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

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Figure 1 – Conceptual research model.drawio	

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

- The supply chain (SC) vulnerabilities caused by additive manufacturing technology adoption are identified.
- The SC resilience outcomes of the identified SC vulnerabilities are proposed.
- Practices for mitigating the identified SC vulnerabilities are suggested.
- An empirical framework is put forward that outlines the findings of the study.

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 cause 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 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 supply chain 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 and Wankmüller, 2020; Spieske and 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 and Ivanov, 2020; Naghshineh and 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 and 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 and 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 adoption 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 and 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 and 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 capabilities 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 and 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 and Holcomb, 2009; El Baz and Ruel, 2021).

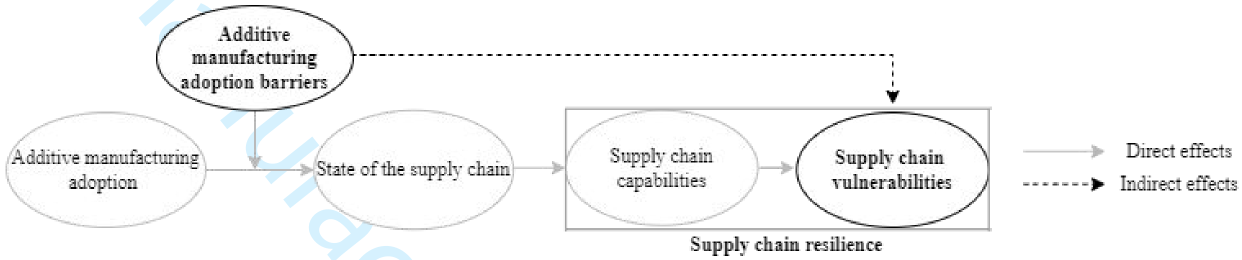

Figure 1 – Conceptual research model adapted from Naghshineh and Carvalho (2022)

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 and 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 and 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 and 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 I.

>> Insert Table I <<

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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and Carvalho, 2022).

The unceasing concern to protect IP rights (Kurpjuweit *et al*., 2019; Luomaranta and 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 and 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 and 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 and 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 II 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 and 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 and 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.

>> Insert Table II <<

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 II).

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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Table I – 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.

Table II – 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 Supplier capacity Production capacity	Reduced flexibility (in sourcing and order fulfilment)	• Close collaboration with SC partners • Source from trusted suppliers
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 Supplier capacity Production capacity Reliance on specialty sources	Reduced flexibility (in sourcing and order fulfilment)	• Close collaboration with SC partners
Excessive post-processing requirements	Unpredictability in customer demand	Reduced adaptability	• Design optimization
Instability in AM processes	Reliability of equipment	Reduced capacity Reduced efficiency	• In-process monitoring • Certification of the production processes
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

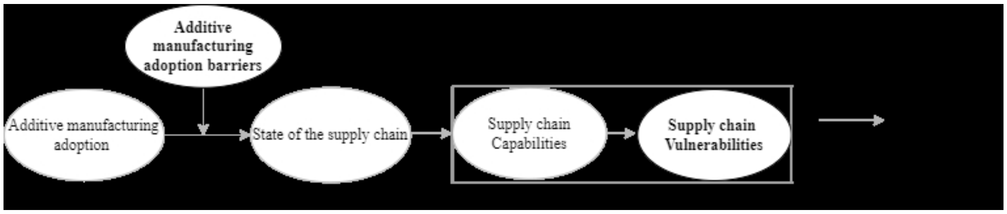

Figure 1 – Conceptual research model

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