabilities and vulnerabilities that underlie SCR by affecting the state of the SC, which is aligned with RG1.

Subsequently, we performed an exploratory survey research aimed at collecting both quantitative and qualitative data from companies involved in industries at the forefront of AM technology adoption. Drawing on the collected empirical data, we managed to put forward relevant propositions and derive two empirical frameworks at this stage:

- The propositions and first empirical framework (i.e., AM-SCS, Figure 2) in Chapter 3 suggest how and to what extent certain features and barriers of AM technology adoption affect different SC state variables that represent the state of the SC, which serve to accomplish RG2.
- The propositions and second empirical framework (i.e., AM-SCRP, Figure 4) in Chapter 4 suggest how and to what extent AM technology adoption affects different resilience practices

aimed at building SC capabilities that decrease SC vulnerabilities and improve SCR, which serve to accomplish RG3.

Lastly, a case study was performed to identify potential interrelations between AM adoption barriers and SC vulnerabilities that deteriorate SCR. Given the findings of the case study in Chapter 5, an empirical framework (i.e., AM-SCV, Table 2) was then put forward that illustrates the negative SCR outcomes of the identified interrelations between AM adoption barriers and SC vulnerabilities and suggests practices for counteracting them. This framework is also in line with RG3 as it serves to propose different practices that can be used to mitigate SC vulnerabilities and therefore enhance SCR. Figure 1 illustrates the summary overview of the thesis.



Illustrates how and to what extent different features and barriers of AM technology adoption affect different SC state variables, addressing RQs 1 and 2 based on empirical evidence.

Illustrates how AM technology adoption features and barriers influence certain SC capabilities and vulnerabilities that underlie SCR via affecting the state of the SC, thus addressing RQs 1, 2, and 3 theoretically.

Illustrates how and to what extent AM technology adoption affects different resilience practices aimed at building SC capabilities that decrease SC vulnerabilities, addressing RQs 3 and 4 based on empirical evidence.

Illustrates the negative SCR outcomes of the identified interrelations between AM adoption barriers and SC vulnerabilities and suggests practices for mitigating them, empirically addressing RQs 2, 3, and 4.

Figure 1. Thesis overview

6.2 Main results

Given RQ1. *"How does AM technology adoption affect the state of the SC?*", the findings suggest that overall AM technology adoption enhances the state of the SC. This finding is primarily backed up by empirical evidence indicating that AM adoption enhances all the SC state variables (with the exception of "available alternatives for sources of supply"). Among the SC state variables, "production schedule adaptability" is shown to be enhanced the most. Such enhancing effect on this SC state variable is attributed to different AM adoption features such as the use of "fewer materials and inventory" in the SC, "fast production setup", use of "digital inventory", and "tool-less manufacturing". The only contradictory instance where adopting AM technology is likely to have a limiting effect on the state of the SC is related to the SC state variable "available alternatives for sources of supply". Based on the data analysis of the empirical data in Chapter 3, the overall extent to which AM technology adoption affects the state of the SC is estimated as "Moderate". However, this effect is expected to increase as AM adoption barriers disappear. Nonetheless, the results indicate that AM adoption affects each SC state variable to a different extent.

Considering RQ2. "*Which barriers inhibit the effects of AM technology adoption on the state of the SC*?" multiple barriers were identified throughout the study. Among the identified AM adoption barriers, some seem to be more commonplace than others, which inhibit the effects of AM technology adoption on different SC state variables. For instance, as noted in the AM-SCS framework (Figure 2 in Chapter 3), "Excessive post-processing requirements" commonly appears to inhibit the highly affected SC state variables "Delivery lead time", "Production lead time", and "Production schedule adaptability". Another interesting observation is that some of the identified AM adoption barriers not only inhibit the direct effects of AM technology adoption on different SC state variables, but also can give rise to different SC vulnerabilities, which appear in color red in the AM-SCR and AM-SCRP frameworks. This is especially true in the case of the SC state variable "available alternatives for sources of supply" where the limiting effect of AM technology adoption is reinforced by the "Limited variety and supply of AM materials", "High cost of AM materials" and the "Lack of AM material standardization. In this instance, not only the sourcing flexibility would deteriorate but also the production capacity of the manufacturing firm would be compromised due to potential cases of material shortage.

Given RQ3. "*How does AM technology adoption influence different SC capabilities and SC vulnerabilities that underlie SCR*?", it was noted throughout the study that generally AM adoption provides opportunities to improve different SC capabilities, which are necessary to mitigate different SC vulnerabilities, thus improving SCR against disruption vulnerabilities. Among these SC capabilities, "Flexibility" and "Adaptability" are affected the most. While in most cases the expected effect on these SC capabilities is positive, in few instances AM adoption can lead to their deterioration, mainly due to certain adoption barriers. For instance (as noted in the previous paragraph), the sourcing flexibility of the SC can deteriorate mainly due to the adoption barriers concerning AM materials; or SC adaptability may be compromised due to the present instability in AM processes, i.e., "Unstable AM processes". In the same vein, SC "Collaboration" and "Visibility" can be undermined due to "IP rights complications" as well as “ICT inadequacies”. Relevantly, we also managed to identify the existing interrelations between certain AM technology adoption barriers and SC vulnerabilities based on an empirical study. More specifically, we conducted a case study of a leading OEM located in Europe, which uses AM technology to produce high-end metal parts for different industries, in order to understand how certain barriers of AM technology adoption may give rise to different SC vulnerabilities, and how these SC vulnerabilities, in turn, would negatively affect SCR. Hence, we managed to identify twelve different AM adoption barriers that give rise to twelve distinct SC vulnerabilities as noted in the AM-SCV framework in Chapter 5. Subsequently, practices were suggested for mitigating these SC vulnerabilities.

Lastly, to address RQ4. “*What resilience practices enhance SCR in the context of AM technology adoption*?”, we analyzed the gathered empirical survey data to understand how and to what extent AM adoption affects different resilience practices, in turn affecting the SC capabilities and vulnerabilities that underlie SCR. The results indicate that AM technology adoption affects each resilience practice to a different extent due to different AM adoption features and barriers. The most effective AM-enabled resilience practices are “Change the production schedules”, “Reduce delivery lead time”, “Reduce response time”, and “Use maximum capacity”, which would positively affect the SC capabilities necessary to deal with SC vulnerabilities. For instance, in the case of “Change the production schedule”, this AM-enabled resilience practice would enhance the flexibility of the SC in customer order fulfilment, mainly due to the possibility to postpone the production schedules, thus allowing the SC to cope with the unpredictability in customer demand and mitigate SC turbulence. Overall, the findings suggest that AM adoption considerably affects the SC capabilities “Flexibility” and “Adaptability” via different AM-enabled resilience practices. These results made it possible to derive the AM-SCR*P* framework in Chapter 4. Furthermore, in our case study in Chapter 5, we managed to identify several practices that can be used to mitigate the potential SC vulnerabilities that may be caused by the adoption barriers of AM technology. These practices serve to enhance the resilience of the SC by mitigating multiple SC vulnerabilities.

6.3 Main contributions

We performed multiple exploratory studies to understand how adopting AM technology affects the state of the SC as well as different resilience practices, thus influencing the antecedent SC capabilities and vulnerabilities that underlie the concept of SCR. The use of the SC state variables played an important role in making it possible to employ a dynamic perspective and relate the effects of AM technology adoption to the SC capabilities and vulnerabilities while considering the changes that take place in the state of the SC. Subsequently, we put forward propositions that reflect the theoretical implications of this research.

Given the lack of empirical research at the intersection of AM technology adoption and SCR (Ali & Gölgeci, 2019), by putting forward a set of propositions throughout Chapters 3 and 4 that are backed up by empirical evidence, we managed to provide a comprehensive research agenda for future research to further investigate the subject matter. Hence, from a theoretical standpoint, by performing this multimethod research following an exploratory approach, we managed to address an important gap in the body of literature concerning this nascent subject area. Besides, we managed to put forward four frameworks, laying out the foundation for future research that intend to further look into the implications of AM technology adoption for SCR.

From a practical standpoint, there are managerial takeaways to note. Given that currently there are a limited number of sources that can provide AM materials following stringent quality standards, it is important that SC managers and decision-makers carefully consider the supply availability of the necessary AM materials, as well as their cost and quality standards, before committing to substantial AM technology adoption investments. Considerations regarding the use of restricted materials are also crucial since the traceability of AM materials is currently limited and until widely accepted standards are in place, caution should be exercised when sourcing AM materials to avoid potential disruptions that can take away from the resilience of the SC. While AM technology is a useful resource that SCM can adopt in order to enable different resilience practices and build SC capabilities to counteract SC vulnerabilities and promote SCR, it can also give rise to certain SC vulnerabilities, most of which are interrelated with certain AM adoption barriers. Therefore, potential interrelations between AM adoption barriers and SC vulnerabilities should be traced and controlled to avoid negative SCR outcomes. Considering that most of the identified AM adoption barriers in this study are technological, their inhibiting effects are expected to diminish as the technology advances. However, at the moment, such barriers should be carefully considered before proceeding with AM technology adoption to avoid causing SC vulnerabilities, and as a consequence deteriorate the resilience of the SC. Moreover, the proposed mitigation practices in this study can be utilized to counteract the potential negative SCR outcomes of AM adoption barriers and their interrelated SC vulnerabilities.

6.4 Limitations and future work

This study, like many others, faces some limitations that present opportunities for future research. Considering the lack of empirical evidence regarding the subject matter due to its novelty, in this study, we chose to employ an exploratory research approach. Therefore, we urge future research to take on different approaches towards validating the generalizability of the findings. We needed to limit the number of the SC state variables and resilience practices so that we could control the scope of the study, and therefore future research may choose to examine the effects of AM technology adoption on other possible SC state variables and resilience practices. Also, future research can examine the importance of the SC state variables within certain types of SCs and assign relative weights to them accordingly, which may yield different estimations of the effects of AM adoption on the state of the SC.

Some SC capabilities (e.g., financial strength) were not considered in this study due to the absence of adequate supporting evidence for their inclusion. Hence, we recommend future research to look into such SC capabilities in the context of AM technology adoption and SCR management. In order to achieve comprehensive results regarding the subject matter, we considered different types of AM processes and applications, as well as various types of SCs and industries where AM technology is adopted. Hence, future research may carry out surveys and case studies that target specific AM processes and applications in specific types of SCs and industries to compare and validate the findings of this study. Particularly, we urge case studies aimed at validating the proposed frameworks under such specific conditions.

Since we aimed to collect data mainly from experts with first-hand experience in the automotive, aerospace, energy, and medical industries that are at the forefront of AM technology adoption (Wohlers et al., 2021), we made use of expert sampling via the LinkedIn professional network platform, which as a non-probability sampling technique can impose some limitations such as researcher bias in the expert selection phase or the exclusion of experts that are not registered on the LinkedIn platform. Such issues may affect the representativeness of the sample. Nevertheless, as our study is the first to empirically investigate the implications of AM adoption for SCR and resilience practices, instead of claiming the generalizing of its results, we put forward testable propositions. Therefore, we recommend future research to test the generalizability of these propositions via case studies or extensive surveys with larger sample sizes using inferential statistics methods.

Last but not least, longitudinal research may be performed to examine the veracity of the findings over time as AM technology advances and its adoption barriers gradually disappear. Relevantly, sensitivity analysis can help determine the extent to which the specified AM adoption barriers may intensify the SC vulnerabilities and deteriorate SCR.

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UNIVERSIDADE NOVA DE LISBOA

THE IMPLICATIONS OF ADDITIVE MANUFACTURING TECHNOLOGY ADOPTION FOR SUPPLY CHAIN RESILIENCE

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2023