Master's thesis

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Additive Manufacturing Adoption for Supply Chain Resilience: An Empirical Investigation

Master's thesis in Global Manufacturing Management
Supervisor: Mirco Peron
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Preface

The global business environment is becoming increasingly complex and unpredictable, with supply chain disruptions posing a major threat to organizations' operations and profitability. In recent years, additive manufacturing, also known as 3D printing, has emerged as a promising technology for enhancing supply chain resilience by providing a more flexible and adaptable manufacturing process. However, the empirical evidence on the impact of additive manufacturing on supply chain resilience is limited, and the factors that influence the adoption and implementation of this technology in the supply chain context are not well understood.

The research presented in this report is based on the conviction that additive manufacturing can play a crucial role in enhancing supply chain resilience, particularly in the face of increasing supply chain disruptions and risks. By providing a more flexible and adaptable manufacturing process, additive manufacturing can help organizations mitigate the risks associated with supply chain disruptions and build a more resilient supply chain.

I hope that this thesis will provide a valuable contribution to the literature on additive manufacturing and supply chain resilience and will stimulate further research and discussion on this important topic.

This report is a master's thesis in Production Management as part of the Global Manufacturing Management study program, at Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology. The study was conducted in the spring semester of 2023.

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Abstract

Supply chain disruptions are a major concern for organizations, as they can lead to delays, increased costs, and lost revenue. Additive manufacturing, also known as 3D printing, has emerged as a promising technology for enhancing supply chain resilience by providing a more flexible and adaptable manufacturing process. This technology can act as an important tool in mitigating disruptions in the supply chain. However, the empirical evidence on the impact of additive manufacturing on supply chain resilience is limited.

This thesis presents an empirical investigation of the use of additive manufacturing for supply chain resilience. The study involved a Delphi study methodology, including a questionnaire sent to a panel of experts in industry from organizations that have implemented additive manufacturing in their supply chain. The study gathered expert opinion on the adoption of additive manufacturing, the perceived benefits and challenges of additive manufacturing for supply chain resilience, and the factors that influence the adoption of additive manufacturing.

The results provided insights into the current challenges and opportunities of adopting additive manufacturing in supply chains, as well as possible countermeasures that could be exploited to overcome the identified challenges. The findings of the study suggest that additive manufacturing can enhance supply chain resilience by enabling faster time-to-market, reduced lead times, improved customization, reduced waste, and increased supply chain flexibility. However, the successful implementation of additive manufacturing in the supply chain requires careful consideration of the challenges and opportunities presented by this technology, as well as the development of a strategic approach that takes into account the unique characteristics of the organization and its supply chain.

The study also identified several factors that influence the adoption of additive manufacturing, including the availability of skilled personnel, the availability of materials, the suitability of additive manufacturing for specific applications, and the level of collaboration and communication among stakeholders in the supply chain. Overall, the findings of this study provide important insights into the use of additive manufacturing for enhancing supply chain resilience. The study contributes to the academic literature on additive manufacturing and supply chain resilience and provides practical guidance for organizations that are considering the adoption of additive manufacturing in their supply chain.

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List of Abbreviations

AM: Additive Manufacturing

AM-SCR: Additive Manufacturing-Supply Chain Resilience

CM: Conventional Manufacturing

CODP: Customer Order Decoupling Point

COVID-19: Coronavirus disease

PPE: Personal Protective Equipment

R & D: Research and Development

SC: Supply Chain(s)

SCM: Supply Chain Management

SCR: Supply Chain Resilience

SCRAM: Supply Chain Resilience Assessment and Management

1. Introduction

This chapter presents the background for this master thesis, and the problem that justifies this research area. Next, the research scope and objectives are defined to guide the research process. Lastly the research questions in this thesis are presented and argued for.

1.1 Background

Supply chain disruptions are generally viewed as the combination of unintended and unexpected events that occur upstream in the supply network, in the inbound logistics network, in the sourcing environment or further downstream that have consequences which threaten the normal business operations of the focal organization (Messina, et al., 2020; Bode & Macdonald, 2017). Supply chains (SC) almost always turn out to be vulnerable to disruptions. A good example of such disruption is the recent outbreak of the COVID-19 pandemic that caused consequential reductions in the supply and availability of products spanning different industries on a global scale. Other examples of supply chain disruptions are natural disasters, transportation failure and delays like the crisis at the Suez Canal in 2021, price fluctuations, legal contract disputes, epidemics and pandemics, political crises, and cyber-attacks, all of which make the supply chain more vulnerable and at risk to severe consequences (Ivanov, 2021).

Supply chain risks are broadly defined as any chance for the possibility and effect of a mismatch between supply and demand (Christopher, et al., 2003). These risks potentially could disrupt the information, material and product flows from suppliers to the end user in the supply chain. Risk sources in the supply chain could be operational or supply chain related activities that have impactful consequences on supply chain outcome variables like cost and quality (Christopher, et al., 2003).

Operational risks are described as supply-demand coordinated events which may result from inadequate processes, people or systems; thus, they are more controllable than disruption risks (Shekarian & Parast, 2021). Disruption risks are defined as unplanned events that restrict a company’s supply chain system (Shekarian & Parast, 2021). Supply chain disruption risks arise from the vulnerabilities of the interconnected flow of materials and information between inter-company networks since all companies are dependent somewhat on external sources and supply chain relationships (Bode & Macdonald, 2017). Disruption risks may also result from; supply chain complexity due to increased globalization and outsourcing, disruptions at a supply base due to increased specialization and geographical concentration of manufacturing, which imply that a disruption at one or more points will affect almost all the points and links in the supply chain (Ivanov, 2021). These potential shortcomings drive supply chains to be more resilient to disruptions taking into account that most contemporary supply chains operate globally which makes them even more vulnerable to several disruptions (Naghshineh & Carvalho, 2021)

Supply chain risk and disruption management aims to identify the potential sources of risk and implement appropriate actions to avoid or contain supply chain vulnerability. This could be done by identifying organizational capabilities such a flexibility, agility, collaboration and redundant strategies that make a firm more resilient to supply chain disruptions (Shekarian & Parast, 2021). Supply chain resilience has received more attention over the last decade and has become very necessary for companies in ensuring stability and dealing with unexpected disruptions. Supply chain resilience is defined by (Hohenstein, et al., 2015) as the supply chain’s ability to be prepared for unexpected risk occurrence, respond to and recover quickly from potential disruptions, return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance. Supply chain resilience aims to reduce the impact of disruptions by identifying strategies which allow a supply chain to react to a disruption while recovering to its original functioning state or better (Shekarian & Parast, 2021). The concept of supply chain vulnerabilities and capabilities as constructs of supply chain resilience was introduced by (Pettit, et al., 2011) as an approach in risk management to enable a supply chain to categorize and survive unexpected disruptions.

Supply chain capabilities are therefore defined as attributes that enable an organization anticipate and overcome disruptions (Pettit, et al., 2011), while supply chain vulnerabilities are defined as fundamental risk sources which outweigh risk mitigating strategies that make an organization susceptible to disruptions and adverse supply chain consequences (Pettit, et al., 2011; Christopher, et al., 2003). A way to enhance supply chain capabilities is the adoption of innovative technologies like additive manufacturing which impacts the state and dynamics of the supply chain by influencing its capacity to be resilient to disruptions (Naghshineh & Carvalho, 2021). However, it must be said that the adoption of additive manufacturing also causes certain vulnerabilities which weaken the resilience of the supply chain.

Additive manufacturing (AM) also known as 3D printing, rapid manufacturing, rapid prototyping, or digital manufacturing is an innovative technology that enables the fast production of complex geometries and near-net shape components, its name stems from the fact that it builds a component, part or product from raw materials layer by layer, additively (Zijm, et al., 2019). This technology has become more popular and is adopted in supply chains because of its potential to reduce inventory holding costs and allow on-demand production of customized products within a short time. Additive manufacturing technology emerged as a mitigation tool to effectively mitigate disruptions caused by the COVID-19 pandemic that affected supply chains. The role of additive manufacturing in the medical industry during the pandemic was to stop the shortage of medical devices and personal protective equipment. In the aftermath of the pandemic, companies, groups and individuals started to cooperate to supply people and hospitals that were facing items shortage (Longhitano, et al., 2021). One of the main reasons that medical device supply chains became resilient after this major disruption was the ability of 3D printers to rapidly produce specialized medical devices that complied with regulatory standards.

In addition to medical supply chains, additive manufacturing has also been adopted for use in electronic and automotive spare parts supply chains. In the spare parts supply chain, the adoption of additive manufacturing attempts to reduce operating costs and keep customer's satisfaction at an acceptable level by enabling suppliers to overcome the unpredictability of demand and make key decisions regarding trade-offs between operating cost, inventory level and delivery time (Li, et al., 2017).

1.2 Research problem

Additive manufacturing has emerged as a tool widely adopted in many supply chains since it can lead to a series of benefits such as lead time reduction in production, minimization of inventory, efficient utilization of capacity and customer-centric production; all of which contribute to resilience in the supply chain (Naghshineh & Carvalho, 2021). Despite these benefits, there exists some drawbacks as well such as capacity limits which could threaten normal operations and weaken resilience in the supply chain. The publication by (Naghshineh & Carvalho, 2021) addresses how the adoption of AM influences the state and dynamics of the supply chain and makes the supply chain more resilient. However, there is limited empirical evidence in existing literature on how the adoption of additive manufacturing improves resilience in industrial practice.

Therefore, there is a need for an empirical investigation on how additive manufacturing impacts supply chain resilience in an industrial context, by validating propositions made in academic research.

1.3 Research questions and objectives

The primary objective of this thesis is to investigate how additive manufacturing impacts supply chain resilience as seen in industrial practice. To achieve this, a Delphi study was planned. A Delphi study is structured as an iterative questionnaire process, that stops when a consensus is reached (usually in 3 rounds). This method aims at achieving a consensus from a panel of experts of industrial backgrounds in this research field. The study will result in an overview of the current challenges and opportunities of adopting additive manufacturing in supply chains, as well as the possible countermeasures that could be exploited to overcome the identified challenges. To attain the above research objectives, this thesis will focus on answering the following research questions:

RQ 1: How relevant is the adoption of additive manufacturing in enhancing supply chain resilience?

RQ 2: How relevant are the adoption impacts of additive manufacturing on supply chain capabilities?

RQ 3: How relevant are the adoption impacts of additive manufacturing on supply chain vulnerabilities?

1.4 Research scope

The scope of this thesis is confined to industrial practitioners that adopt additive manufacturing in their operations and supply chain. These practitioners have adopted additive manufacturing in their respective organizations but may not fully pay attention to the resulting impacts of adopting the technology and how these impacts affect resilience in their supply chains.

To obtain empirical evidence on how the adoption of additive manufacturing impacts supply chain resilience, the below research areas will be studied critically to provide a basis for the investigation:

- Supply Chain Capabilities
- Supply Chain Vulnerabilities

The complete development of this research originates from the specialization project conducted at NTNU in the autumn semester of 2022. The propositions generated in the specialization project serve as part of the theoretical background for this study.

1.5 Thesis outline

This thesis consists of five chapters. Its content is briefly presented in the table below.

Chapter	Content
Chapter 1 Introduction	This chapter provides an overview of the research topic, highlights the significance of additive manufacturing (AM) for supply chain resilience, and outlines the research objectives and structure of the thesis.
Chapter 2 Theory	This chapter explores the relevant theoretical concepts and frameworks related to supply chain resilience and AM. The chapter concludes with a set of key propositions that will be important for the Delphi study.
Chapter 3 Methodology	This chapter describes the research methodology employed in the study, which includes a Delphi study approach involving industrial experts. It outlines the selection and recruitment process of the participants, the data collection methods, and the steps taken to ensure the validity and reliability of the findings.
Chapter 4 Results and discussion	This chapter presents the findings of the Delphi study and provides a detailed analysis and interpretation of the results. It examines the impact of AM on supply chain resilience, capabilities, and vulnerabilities, drawing insights from the expert opinions and discussions. The chapter also explores the identified challenges and proposes countermeasures based on a literature review.
Chapter 5 Conclusion	This chapter summarizes the key findings of the study. It discusses the implications of the research findings for both theory and practice, highlights the contributions of the study, and provides recommendations for future research. The chapter concludes by emphasizing the importance of AM adoption for enhancing supply chain resilience and outlines the potential areas for further exploration in this field.

Table 1: Outline of the master thesis

2. Theoretical background

This chapter provides the theoretical framework for this study. This chapter is divided into three parts; supply chain capabilities, supply chain vulnerabilities, and the chapter ends with a summary of propositions which form the basis of the investigation later in this study.

2.1 Supply chain capabilities

This section gives insight on how the adoption of additive manufacturing affects supply chain capabilities and impacts resilience. The findings from research on SC capabilities show that the adoption of additive manufacturing in the supply chain will lead to more on-demand manufacturing, more flexibility/postponement of orders, increased collaboration between partners in the supply chain and improved transparency. A common discovery in the research is the reduction of production and delivery lead times by the adoption of additive manufacturing which improves a firm's relationship with its customers. Future research on the use of additive manufacturing in enhancing supply chain capabilities can be on how AM adoption affects procurement practices and logistics multisourcing.

2.1.1 Adaptability

Adaptability is the capability of a firm to adjust operations to respond to challenges or opportunities (Naghshineh & Carvalho, 2021). In the medical and automotive spare parts supply chains, customer satisfaction is highly dependent on lead times, therefore the adoption of additive manufacturing enables shorter lead times in production, sourcing and delivery of the final product to the customer (Ivanov, et al., 2019, Sabarish, et al., 2021). However, supply chains are exposed to external risks if a disruption happens in the upstream SC since there is no intermediate inventory in between the stages because of AM's capability to eliminate inventory. The need to optimize manufacturing operations leads to the adoption of additive manufacturing as a technology due to AM's functionality in rapidly creating complex parts, and this enables the production of components in a make-to-order strategy (de Brito, Filipe M, et al., 2019).

Proposition: AM adoption positively affects adaptability since short lead times and the possibility to reallocate production enables the supply chain to quickly respond to disruptions.

2.1.2 Capacity

This capability indicates how producers can gain access to additional equipment, material, or labour, to promptly increase outputs if necessary (Naghshineh & Carvalho, 2021). The adoption of additive manufacturing increases the innovation and R & D capacity of a firm (Magnani, et al., 2022). In addition to this, AM reduces on-hand inventory upstream in the supply chain and creates a supply pool by aggregating downstream demand, upscaling production to satisfy demand when need be and avoiding excess capacity (McDermott, et al., 2021). Additive manufacturing equipment can be added to a firm's production system to provide emergency cover for machine failures. This enables the achievement of capacity flexibility and lead time reduction in such events (Ryan, et al., 2017).

Proposition: AM adoption positively affects capacity since AM enables redundancy in production and facilitates production scalability by providing a buffer to address volatile demand.

2.1.3 Collaboration

This capability indicates how effectively a firm works with other firms i.e., in the same supply chain for mutual benefit (Naghshineh & Carvalho, 2021). The adoption of additive manufacturing technology increases the need for close collaboration between the suppliers of the machines and material, and the manufacturers of the product/components, because the materials and machines for AM need to be compatible with each other to achieve optimal outcomes (Oettmeier & Hofmann, 2016). As a result of the COVID-19 pandemic, data and information sharing rapidly increased between companies and individuals due to the increased demand for medical devices and items. AM emerged as an important tool during the COVID-19 pandemic in supplying medical items because companies and individuals that own a 3D printer could easily access 3D printable files from open-design platforms and quickly produce parts (Longhitano, et al., 2021).

The integration of AM technology with sensors, data integration, predictive analysis, innovation, vertical and horizontal collaboration can develop capabilities which will benefit the supply chain by ensuring a simplified supply chain and on-time production of high-quality products at a reasonable cost (Belhadi, et al., 2022). Collaborative design challenges the boundaries between firms and customers. The use of data in collaboration enables greater specification of value propositions and pushes the power shift further towards consumers. The use of AM and enhanced information flows in the supply chain will lower inventory and quicken customer response (Christopher & Ryals, 2014).

Proposition: AM adoption positively affects collaboration since AM facilitates order postponement, collaborative information sharing and collaborative demand forecasting.

2.1.4 Dispersion

This capability indicates how effectively a firm can distribute production assets in different geographical locations and sell products to customers in those locations. The adoption of additive manufacturing can provide an alternative to production facilities by enabling distributed ways of manufacturing and allow manufacturers have access to geographically dispersed facilities which aids in quickly rerouting manufacturing capacity requirements in case of disruptions (Naghshineh & Carvalho, 2021). The adoption of AM leads to distributed manufacturing which allows a decentralized supply chain strategy to be implemented and this moves the finished products nearer to the different points of sale (Sisca, et al., 2016). Distributed manufacturing improves responsiveness in the supply chain by shorter repair times, shorter time to market, faster product availability and reduced transportation costs. However, in contrast to centralized manufacturing, distributed manufacturing locations may have limitations in economies of scope in terms of equipment utilization, raw material purchasing, and (Verboeket, et al., 2021).

Proposition: AM adoption positively affects dispersion since AM enhances the possibility to distribute capacity in multiple locations, also facilitating the dispersion of markets.

2.1.5 Efficiency

This is the capability to generate outputs with minimal resource requirements (Naghshineh & Carvalho, 2021). Additive manufacturing adoption can increase production efficiency because it can reduce the number of obsolete products and minimize manufacturing waste by using less raw materials during production and simplified production operations. AM adoption also improves internal operational performance measures like production complexity, production flexibility, lean manufacturing and logistics efficiency (Franco, et al., 2020). Additive manufacturing uses a limited and specific type of input materials for production, this also makes materials requirement planning more efficient. AM adoption can improve the structural flexibility of a supply chain by asset sharing i.e., sharing of capacity, materials, machines and labour by different partners in the supply chain. AM technology limits the number and type of materials required to build products.

Therefore, this can facilitate asset sharing in terms of both capacity and inventory. (Mashhadi, et al., 2015).

Proposition: AM adoption positively affects efficiency since AM allows minimum raw material consumption, capacity sharing, production of complex products in an easy way, tool-less manufacturing approach, reduced labour need, on-demand manufacturing, and the extension of the product's life cycle via in situ remanufacturing.

2.1.6 Flexibility in order fulfilment

This is the capability to promptly adjust outputs or the mode of delivering outputs. It includes reallocation of production, production postponement, logistics multisourcing, inventory management and having alternate distribution channels (Naghshineh & Carvalho, 2021). The adoption of AM can enable manufacturing firms to be flexible in responding to changes in customer requests that may come in the form of increasing, decreasing, cancelling, or changing the timing of orders. This flexibility can be achieved due to the unique characteristics of AM such as lack of tooling, on-demand production and freedom of geometry (Alogla, et al., 2021). The adoption of AM in production can support very high degrees of postponement which enables firms to potentially become proactive in predicting production difficulties. This means that it is possible for firms to postpone product differentiation until a customer order is received (Delic & Eyers, 2020). AM’s flexibility to produce on demand means that parts can be produced as required rather than hold inventories of stock in anticipation of future demand (Eyers, et al., 2018). This would lead to effective management of inventories and reduction of the associated costs. Distributed manufacturing as an outcome of AM also leads to improved flexibility in job order fulfilment (Sisca, et al., 2016). Having multiple production facilities that adopt AM increases flexibility in meeting erratic customer demands.

Proposition: AM adoption positively affects flexibility in order fulfilment since AM facilitates on-demand production, order postponement and rerouting of production capacity to different facilities.

2.1.7 Flexibility in sourcing

This is the capability to promptly adjust inputs or the mode of receiving inputs by engaging multiple suppliers for sourcing and having multiple methods for production (Naghshineh & Carvalho, 2021). The adoption of AM allows for alternate sourcing of required components, overcoming sourcing issues in the supply chain. For example, in the medical industry, ventilator components used in hospitals like valves, tubing connectors and adapters can be replaced with 3D printed alternatives when necessary (Narayan, et al., 2022). Moreover, sourcing from two or several suppliers instead of one would enable the focal firm to reduce its ordering costs (Tang & Tomlin, 2008). However, it must be said that there exists a limited availability of suppliers and materials for production using AM. The adoption of AM also enables suppliers to quickly introduce new products into the market by allowing the suppliers operate at different level of production volume and variety (Delic & Eyers, 2020). Additionally, as sourcing large quantities of products of components with AM may be costly, a firm can configure its sourcing process differently by using "AM insourcing" by maintaining its own AM capabilities, such as machines and raw material (Meyer, et al., 2021).

Proposition: AM adoption negatively affects flexibility in sourcing due to limited availability of substitute suppliers and limited raw materials for production.

2.1.8 Market position

This capability indicates how well a firm can maintain its position in specific markets and maintain strong long-term relationships with customers. Additive manufacturing features like make to order production, customer-centric production, co-creation/co-design, and production postponement allow manufacturers closely collaborate with customers enabling them to effectively deal with the unpredictability in customer demands. These AM features strengthen customer relationships and gives manufacturers a strong market position by allowing them deal quickly with erratic customer demands (Naghshineh & Carvalho, 2021). When adopted in supply chains, AM can enable increased interaction between a firm and its customers and form new partnerships in customizing products. Additive manufacturing has the potential to impact networking activities of suppliers by influencing the relative power distribution along the supply chain (Hannibal, 2020). Since the present potential of AM lies in quick customization of tailor-made products that match the customers specifications, quick inspection of finished products and fast implementation of change requests will maintain good relations between suppliers, firms and customers.

Proposition: AM adoption positively affects market position since AM features like co-design and customer-focused production allow close collaboration with customers which improve customer relationships.

2.1.9 Recovery

Recovery enables a production system or supply chain to quickly return to the normal state of operations after being disrupted (Naghshineh & Carvalho, 2021). Most firms believe that they have a highly resilient supply chain, but the resilience of a supply chain cannot fully be measured unless it has faced disruptions, recovered from disruptions and then developed preventive measures against disruptions. Additive Manufacturing plays a crucial role in making the supply chain more resilient and less vulnerable to disruption by reducing the recovery time of the supply chain to a significant level. The adoption of AM technology in a spare parts supply chain for example helps build a rigid system that would help a firm survive unexpected disruptions in parts unavailability (Muthukumarasamy, et al., 2018).

Proposition: AM adoption positively affects recovery since AM facilitates outsourcing of production in the event of capacity or distribution shortages, breakdown of production equipment and geopolitical crisis.

2.1.10 Visibility

Visibility provides firms information about the supply chain environment as well as the status of operating assets (Naghshineh & Carvalho, 2021). These assets may include inventories, demand, and supply conditions, as well as production and purchasing schedules (Christopher & Peck, 2004). The adoption of AM will improve information sharing between the supply chain partners which will ultimately make inventory management more efficient, make the supply chain more transparent, make collaborative forecasting easier and enable the supply chain partners anticipate customer demand better (Naghshineh & Carvalho, 2021).

Proposition: AM adoption positively affects visibility due to the reliability on ICT systems by partners in the supply chain, this promotes information sharing across the SC and enables the supply chain better anticipate customer demands.

2.1.11 Discussion on capabilities

The findings on supply chain capabilities reveal that the adoption of additive manufacturing has some positive and negative impacts on supply chain performance. Using additive manufacturing, a firm can adapt operations in times of disruptions to have even shorter production lead times in responding to erratic customer demands. In achieving shorter production lead times, facilities can be decentralized and located close to the customer in various geographical locations.

Decentralization will lead to increased collaboration and transparency between the different partners in the supply chain. From the literature, additive manufacturing is said to also enhance flexibility in the supply chain which can have an influence on the recovery of the supply chain from disruptions. In choosing to adopt additive manufacturing in production operations, managers and firms must decide which capability best fits their supply chain needs to adequately handle disruptions.

2.2 Supply chain vulnerabilities

This section gives insight on how the adoption of AM reduces vulnerabilities in the supply chain. The findings from research on SC vulnerabilities point that the adoption of additive manufacturing in the SC will lead to more complex and vulnerable information systems, although the number of suppliers may be reduced. Issues like use of sensitive materials for AM which may lead to material shortage also pose a threat to the supply chain.

A general theme in the research on vulnerabilities is that although the introduction of additive manufacturing in the supply chain makes the SC less vulnerable to unpredictable customer demands, it also makes the SC vulnerable to cyber-attacks that can cause catastrophic effects. Future research on the use of AM technology in addressing supply chain vulnerabilities can be on how AM adoption affects customer disruptions, distribution networks and how secure IT platforms can be established in the supply chain with the introduction of AM.

2.2.1 Connectivity

This vulnerability refers to the degree of interdependence of a firm or supply chain on external entities or partners (Naghshineh & Carvalho, 2021). Increased vulnerabilities in the SC arise from the complexity of interconnected systems and complex information flows. The adoption of AM enables companies transition towards an on-demand supply chain, this significantly reduces the number of suppliers that must be consolidated for production (Ivanov, et al., 2019), hereby reducing complexity of information exchange, thus making the supply chain less vulnerable to disruption risks and more in control of production (Rahman, et al., 2021). However, having fewer suppliers in the SC might increase vulnerability to disruptions like the COVID-19 pandemic and global material shortage required for AM for example.

Proposition: AM adoption positively affects connectivity since AM facilitates an increase in the degree of outsourcing of production to external entities due to the digital nature of AM technology.

However, there is a negative impact since the high reliance upon information flow can create connectivity issues when adequate ICT infrastructures are missing. Similarly, the limited number of suppliers of raw materials increased the reliance upon specialty sources.

2.2.2 Deliberate threats

This vulnerability refers to deliberate attacks that can cause financial harm or disrupt operations. With the adoption of AM in supply chains, there will be increased information sharing between the SC partners, however IT may not be as reliable and this creates cybersecurity threats and knowledge leaks that may cause industrial espionage (Naghshineh & Carvalho, 2021). The types of attacks (Gupta, et al., 2020) that could make the SC vulnerable are: Printer hardware attacks by malware, raw material attacks which can cause shipment delay, and design-file attacks by IP theft or file corruption (Gupta, et al., 2020). Therefore, secure IT requirements need to be in place before proceeding with information sharing and exchange in the SC.

Proposition: AM adoption positively affects resilience to deliberate threats since AM facilitates the dispersion of capacity to multiple facilities (redundancy in production). However, there is also a negative impact since the high level of information exchange exposes SC to industrial espionage.

2.2.3 Resource limits

This refers to output constraints caused by the unavailability of production factors like production capacity, supplier capacity and raw material availability. Additive manufacturing enables the possibility to outsource production processes to external entities which facilitates the quick reallocation of production and rerouting of requirements in case of distribution or production capacity shortages (Naghshineh & Carvalho, 2021). In the spare parts supply chain, AM can increase the availability of spare parts and change the supply chain configuration by moving closer to user locations (Xu, et al., 2021). Sourcing with the use of an adaptable AM supply chain is also beneficial for small demand quantity of products like medical supplies under high supply risks (Glas, et al., 2022). However, the fact that AM requires a secondary supply chain for raw material and machine procurement gives the supply chain its own vulnerability to the associated risks (Parikh, et al., 2018).

Proposition: AM adoption negatively affects resource limits due to its reliance on very few suppliers in the supply chain, causing an exposure to raw material and supplier unavailability.

2.2.4 Sensitivity

This vulnerability refers to the reliance of manufacturing on carefully controlled conditions for product and process integrity. AM adoption increases the susceptibility to problems concerning the reliability of equipment, utilization of scarce materials and product purity as AM processes become more standardized (Naghshineh & Carvalho, 2021). Therefore, supply chains are vulnerable in this context, especially humanitarian aid supply chains, as 3D printers are not usually mobile and tough enough to operate in many different environments (Lipsky, et al., 2019). Specifications like portability, durability, and ability to print off-grid must be addressed in the context of additive manufacturing in supply chains.

Proposition: AM adoption negatively affects sensitivity due to problems on the reliability of equipment and utilization of limited materials, as well as the importance of their purity.

2.2.5 Supplier-customer disruptions

This refers to the vulnerability of customers and suppliers to disruptions which in turn can make the entire supply chain vulnerable. The adoption of additive manufacturing in a production setting as well as the use of collaborative information sharing and exchange among the partners in the supply chain will enable the SC partners better anticipate customer and supplier disruptions (Naghshineh & Carvalho, 2021). However, the introduction of AM to a supply chain may disrupt several supply chain roles. Machinery and raw material producers in traditional manufacturing processes become wiped out as manufacturing becomes internalised and localised by the introduction of AM, hence sub-suppliers and manufacturing tools for traditional production gradually become obsolete (Öberg, 2021). This suggests how suppliers and other partners in a conventional manufacturing SC become vulnerable by the introduction of AM.

Proposition: AM adoption positively affects supplier-customer disruptions thanks to the possibility to reallocate production, distribute capacity and potential to reroute requirements.

2.2.6 Turbulence

Turbulence refers to reoccurring changes in external factors that are beyond the focal firm's control (Naghshineh & Carvalho, 2021). In the manufacturing and distribution processes, supply chain vulnerability appears from product diversity, repeated changes in demand, shorter product life cycles, complex global distribution markets and logistics network relationships (Wu, et al., 2020). Due to its high degree of production flexibility, additive manufacturing shortens delivery times of products in times of uncertain demand and meet diverse product needs through customer-focused manufacturing (Ivanov, et al., 2019).

Proposition: AM adoption positively affects turbulence since AM facilitates lead time reduction and distributing capacity to different locations which promote the recovery of the supply chain from disruptions like unsteady customer demands and geopolitical upsets.

2.2.7 Discussion on vulnerabilities

The findings on supply chain vulnerabilities show that the adoption of additive manufacturing will highlight more complexities in the supply chain concerning materials and information systems. The use of additive manufacturing in dealing with turbulent supplier/customer disruptions will allow for reduction in production lead times and postponement of orders, but challenges lie with the reliability of AM processes on scarce materials and with the security of AM files in the supply network. In adopting additive manufacturing to prepare for and respond to disruptions, practitioners must ensure that potential issues with materials and cybersecurity are resolved in the first instance.

The adoption of AM for supply chain resilience also comes with some barriers which affect vulnerabilities in the supply chain. Examples of such barriers are high dependence on AM machine suppliers, lack of regulation and standardization of AM materials and a lack of AM process standards; all of which affect vulnerability subfactors like connectivity and sensitivity (Naghshineh & Carvalho, 2022). The correlation between AM adoption barriers, supply chain vulnerabilities and supply chain resilience are shown in the figure below.

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 fulfillment)	Close collaboration with SC partners Source from trusted suppliers
Limited traceability of AM materials	Importance of product purity	Reduced flexibility (in order fulfillment)	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 fulfillment)	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 fulfillment)	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: AM adoption barriers and SCR (Naghshineh & Carvalho, 2022)

2.3 Propositions

The propositions outlined in the table below form the basis for the questionnaire used in the Delphi study for this research.

Capability sub-factor	Proposition
Adaptability	AM adoption positively affects adaptability since short lead times and the possibility to reallocate production enables the supply chain to quickly respond to disruptions.
Capacity	AM adoption positively affects capacity since AM enables redundancy in production and facilitates production scalability by providing a buffer to address volatile demand.
Collaboration	AM adoption positively affects collaboration since AM facilitates order postponement, collaborative information sharing and collaborative demand forecasting.
Dispersion	AM adoption positively affects dispersion since AM enhances the possibility to distribute capacity in multiple locations, also facilitating the dispersion of markets.
Efficiency	AM adoption positively affects efficiency since AM allows minimum raw material consumption, capacity sharing, production of complex products in an easy way, tool-less manufacturing approach, reduced labour need, on-demand manufacturing, and the extension of the product's life cycle via in situ remanufacturing.
Flexibility in order fulfilment	AM adoption positively affects flexibility in order fulfilment since AM facilitates on-demand production, order postponement and rerouting of production capacity to different facilities.
Flexibility in sourcing	AM adoption negatively affects flexibility in sourcing due to limited availability of substitute suppliers and limited raw materials for production.
Market position	AM adoption positively affects market position since AM features like co-design and customer-focused production allow close collaboration with customers which improve customer relationships.
Recovery	AM adoption positively affects recovery since AM facilitates outsourcing of production in the event of capacity or distribution shortages, breakdown of production equipment and geopolitical crisis.
Visibility	AM adoption positively affects visibility due to the reliability on ICT systems by partners in the supply chain, this promotes information sharing across the SC and enables the supply chain better anticipate customer demands.

Vulnerability sub-factor	Proposition
Connectivity	AM adoption positively affects connectivity since AM facilitates an increase in the degree of outsourcing of production to external entities due to the digital nature of AM technology. However, there is a negative impact since the high reliance upon information flow can create

	connectivity issues when adequate ICT infrastructures are missing. Similarly, the limited number of suppliers of raw materials increased the reliance upon specialty sources.
Deliberate threats	AM adoption positively affects resilience to deliberate threats since AM facilitates the dispersion of capacity to multiple facilities (redundancy in production). However, there is also a negative impact since the high level of information exchange exposes SC to industrial espionage.
Resource limits	AM adoption negatively affects resource limits due to its reliance on very few suppliers in the supply chain, causing an exposure to raw material and supplier unavailability.
Sensitivity	AM adoption negatively affects sensitivity due to problems on the reliability of equipment and utilization of limited materials, as well as the importance of their purity.
Supplier-customer disruptions	AM adoption positively affects supplier-customer disruptions thanks to the possibility to reallocate production, distribute capacity and potential to reroute requirements.
Turbulence	AM adoption positively affects turbulence since AM facilitates lead time reduction and distributing capacity to different locations which promote the recovery of the supply chain from disruptions like unsteady customer demands and geopolitical upsets.

Table 2: Propositions

These propositions highlight the opportunities that additive manufacturing (AM) presents for supply chains in terms of enhancing capabilities and mitigating vulnerabilities. By leveraging the capabilities of AM such as adaptability and flexibility, supply chains can enhance their ability to withstand disruptions and effectively meet customer demands. However, it is essential to address the vulnerabilities associated with connectivity and, resource limits. By understanding these opportunities and challenges of AM, and implementing appropriate strategies and countermeasures, supply chains can fully leverage the benefits of AM while mitigating potential risks, thus achieving a resilient and competitive position in the marketplace.

3. Methodology

The Delphi study methodology comprises of a multi-stage procedure that focuses on the systematic collection, consolidation and analysis of multiple expert opinions pertaining to the field of study (Gordon & Helmer, 1964). It was developed in the 1950s by the RAND corporation to support the decision-making process by forecasting the development of strategic decisions and technology use in war. Since then, it has been further developed and refined across several scientific disciplines (Meyer, et al., 2022). A Delphi study has multiple fields for application and methods of execution including the use of a formal questionnaire, interview of experts, anonymous participant answers, determination of a statistical group answer, communication of the group answer to each participant, and several iterations of the survey (Häder & Häder, 2000).

For this thesis, a Delphi study methodology was chosen to achieve a consensus from a panel of experts from several industrial backgrounds that adopt the use of additive manufacturing in their respective production operations. The Delphi Study is structured as an iterative questionnaire process, that stops when the consensus is reached (in 3 rounds). The process of study preparation, expert selection, study execution, group feedback and evaluation (Wolf, 2017) will be discussed in the following sections.

3.1 Delphi study preparation and expert selection

The Delphi study was conducted from March to June 2023. In the preliminary stage, propositions regarding supply chain capabilities and vulnerabilities (Pettit, et al., 2011) developed from previous research were identified and developed into a questionnaire. The propositions include the perspectives from the publication by (Naghshineh & Carvalho, 2021) to obtain further inputs on the adoption impacts of additive manufacturing on supply chain resilience. A summary of the propositions is shown in table 2, and a full overview is given in the appendix of this report. The formulation of the propositions was carefully done as their overall quality and comprehensibility impacts the quality of the outcome immensely (Mićić, 2007). To ensure methodological rigor and to achieve precision in formulation, the propositions were checked for ambiguity by two senior researchers familiar with additive manufacturing and supply chain resilience. Finally, the propositions were implemented as sets of questionnaires in google forms.

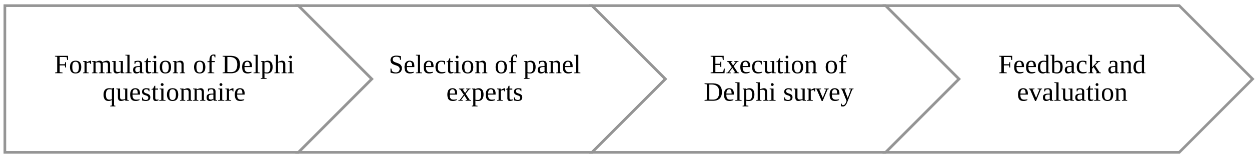

Figure 2: Delphi study steps

Next, the panel of experts were composed by identifying, evaluating, and selecting relevant experts in the field. The panel size was determined to be a minimum of five due to the research scope, desired panel heterogeneity and the availability of experts in this research field (Loo, 2002). The selection criteria for the expert group of participants were those with profound expertise in additive manufacturing and supply chains in combination with operations management expertise. Thus, different stakeholders from industry and academia, also from diverse nationalities were included. Potential experts were identified by database search, a networking approach, and search in professional social networks (such as LinkedIn). The experts needed to be both capable of delivering suitable evaluations and to be interested in the results of the study, otherwise the experts may have lacked the motivation to reconsider their own evaluations. After the screening process, a total of 35 potential experts were invited to participate via email. Six individuals participated in the first round of the study, and the number reduced to five in the second and third rounds. Table 3 shows the heterogenous distribution among different industries and hierarchies.

Sector	Roles	Experience (Years)	Gender	Geographic Location
Electronics manufacturing	Supply chain manager	12	Male (5)	Norway (4)
Academia	Researcher	2	Female (1)	United Kingdom (1)
Aerospace manufacturing	Production manager	6		Europe (1)
Space research and technology	Technical purchaser	3		
Consumer products	Chief engineer	3		
	Material planner	1		

Table 3: Distribution of experts

3.2 Execution of Delphi survey

For this Delphi survey, the collection of inputs from the participants was done using google forms. All the inputs needed were obtained in three rounds of questionnaires. The first round was guided by a questionnaire on evaluating agreements with projections (propositions developed from the literature review) on supply chain vulnerabilities and capabilities, the second and third rounds guided by remaining projections from the previous rounds to obtain a consensus.

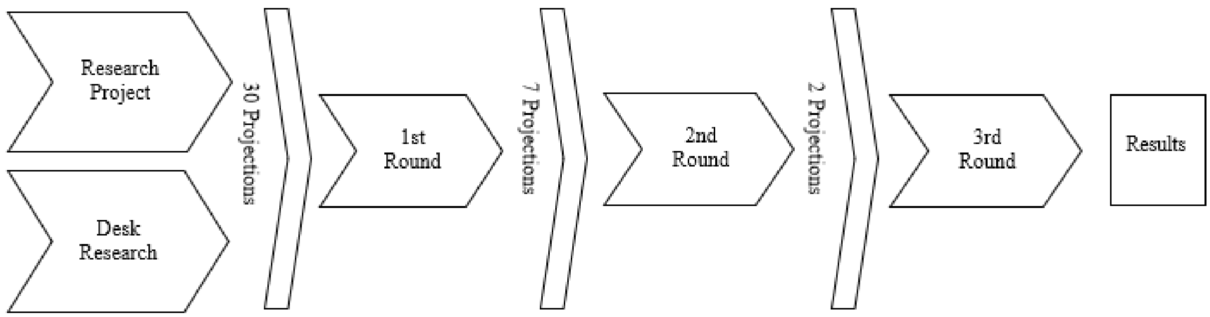

Figure 3: Delphi survey execution

In the first round, the questionnaire consisted of closed ended statements to evaluate how additive manufacturing impacts in industry each supply chain capability and vulnerability identified in previous research. In the second round, the close ended statements on each capability and vulnerability that didn't attain a consensus from the experts in the first round that is, statements with an interquartile range (IQR) greater than 1 were put forward again. In the third round, the statements without a consensus from round 2 were put forward again, after which the survey stopped. At the end of each round, the mean and standard deviation on each projection were calculated. Following the experts' evaluations, agreements on capabilities and vulnerabilities were measured again in the final round. For all the challenges and countermeasures that attained agreement within the group of experts in all 3 rounds, relevance was calculated. The output of the third round was the final set of challenges and countermeasures and their relevance.

To reduce information overload, the projections were presented in a clear manner, and the experts were asked to evaluate them based on their own experience. The evaluations were measured on a 5-point Likert scale (ranging from 1 = 'strongly disagree' to 5 = 'strongly agree') and grouped into percentages to show the consensus achieved. The Delphi technique gives participants the possibility to adjust their evaluations at least once (Gordon & Helmer, 1964). This provided the panel experts the opportunity to change their opinions in the second and third round of the study to allow for a thorough assessment on the research topic.

SCR subfactors	Code	Projections
Adaptability	C1i	AM strengthens this capability by supporting short lead times in production which enables the supply chain quickly respond to disruptions.
	C1ii	AM strengthens this capability by supporting the possibility to reallocate production which enables the supply chain quickly respond to disruptions.
Capacity	C2i	AM strengthens this capability by providing a buffer to address volatile demand which facilitates redundancy in production.
	C2ii	AM strengthens this capability by increasing production scalability which addresses unstable customer demand.
Collaboration	C3i	AM strengthens this capability by promoting an increase in collaborative information sharing between supply chain partners.
	C3ii	AM strengthens this capability by enhancing the increase in collaborative demand forecasting between partners in the supply chain.
Dispersion	C4	AM strengthens this capability by enhancing the ability to distribute capacity in multiple locations.
Efficiency	C5i	AM strengthens this capability because there is minimum raw material consumption during production.
	C5ii	AM strengthens this capability because there is increased capacity sharing.
	C5iii	AM strengthens this capability by allowing complex products to be produced in an easy way.
	C5iv	AM strengthens this capability because AM promotes a tool-less manufacturing approach.
	C5v	AM strengthens this capability because there is an extension of the product's life cycle.
	C5vi	AM strengthens this capability because there is a reduced need for labour.
	C5vii	AM strengthens this capability because production is on-demand according to customer orders.
Flexibility in order fulfilment	C6	AM strengthens this capability by allowing possibility to postpone orders until a customer order is received.
Flexibility in sourcing	C7i	AM weakens this capability because there is a limited availability of substitute suppliers.
	C7ii	AM weakens this capability because there is a limited availability of raw materials required for production.

Market position	C8i	AM strengthens this capability because it provides room for co-design of products with customers.
	C8ii	AM strengthens this capability because production is more customer-focused and customer relationships are improved as a result.
Recovery	C9	AM strengthens this capability by enhancing the ability to outsource production in the event of capacity/distribution shortages.
Visibility	C10	AM strengthens this capability because the reliance on ICT systems for information sharing helps in anticipating customer demands.
Connectivity	V1i	AM mitigates this vulnerability as there is an increase in the degree of outsourcing of production to external entities due to the digital nature of AM technology.
	V1ii	AM increases this vulnerability as the high reliance upon information flow can create connectivity issues when adequate ICT infrastructures are missing.
	V1iii	AM increases this vulnerability as the limited number of suppliers of raw materials increases the reliance upon specialty sources.
Deliberate threats	V2i	AM increases this vulnerability as the high level of information exchange between partners in the supply chain exposes the supply chain to industrial espionage.
	V2ii	AM mitigates this vulnerability as the ability to disperse capacity to multiple production facilities increases resilience against threats; threats meaning theft, sabotage, product liability.
Resource limits	V3	AM increases this vulnerability as the reliance on very few suppliers in the supply chain causes an exposure to raw material and supplier unavailability.
Sensitivity	V4	AM increases this vulnerability because issues on the reliability of equipment and utilization of limited materials arise from stringent conditions required for the use of AM.
Supplier-customer disruptions	V5	The possibility to reallocate production and distribute capacity to alternate production facilities by using AM mitigates this vulnerability.
Turbulence	V6	The possibility to reduce production lead time by using AM mitigates this vulnerability by promoting the recovery of the supply chain from disruptions; disruptions meant as unsteady customer demands and geopolitical upsets.

Table 4: Delphi study projections

3.3 Feedback and evaluation

After collecting a sufficient number of responses in each round, the results were analysed by calculating the interquartile range, mean and standard deviation on each statement projected to the experts. These values obtained from previous rounds were included in the questionnaire for the next rounds to give the participants a clear view while trying to obtain a consensus. For brevity, figure 4 depicts the Delphi study outputs in its entirety, grouped by SCR subfactors, alongside their mean, IQR and standard deviation values gathered from all 3 rounds.

SCR sub-factors	Round 1					Round 2					Round 3				
	No. of projections	Code	IQR	M	SD	No. of projections	Code	IQR	M	SD	No. of projections	Code	IQR	M	SD
Adaptability	2	C1i	1	3.33	1.3165										
		C1ii	1	4	0.6324										
Capacity	2	C2i	1	2.33	0.966										
		C2ii	1	3.5	1										
Collaboration	2	C3i	2	2.5	1	1	C3i	1	3.5	0.7905					
		C3ii	1	3.5	1										
Dispersion	1	C4	1	2.5	0.9486										
Efficiency	7	C5i	1	3.66	0.9661	2					1				
		C5ii	1	2.66	0.9661										
		C5iii	1	3.33	1.3165										
		C5iv	1	2.33	0.966										
		C5v	2	3.5	1		C5v	1	4	0.5					
		C5vi	1	2.33	0.966										
		C5vii	2	2.5	1		C5vii	2	3	1.2247		C5vii	1	3.5	0.7905
Flexibility in order fulfilment	1	C6	1	2.66	0.9661										
Flexibility in sourcing	2	C7i	2	3.5	1	1	C7i	1	3	1.4142					
		C7ii	1	3.33	0.966										
Market position	2	C8i	1	4.5	0.3162										
		C8ii	1	2.66	0.9661										
Recovery	1	C9	1	2.5	1										
Visibility	1	C10	1	2.5	1										
Connectivity	3	V1i	1	3	0.6324	1									
		V1ii	1	3.33	0.966										
		V1iii	2	2.5	1		V1iii	1	3	1.4142					
Deliberate threats	2	V2i	2	3.5	1	2	V2i	1	3	1.4142	1				
		V2ii	2	2.5	1		V2ii	2	3	1.2247		V2ii	1	3.5	0.7905
Resource limits	1	V3	1	3.5	1										
Sensitivity	1	V4	1	2.5	1										
Supplier-customer disruptions	1	V5	1	4	0.6324										
Turbulence	1	V6	1	2.5	1										

Figure 4: Delphi study rounds

The final results from the Delphi study were reported to the participants in the form of challenges and countermeasures and will be used to define future research in this field.

4. Results and discussion

This chapter will present the empirical findings in this research. First the challenges to adopting additive manufacturing resulting from the experts' opinion from the Delphi study are outlined and discussed. Subsequently, the countermeasures and opportunities obtained from the study are reported.

4.1 Identification of challenges

A number of challenges with adopting additive manufacturing were obtained from the results of all three rounds of the Delphi study. The challenges identified by the experts provide a match with some of the propositions developed in the literature review. For instance, challenges with information sharing, IT inadequacies and lack of standardization which arise from using AM match with the SCR subfactors deliberate threats, sensitivity and collaboration shown in table 6.

Although many authors in the literature have argued that the adoption of additive manufacturing in the supply chain would support computer aided design (CAD) and enhance advanced collaboration in the supply chain (Belhadi, et al., 2022), the evaluations by the experts from the Delphi study show that this is not necessarily the case as there are still difficulties with information exchange for demand planning and forecasting due to individual organizations choosing to often withhold information about internal processes.

Research from the literature supports the idea that the increased circulation of information and increased reliance on computer hardware and software makes the supply chain more susceptible to cyber attacks (Rahman, et al., 2021). The experts agreed with this, as the consensus regarding information sharing is that it poses a great risk to the intellectual property (IP) of the organization because IT systems cannot safeguard the IP of the organization if the supply chain shifts towards a distributed manufacturing system.

The panel of experts also agreed that the rigid conditions regarding raw materials and equipment reliability in which AM operates is a major challenge to adopting additive manufacturing in the supply chain. The publication by (Naghshineh & Carvalho, 2022) found that there is a lack of standardization for AM equipment and materials which may lead to capacity shortage when AM equipment is faulty or when materials become scarce or delayed by suppliers. Other challenges identified are insufficient information sharing and limited capacity sharing.

4.2 Evaluation of countermeasures

From the Delphi study rounds, a total of 6 challenges were identified regarding the adoption of additive manufacturing for supply chain resilience. Considering the challenges identified from the Delphi study, a set of countermeasures has been proposed to address the issues. The countermeasures were developed based on a review of literature on the themes of the identified challenges, together with suggestions from the panel experts of the Delphi study. Table 5 shows the list of challenges together with countermeasures for each challenge, with details on the mean values of responses and standard deviation. These countermeasures can be classified as internal or external, that is, they can be attributable to the management of an organization or outward to the supply chain.

Code	Challenge	Countermeasure	IQR	Mean	St. Dev.
V2i	High reliance on information flow which expose IT inadequacies	Strengthening IT infrastructure Implementing data security measures	2	3	1.4142
V4	No regulation and standardization for AM materials and processes	Collaborative standardization efforts Certification and validation processes	1	2.5	1
C3i	Insufficient information sharing in the supply chain	Collaborative information sharing platforms Incentivizing information sharing	1	3.5	0.7905
C3ii	Minimal collaborative demand forecasting in the supply chain	Collaborative planning and forecasting Sharing market intelligence	1	3.5	1
C5ii	Limited capacity sharing	Building partnerships and alliances Capacity pooling platforms	1	2.66	0.9661
C10	Inadequate ICT structure for secure information sharing	Upgrading ICT infrastructure Implementing cloud-based solutions	1	2.5	1

Table 5: Delphi study output (challenges and countermeasures)

These countermeasures can be considered as proactive strategies and they address the challenges associated with adopting additive manufacturing for supply chain resilience. However, it is essential to tailor the approaches to the specific context and requirements of each organization.

4.2.1 Strengthening IT infrastructure

A countermeasure to the challenge of high reliance on information flow is the strengthening of IT infrastructure. Organizations can invest in robust information technology (IT) systems to enhance secure data exchange, communication, and integration across the supply chain (Gupta, et al., 2020). The panel experts also recommended that IT security and information encryption should be a top priority when sharing information. Some key aspects to consider when planning to strengthen IT infrastructure are;

- Data Integration and Connectivity: Implementing systems that enable seamless integration of data across various supply chain functions, such as inventory management, production planning, and logistics, can improve information flow and decision-making. This involves deploying enterprise resource planning (ERP) systems or advanced software solutions that can synchronize and harmonize data from multiple sources (Gupta, et al., 2020).
- Communication and Collaboration Tools: Deploying communication and collaboration tools, such as web-based portals, video conferencing systems, and instant messaging platforms, can facilitate efficient and real-time communication among supply chain partners. These tools enable rapid information exchange, collaborative problem-solving, and effective coordination, particularly in geographically dispersed supply chains (Gupta, et al., 2020).
- Cybersecurity and Data Protection: With increased reliance on digital systems and data sharing, organizations must prioritize cybersecurity measures to protect sensitive information and intellectual property. Implementing firewalls, encryption techniques, intrusion detection systems, and regular security audits when designing a supply chain network can help safeguard against cyber threats and ensure data integrity (Wu, et al., 2015).
- IT Talent and Training: Organizations should invest in acquiring IT talent and providing relevant training to ensure the effective utilization and management of IT infrastructure. Having skilled personnel who understand the complexities of supply chain systems, data management, and IT security can enhance the overall effectiveness of IT infrastructure implementation (Gupta, et al., 2020).

Furthermore, inadequacies with IT structures for information sharing can be countered by implementing cloud-based solutions. Leveraging cloud-based platforms can provide scalable and flexible ICT infrastructure for data storage, sharing, and collaboration (Jafari, et al., 2022).

4.2.2 Collaborative demand planning

The challenge with minimal collaborative demand forecasting in the supply chain can be countered by implementing collaborative demand planning processes and tools to enable accurate and synchronized demand forecasts among supply chain partners (Jayaram, et al., 2018). This challenge can be countered by sharing market intelligence across the supply chain by using big data, predictive algorithms and implementing real-time monitoring for sales. Establishing mechanisms for sharing market insights and consumer trends can enhance demand forecasting accuracy and enable proactive decision-making (Dong, et al., 2014). Collaborative demand planning fosters improved demand visibility, reduced demand variability, and enhanced supply chain responsiveness. By involving multiple stakeholders and leveraging their collective intelligence, organizations can achieve more accurate forecasts, reduce stockouts, optimize inventory levels, and enhance overall supply chain performance (Min & Wen-Bin'Vincent, 2008). Information sharing, data analytics, agile planning and performance measurement are important aspects to consider when addressing collaborative demand planning.

4.2.3 Collaborative standardization efforts

The challenge with a lack of regulation and standardization for AM materials and processes can be countered by encouraging collaborative standardization efforts. Stakeholders across the AM ecosystem or network can collaborate to develop industry-wide standards for materials, processes, and quality control (Kawalkar, et al., 2022). Additionally, the challenge can also be countered by a close collaboration between academic research, policy, and industry. Key aspects to consider when implementing collaborative standardization efforts are:

- Industry-wide Collaboration: Collaborative standardization involves active participation and cooperation among stakeholders across the AM ecosystem, including manufacturers, researchers, regulatory bodies, industry associations, and users. This collaborative approach brings together diverse perspectives, expertise, and resources to develop comprehensive and widely accepted standards.
- Material Standards: Additive manufacturing encompasses a wide range of materials, such as metals, polymers, ceramics, and composites. Collaborative efforts should focus on establishing material standards that define material properties, composition, testing

methodologies, and quality control measures. These standards ensure the consistency and reliability of materials used in AM processes.

- Process Standards: Standardization efforts should also address AM process parameters, equipment specifications, and post-processing requirements. Defining standard processes helps ensure repeatability, accuracy, and consistency in manufacturing outcomes, enabling greater trust and reliability in AM applications.
- Quality Assurance Standards: Collaborative efforts should focus on developing quality assurance and testing standards specific to AM. These standards encompass factors such as dimensional accuracy, surface finish, mechanical properties, and non-destructive testing techniques. Implementing standardized testing protocols helps validate and certify the quality of AM products, enhancing their acceptance in various industries.
- Regulatory Compliance: Collaborative standardization efforts should align with regulatory frameworks and compliance requirements. Involvement of regulatory bodies and industry associations ensures that standards adhere to safety, health, environmental, and legal regulations. This collaboration helps build confidence and trust in AM technologies and promotes their adoption in regulated industries.
- Global Harmonization: Collaborative standardization should strive for global harmonization to ensure consistency and compatibility across international boundaries. Efforts such as knowledge sharing, harmonization of existing standards, and mutual recognition of certifications can facilitate global acceptance and facilitate the seamless integration of AM technologies into global supply chains.

Additionally, organizations adopting the use of AM can also establish internal certification and validation procedures to ensure compliance with quality and safety requirements (Vaezi, et al., 2013).

4.2.4 Collaborative information sharing platforms

The challenge with insufficient information sharing in the supply chain can be countered by developing secure collaborative information sharing platforms. Supply chains will benefit from a close collaboration between the SC actors (for example between the end-user and manufacturer or between the supplier and customer). Implementing shared platforms or systems can facilitate real-time information exchange among supply chain partners, enhancing visibility, coordination and decision making in the supply chain (Kurpjuweit, et al., 2019). Real-time data exchange, supply chain transparency, analytics and secure data sharing are important aspects to consider when implementing secure information sharing platforms. Additionally, organizations can incentivize information sharing by promoting a culture of collaboration and trust by offering benefits for active participation (Jain, et al., 2017).

4.2.5 Partnerships

The challenge with limited capacity sharing can be countered by building partnerships and creating capacity pool platforms. Organizations can form partnerships or alliances with other organizations in the same network or with alternate AM equipment suppliers to leverage complementary capabilities and share manufacturing capacity during peak demand periods or supply disruptions. Also, utilizing digital platforms that connect organizations with excess capacity to those in need can facilitate capacity sharing and reduce production bottlenecks (Altay, et al., 2020).

The proposed countermeasures derived from the literature review provide valuable insights into addressing the challenges faced in adopting additive manufacturing for supply chain resilience. By implementing these countermeasures, organizations can enhance their supply chain capabilities, mitigate vulnerabilities, and improve overall resilience. It is important to note that the proposed countermeasures should be tailored to the specific context of each organization and further validated through practical implementation and continuous evaluation.

4.3 Overview of opportunities

Opportunities regarding additive manufacturing adoption for supply chain resilience have been proposed and reviewed from previous research. Based on comparisons with the literature and the results of the Delphi study, several considerations can be deduced.

The adoption of additive manufacturing for outsourcing production in the supply chain presents several opportunities which can bring significant benefits to organizations, some of which include; rapid prototyping and iterative design, cost savings and efficiency, flexibility and allowing companies focus on their core competencies while relying on external expertise for AM-related jobs (Gardan, 2016). AM also offers several opportunities for the reallocation of production and distribution of capacity within supply chains. These are production redesign and optimization, localized spare parts production, on-demand manufacturing, tool-less manufacturing and establishing collaborative manufacturing networks which will streamline the supply chain and reduce production lead time. (Gardan, 2016).

Another consideration is that additive manufacturing eliminates setup costs and allows for rapid design iterations and improvements based on each customer demand. These features provide an opportunity for AM to provide a buffer and adjust production scalability to address unstable demand when needed. Additive manufacturing also increases material efficiency by utilizing only the necessary amount of material required to build the part, thus reducing waste and optimizing material consumption (Gibson, et al., 2021). There are also opportunities for AM to produce on demand which eliminates the need for large inventory and enables a more responsive manufacturing approach (Huang, et al., 2015), and postpone orders in situations where generic or partially completed products are manufactured in advance and customized based on specific customer requirements later in the production process (Huang, et al., 2013).

Code	**Opportunities**
V1i	Production outsourcing
V5	Relocation of production and capacity distribution
V6	Reduction of production lead time
C2	Provision of a buffer & adjusting production scalability to address unstable demand
C5i	Use of minimal raw material consumption and labour to produce complex parts
C5vii	On demand production and the possibility to postpone orders
C8	Co-design of products with customers

Table 6: Opportunities for adopting AM

By leveraging these opportunities offered by AM, supply chains can improve their agility, reduce lead times, optimize inventory levels, and enhance responsiveness to disruptions. These resilience-enhancing measures contribute to maintaining business continuity, reducing supply chain risks, and strengthening the overall resilience of the supply chain network.

4.4 Answering research questions

RQ 1: How relevant is the adoption of additive manufacturing in enhancing supply chain resilience?

The adoption of additive manufacturing (AM) is highly relevant in enhancing supply chain resilience. AM enables organizations to mitigate the challenges identified, such as high reliance on information flow, inadequate information sharing, and limited capacity sharing. By leveraging AM, organizations can overcome supply chain disruptions caused by disruptions in information flow, as AM processes can reduce dependency on traditional supply chain channels and enable localized production. Additionally, AM facilitates enhanced information sharing and collaboration among supply chain partners using digital platforms and real-time data exchange, thereby strengthening supply chain resilience. The countermeasures discussed, such as strengthening IT infrastructure, collaborative standardization efforts, and collaborative information sharing platforms, further reinforce the relevance of AM adoption in enhancing supply chain resilience.

RQ 2: How relevant are the adoption impacts of additive manufacturing on supply chain capabilities?

The adoption impacts of additive manufacturing (AM) are highly relevant in enhancing supply chain capabilities. AM offers several advantages that address the challenges identified, including the lack of regulation and standardization, insufficient information sharing, and minimal collaborative demand planning. By adopting AM, organizations can achieve greater flexibility and responsiveness in their supply chains. AM enables customization, rapid prototyping, and on-demand production, thereby enhancing supply chain capabilities to meet customer-specific requirements and reduce lead times. Additionally, the countermeasures discussed, such as partnerships, strengthening IT infrastructure, and collaborative demand planning, contribute to the improvement of supply chain capabilities by fostering collaboration, knowledge sharing, and innovation among supply chain partners.

RQ 3: How relevant are the adoption impacts of additive manufacturing on supply chain vulnerabilities?

The adoption impacts of additive manufacturing (AM) are highly relevant in addressing supply chain vulnerabilities. AM can help mitigate the vulnerabilities associated with challenges such as insufficient information sharing, limited capacity sharing, and inadequate ICT structure. By adopting AM, organizations can reduce their dependence on traditional supply chain channels and establish localized production capabilities. This reduces the risk of disruptions caused by information asymmetry, capacity limitations, and ICT inadequacies, thereby enhancing supply chain resilience. The countermeasures discussed, including collaborative standardization efforts, strengthening IT infrastructure, and collaborative information sharing platforms, contribute to reducing vulnerabilities by promoting transparency, collaboration, and the exchange of critical information among supply chain partners.

Overall, the adoption of additive manufacturing has a significant relevance in enhancing supply chain resilience, capabilities, and reducing vulnerabilities. The challenges identified can be effectively addressed through the implementation of the suggested countermeasures, thereby leveraging the benefits of additive manufacturing to strengthen the overall performance and resilience of the supply chain.

5. Conclusions

This thesis investigated the potential of additive manufacturing to enhance supply chain resilience. Through a Delphi study with a panel of experts in supply chain management and additive manufacturing, the study identified several challenges and opportunities for using additive manufacturing in supply chains and proposed several strategies for enhancing supply chain resilience through additive manufacturing.

The results of the Delphi study suggest that additive manufacturing has the potential to enhance supply chain resilience by enabling faster time-to-market, reduced lead times, improved customization, reduced waste, and increased supply chain flexibility. However, the experts also identified several challenges to using additive manufacturing in supply chain management, including lack of standardization, high costs, and limited integration with existing systems.

To address these challenges and leverage the opportunities presented by additive manufacturing, the study proposed several countermeasures which could be developed into strategies for using additive manufacturing to enhance supply chain resilience. These countermeasures include strengthening IT infrastructure, implementing data security measures, collaborative standardization efforts, engaging in certification and validation processes, designing collaborative information sharing platforms and building partnerships.

Overall, the findings of this thesis highlight the potential of additive manufacturing to enhance supply chain resilience and provide some guidance on how to effectively implement additive manufacturing in the supply chain. The strategies proposed in this study can help supply chain managers and organizations leverage additive manufacturing to improve their supply chain resilience and competitiveness in an increasingly complex and uncertain business environment.

There are several limitations to this study that should be acknowledged. First, the Delphi study was conducted with a relatively small panel of experts in supply chain management and additive manufacturing. While efforts were made to ensure a diverse range of perspectives and expertise, the findings of this study may not be generalizable to all organizations or industries. Second, the study focused primarily on the potential benefits and challenges of additive manufacturing for supply chain resilience, and did not explore other potential applications of additive manufacturing, such as sustainability or cost reduction.

Future research can build on the findings of this study by exploring additional opportunities and challenges associated with using additive manufacturing in supply chain management, and by investigating the effectiveness of the strategies proposed in this study. Furthermore, future studies can assess the economic feasibility and potential return on investment associated with additive manufacturing implementation in the supply chain. Finally, future research can investigate the impact of additive manufacturing on other dimensions of supply chain performance, such as sustainability, cost reduction, and quality assurance.

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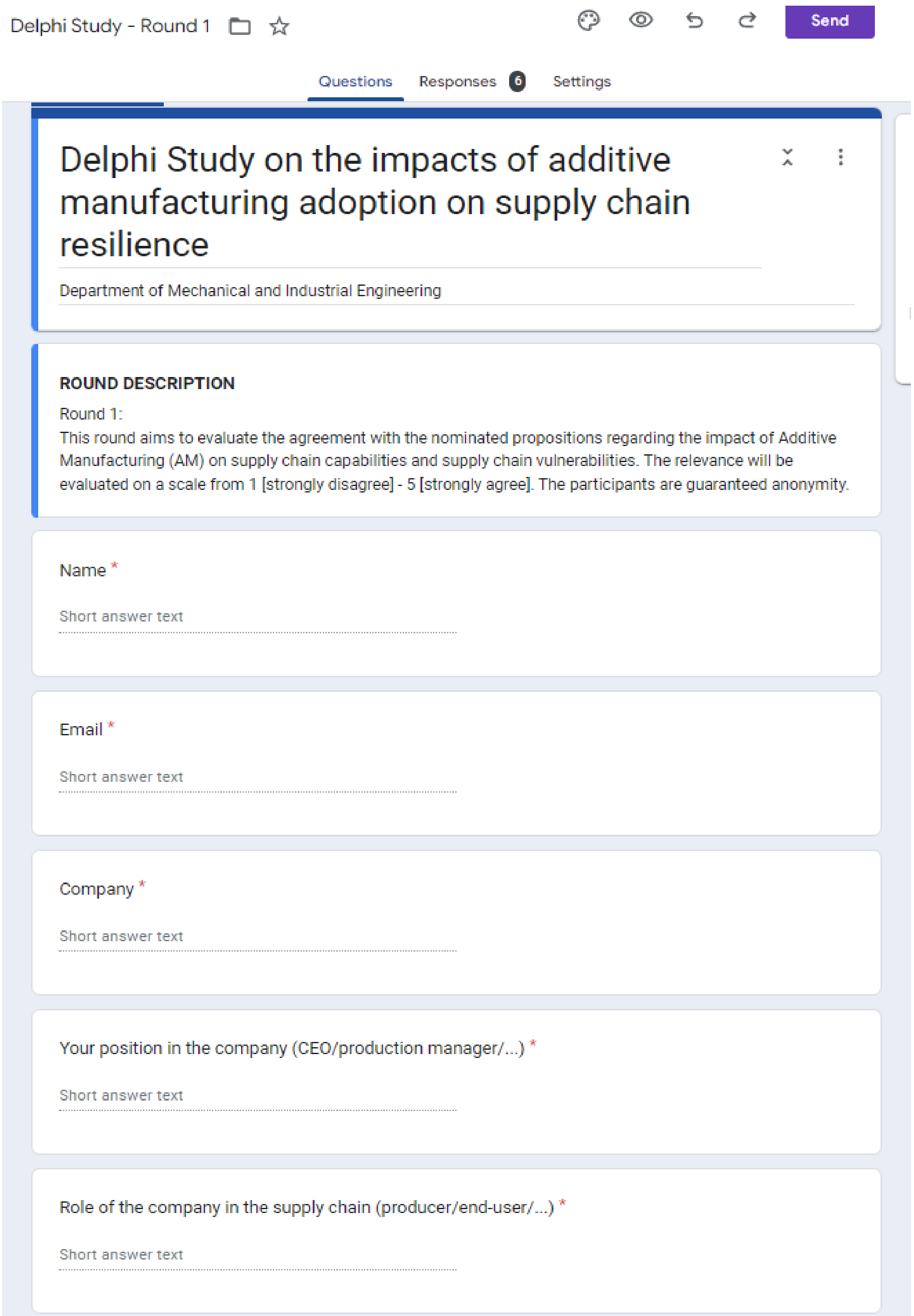
Appendix

A: Delphi study projections


Delphi Study - Round 1

Send

Questions Responses 6 Settings

Delphi Study on the impacts of additive manufacturing adoption on supply chain resilience

Department of Mechanical and Industrial Engineering

ROUND DESCRIPTION

Round 1:

This round aims to evaluate the agreement with the nominated propositions regarding the impact of Additive Manufacturing (AM) on supply chain capabilities and supply chain vulnerabilities. The relevance will be evaluated on a scale from 1 [strongly disagree] - 5 [strongly agree]. The participants are guaranteed anonymity.

Name *

Short answer text

Email *

Short answer text

Company *

Short answer text

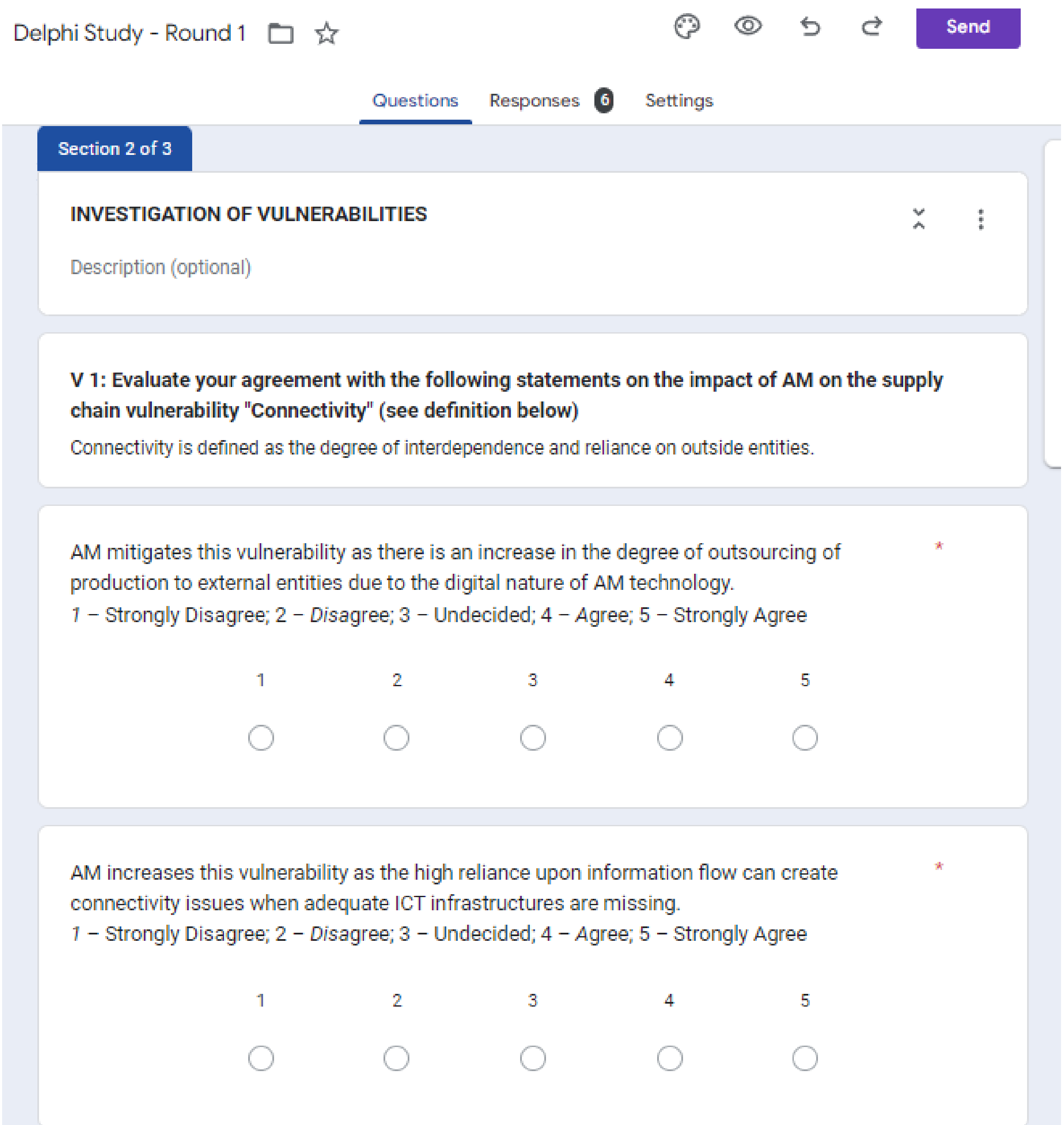
Your position in the company (CEO/production manager/...) *

Short answer text

Role of the company in the supply chain (producer/end-user/...) *

Short answer text

Projections (Round 1)



Delphi Study - Round 1

Send

Questions Responses 6 Settings

Section 2 of 3

INVESTIGATION OF VULNERABILITIES

Description (optional)

V 1: Evaluate your agreement with the following statements on the impact of AM on the supply chain vulnerability "Connectivity" (see definition below)

Connectivity is defined as the degree of interdependence and reliance on outside entities.

AM mitigates this vulnerability as there is an increase in the degree of outsourcing of production to external entities due to the digital nature of AM technology. *

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

1 2 3 4 5

AM increases this vulnerability as the high reliance upon information flow can create connectivity issues when adequate ICT infrastructures are missing. *

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

1 2 3 4 5

Projections (Round 2)

Delphi Study - Round 2

Send

Questions Responses 5 Settings

Section 3 of 3

CAPABILITIES

Description (optional)

C 3: Evaluate your agreement with the following statement on the impact of AM on the supply chain capability "Collaboration" (see definition below)

Collaboration is the ability to work effectively with other entities for mutual benefit.

AM strengthens this capability by promoting an increase in collaborative information sharing between supply chain partners. *

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

From Round 1; Mean score = 2.5, Standard deviation = 1.0

1 2 3 4 5

C 5: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Efficiency" (see definition below)

Efficiency is the capability to produce outputs with minimum resource requirements.

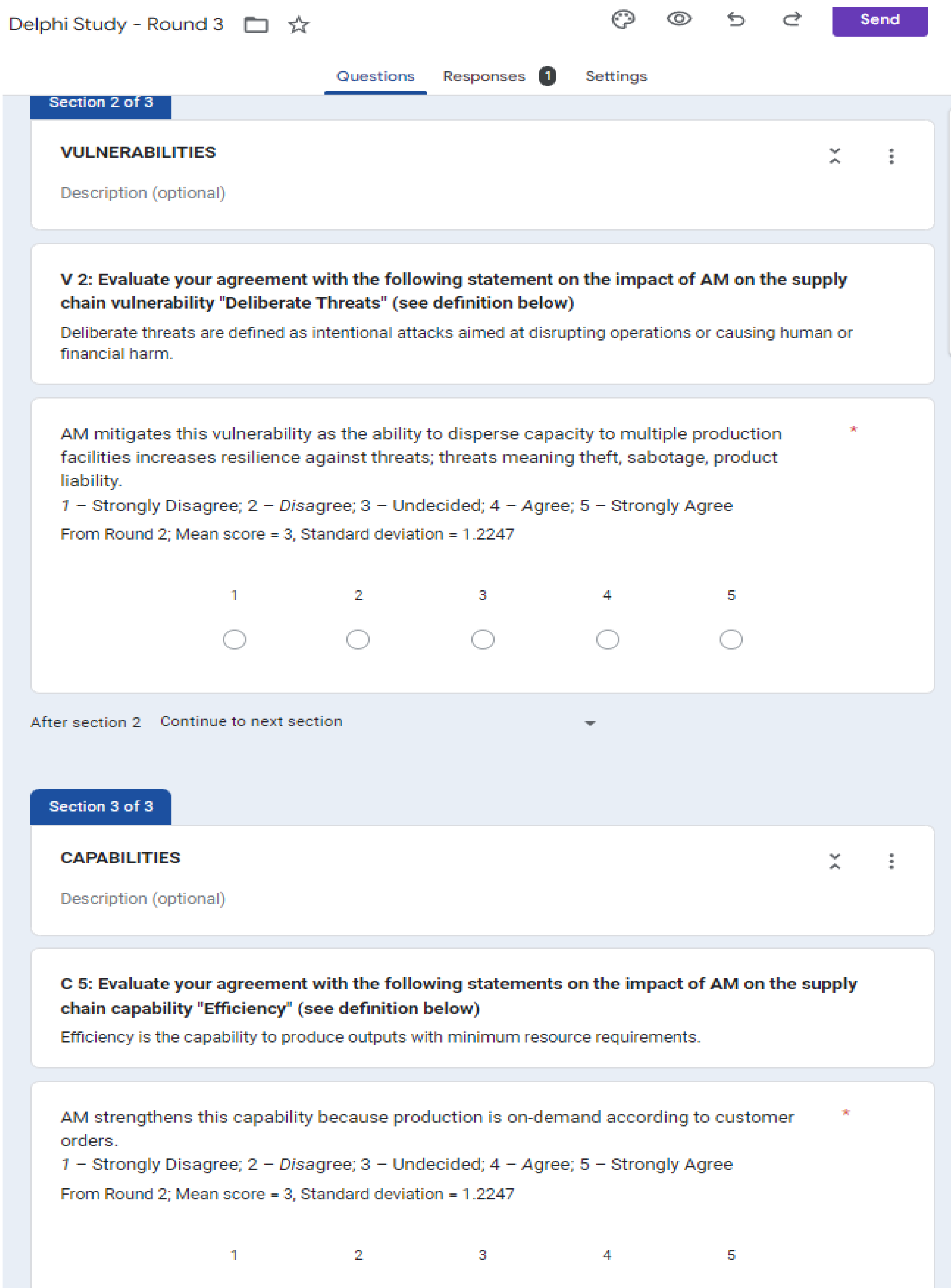
AM strengthens this capability because there is an extension of the product's life cycle. *

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

From Round 1; Mean score = 3.5, Standard deviation = 1.0

1 2 3 4 5

Projections (Round 3)



Delphi Study - Round 3

Send

Questions Responses 1 Settings

Section 2 of 3

VULNERABILITIES

Description (optional)

V 2: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Deliberate Threats" (see definition below)

Deliberate threats are defined as intentional attacks aimed at disrupting operations or causing human or financial harm.

AM mitigates this vulnerability as the ability to disperse capacity to multiple production facilities increases resilience against threats; threats meaning theft, sabotage, product liability. *

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

From Round 2; Mean score = 3, Standard deviation = 1.2247

1 2 3 4 5

After section 2 Continue to next section

Section 3 of 3

CAPABILITIES

Description (optional)

C 5: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Efficiency" (see definition below)

Efficiency is the capability to produce outputs with minimum resource requirements.

AM strengthens this capability because production is on-demand according to customer orders. *

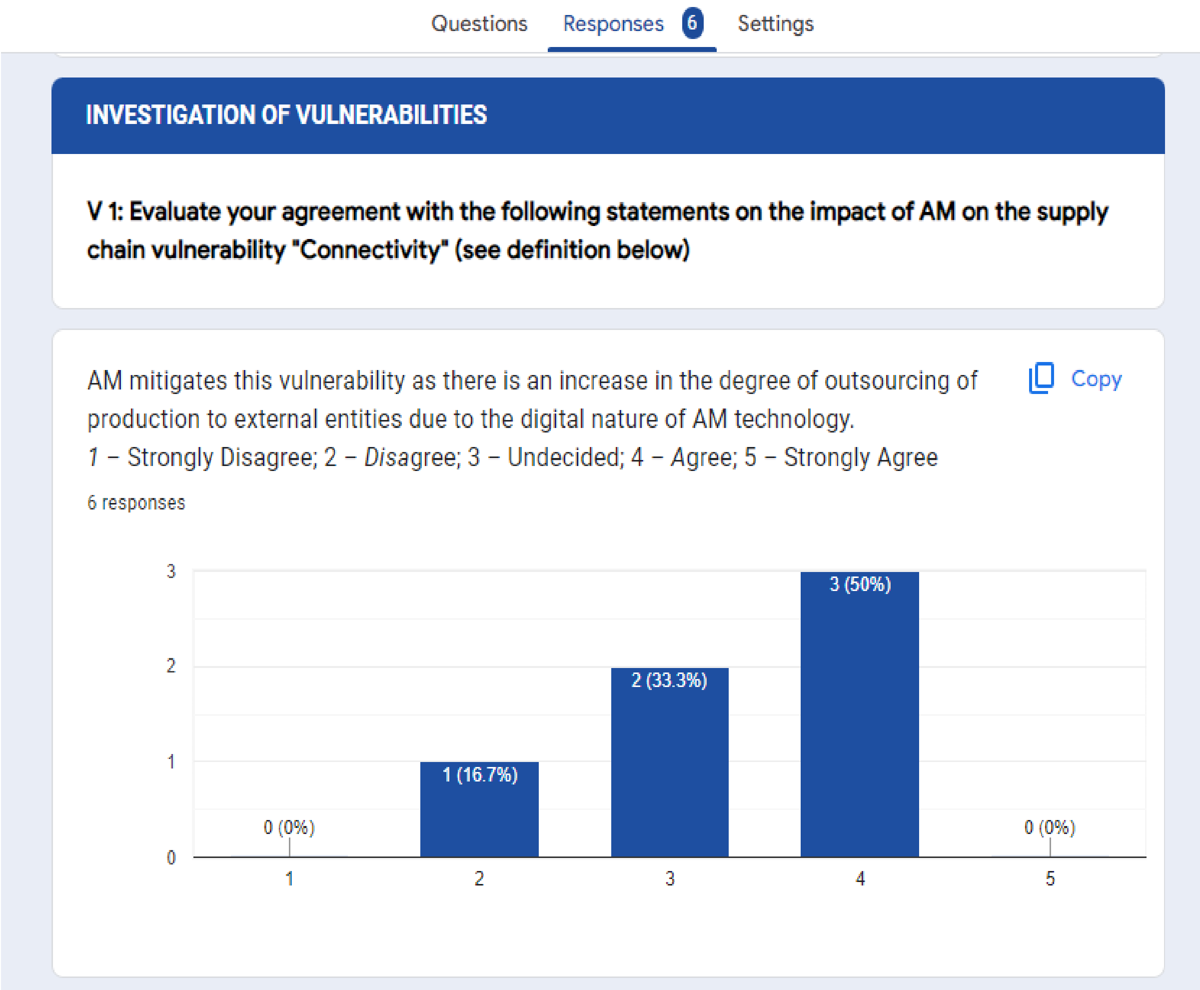
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

From Round 2; Mean score = 3, Standard deviation = 1.2247

1 2 3 4 5

B: Delphi study answers

Round 1

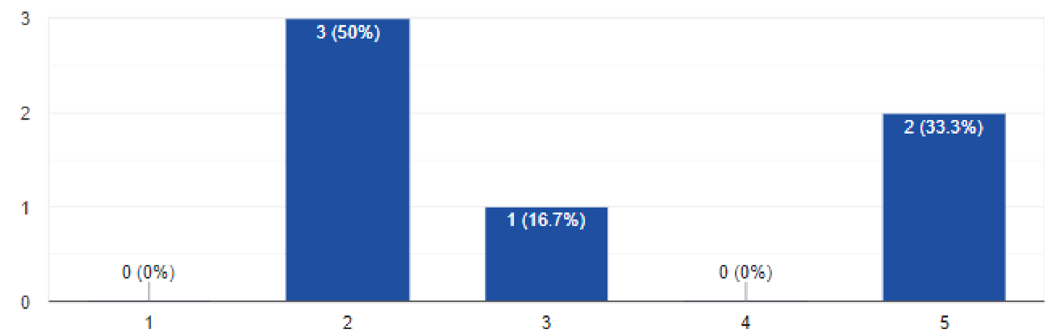


Questions Responses 6 Settings

AM increases this vulnerability as the high reliance upon information flow can create connectivity issues when adequate ICT infrastructures are missing. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

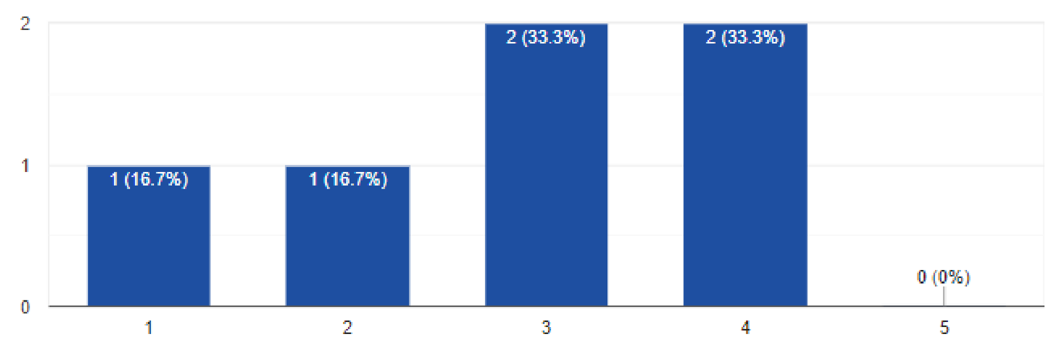
6 responses



AM increases this vulnerability as the limited number of suppliers of raw materials increases the reliance upon specialty sources. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



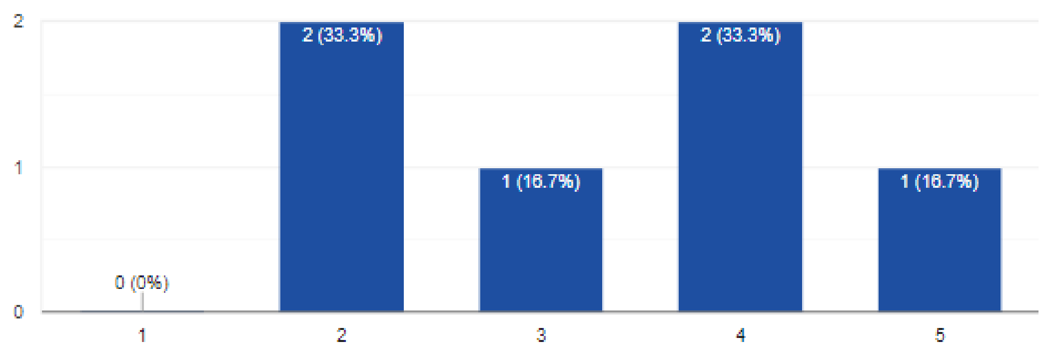
Questions Responses 6 Settings

V 2: Evaluate your agreement with the following statements on the impact of AM on the supply chain vulnerability "Deliberate Threats" (see definition below)

AM increases this vulnerability as the high level of information exchange between partners in the supply chain exposes the supply chain to industrial espionage.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

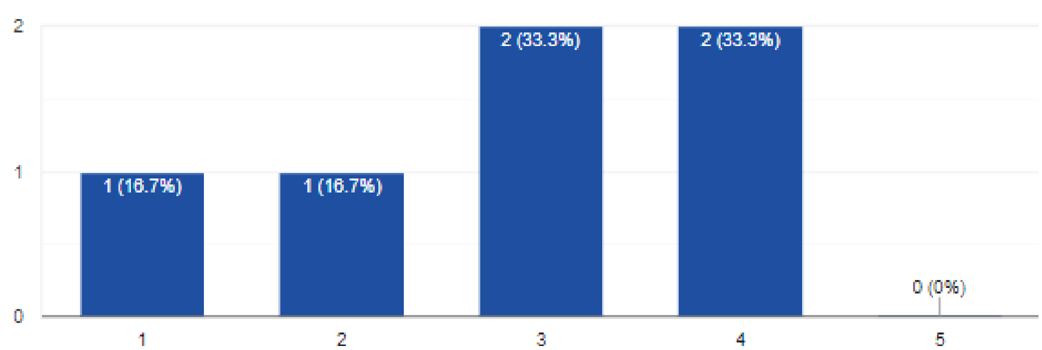
6 responses



AM mitigates this vulnerability as the ability to disperse capacity to multiple production facilities increases resilience against threats; threats meaning theft, sabotage, product liability.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

6 responses



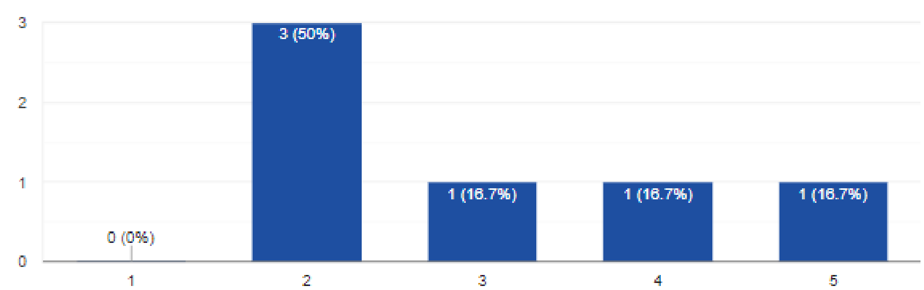
Questions Responses 6 Settings

V 3: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Resource Limits" (see definition below).

AM increases this vulnerability as the reliance on very few suppliers in the supply chain causes an exposure to raw material and supplier unavailability.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

6 responses



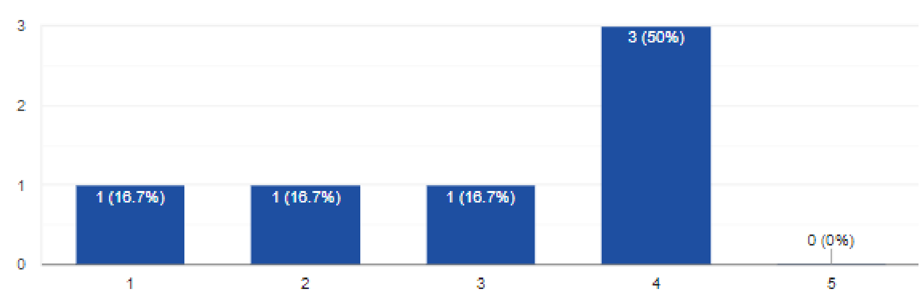
Questions Responses 6 Settings

V 4: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Sensitivity" (see definition below)

AM increases this vulnerability because issues on the reliability of equipment and utilization of limited materials arise from stringent conditions required for the use of AM.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

6 responses



Questions Responses 6 Settings

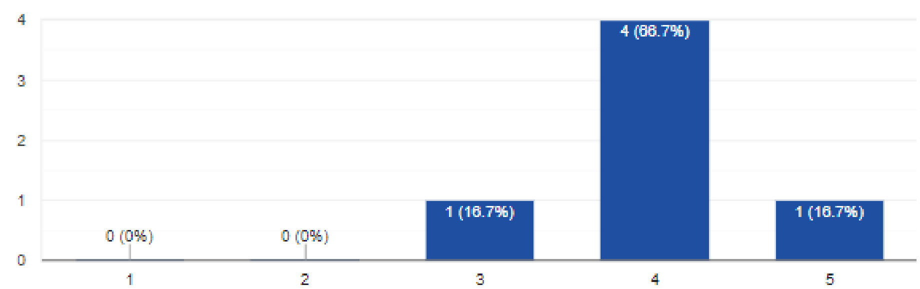
V 5: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Supplier-customer disruptions" (see definition below)

The possibility to reallocate production and distribute capacity to alternate production facilities by using AM mitigates this vulnerability.

Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



Questions Responses 6 Settings

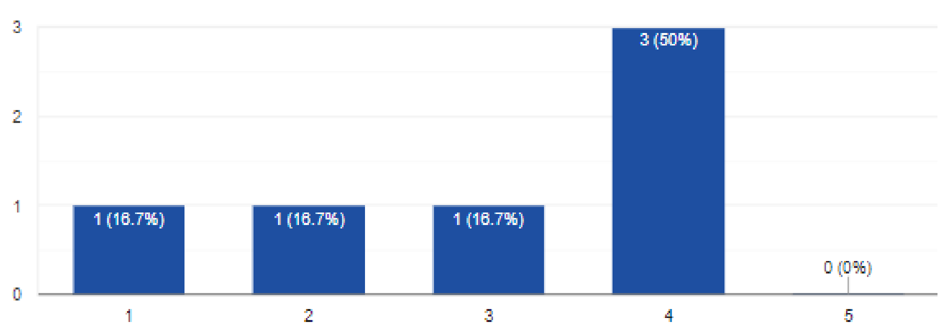
V 6: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Turbulence" (see definition below)

The possibility to reduce production lead time by using AM mitigates this vulnerability by promoting the recovery of the supply chain from disruptions; disruptions meant as unsteady customer demands and geopolitical upsets.

Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



Questions Responses 6 Settings

INVESTIGATION OF CAPABILITIES

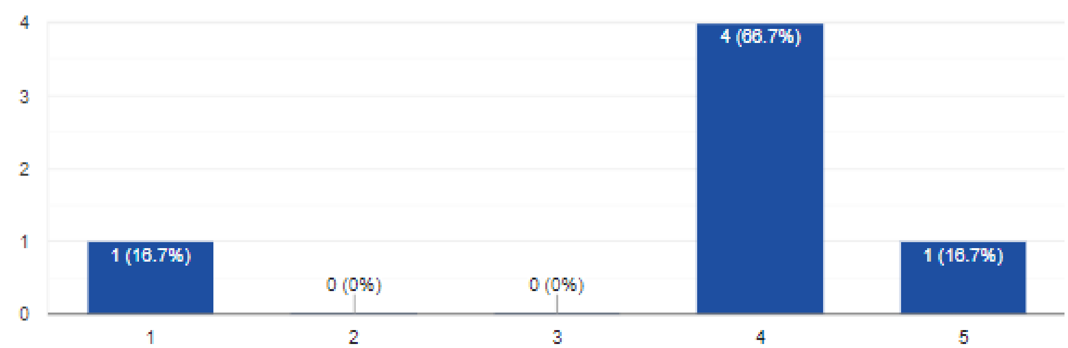
C 1: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Adaptability" (see definition below)

AM strengthens this capability by supporting short lead times in production which enables the supply chain quickly respond to disruptions.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

6 responses



AM strengthens this capability by supporting the possibility to reallocate production which enables the supply chain quickly respond to disruptions.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

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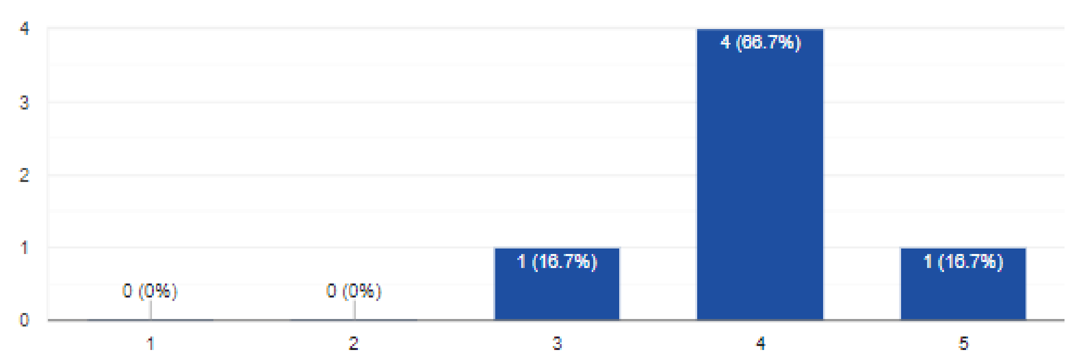
6 responses



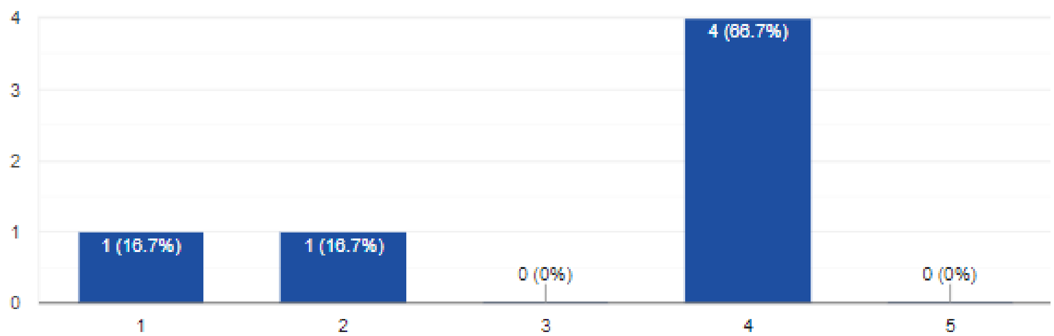
Questions Responses 6 Settings

C 2: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Capacity" (see definition below)

AM strengthens this capability by providing a buffer to address volatile demand which facilitates redundancy in production. Copy

1 – Strongly Disagree; 2 – *Disa*gree; 3 – Undecided; 4 – *A*gree; 5 – Strongly Agree

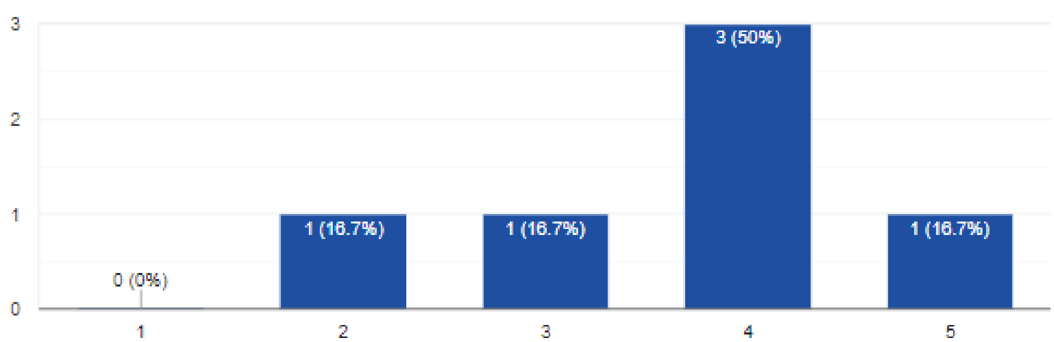
6 responses



AM strengthens this capability by increasing production scalability which addresses unstable customer demand. Copy

1 – Strongly Disagree; 2 – *Disa*gree; 3 – Undecided; 4 – *A*gree; 5 – Strongly Agree

6 responses



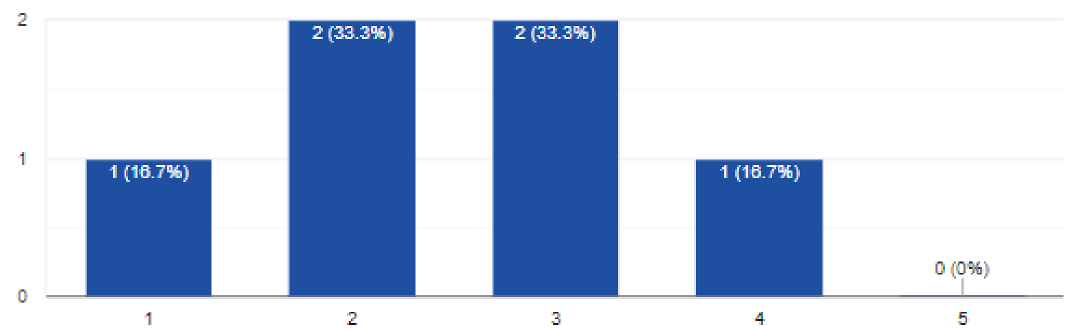
Questions Responses 6 Settings

C 3: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Collaboration" (see definition below)

AM strengthens this capability by promoting an increase in collaborative information sharing between supply chain partners. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

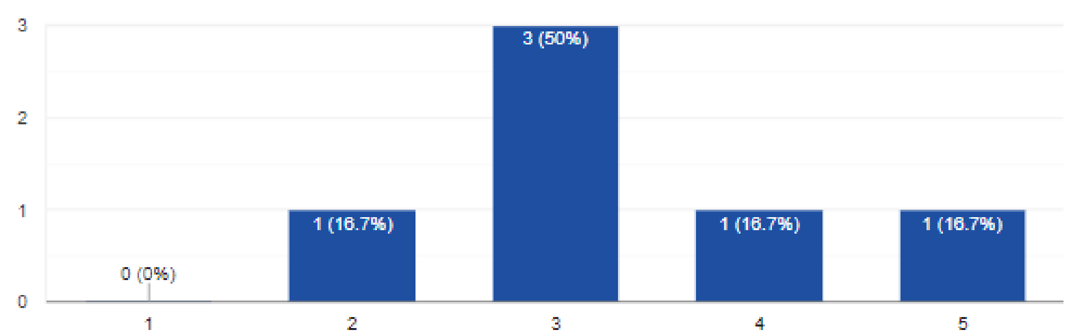
6 responses



AM strengthens this capability by enhancing the increase in collaborative demand forecasting between partners in the supply chain. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



Questions Responses 6 Settings

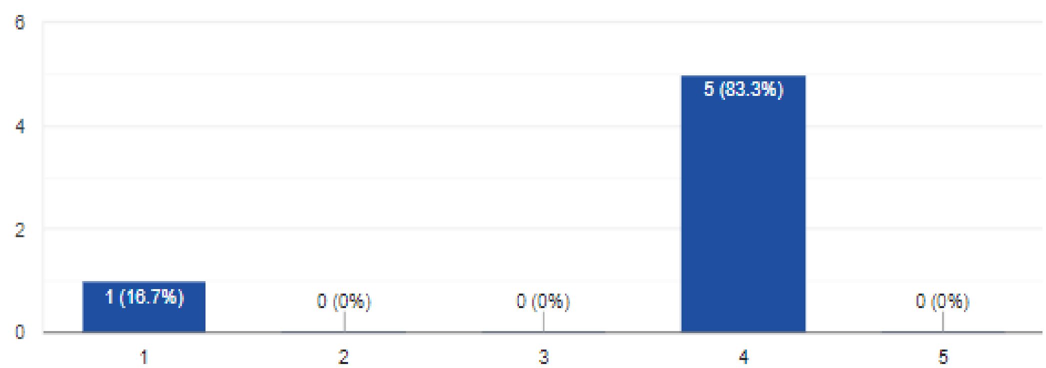
C 4: Evaluate your agreement with the following statement on the impact of AM on the supply chain capability "Dispersion" (see definition below)

AM strengthens this capability by enhancing the ability to distribute capacity in multiple locations.

Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



Questions Responses 6 Settings

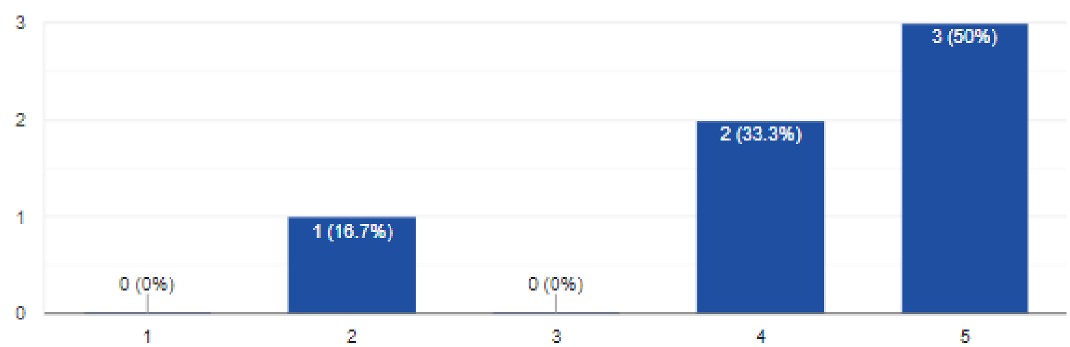
C 5: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Efficiency" (see definition below)

AM strengthens this capability because there is minimum raw material consumption during production.

Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

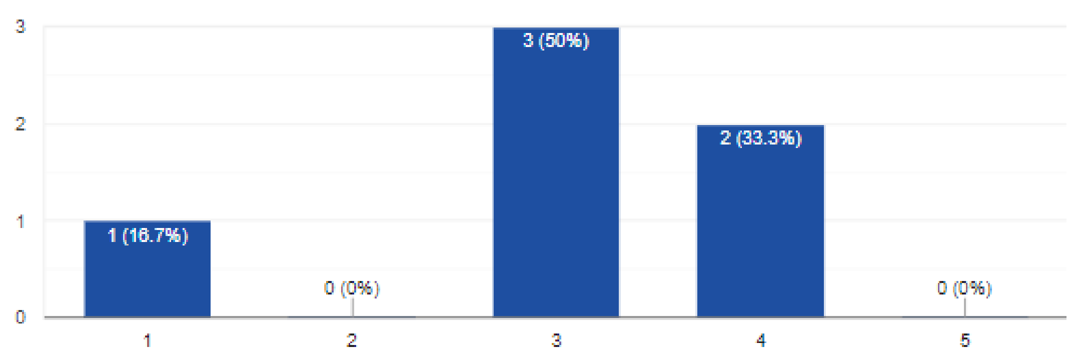


AM strengthens this capability because there is increased capacity sharing.

Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



Questions Responses 6 Settings

AM strengthens this capability by allowing complex products to be produced in an easy way.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

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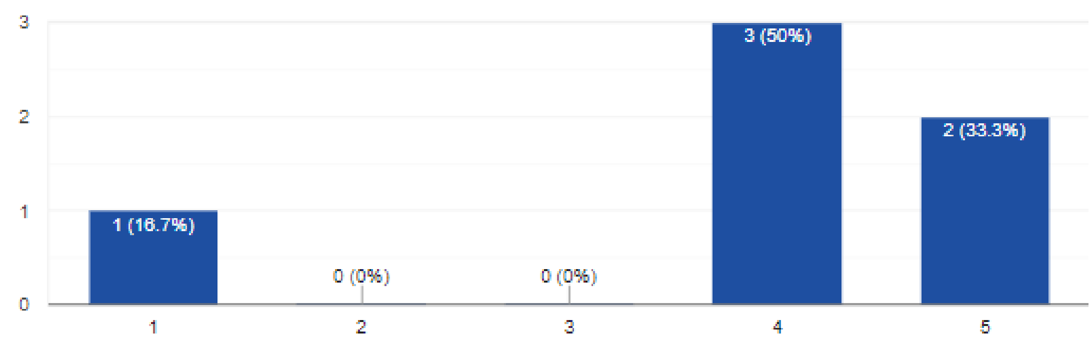

AM strengthens this capability because AM promotes a tool-less manufacturing approach.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

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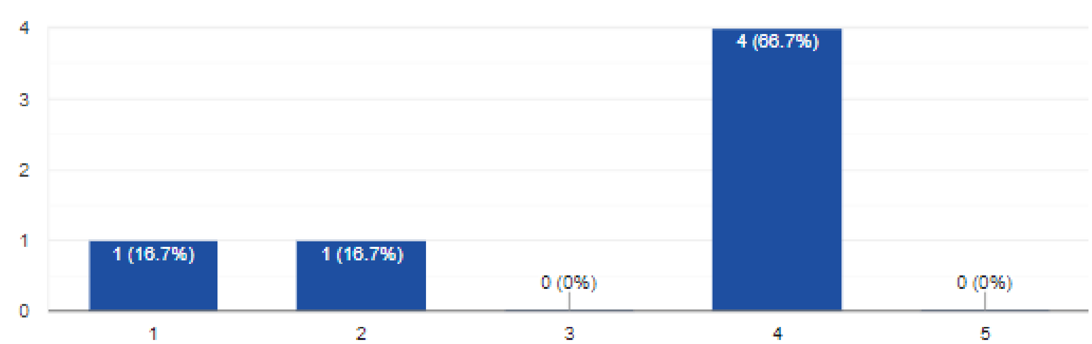

Questions Responses 6 Settings

AM strengthens this capability because there is an extension of the product's life cycle.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

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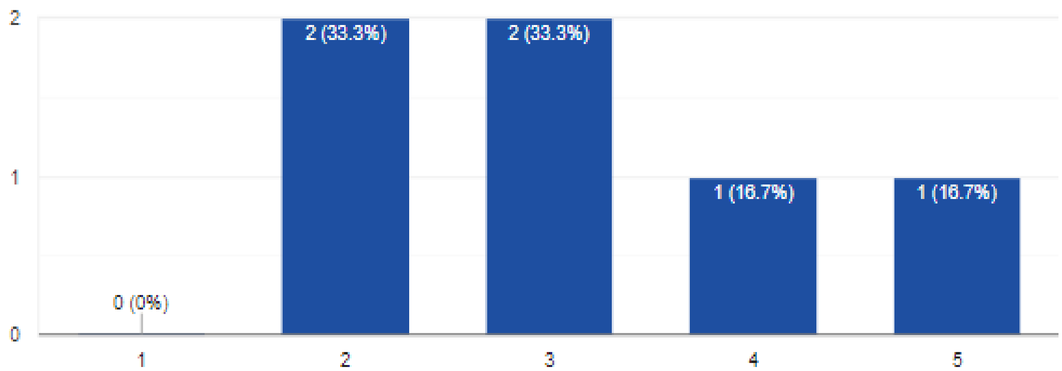

AM strengthens this capability because there is a reduced need for labour.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

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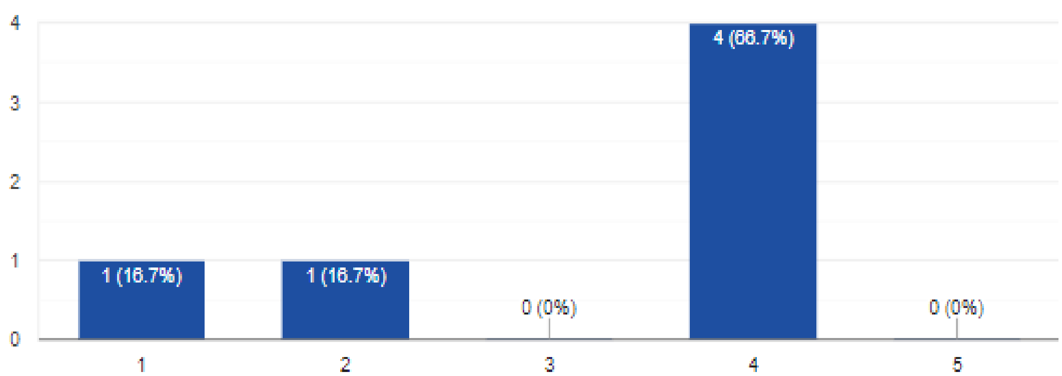

Questions Responses 6 Settings

AM strengthens this capability because production is on-demand according to customer orders.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

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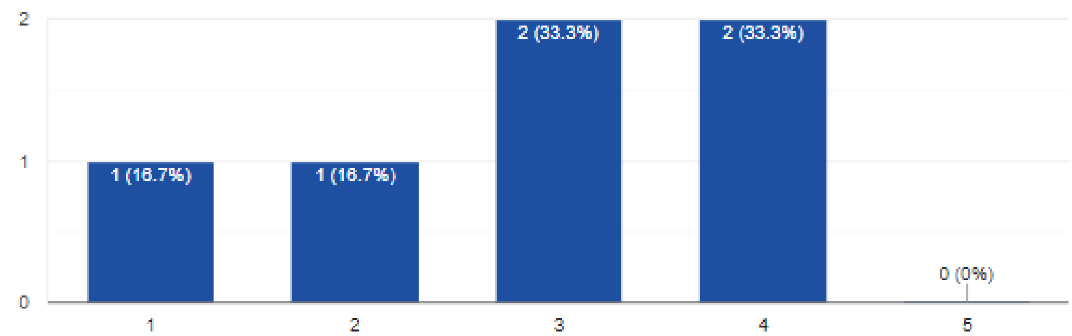

C 6: Evaluate your agreement with the following statement on the impact of AM on the supply chain capability "Flexibility in order fulfilment" (see definition below)

AM strengthens this capability by allowing possibility to postpone orders until a customer order is received.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

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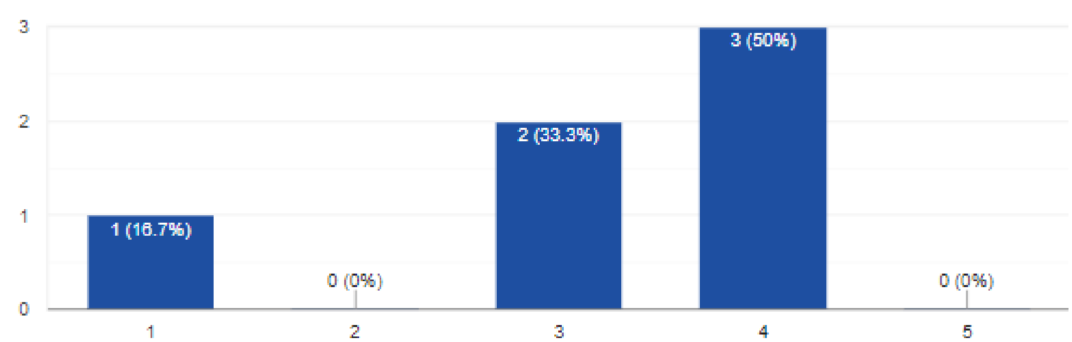


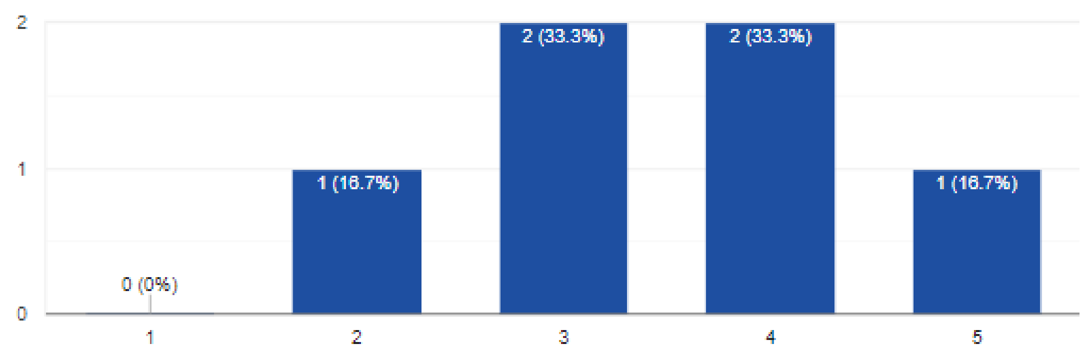
Questions Responses 6 Settings

C 7: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "flexibility in sourcing" (see definition below)

AM weakens this capability because there is a limited availability of substitute suppliers. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

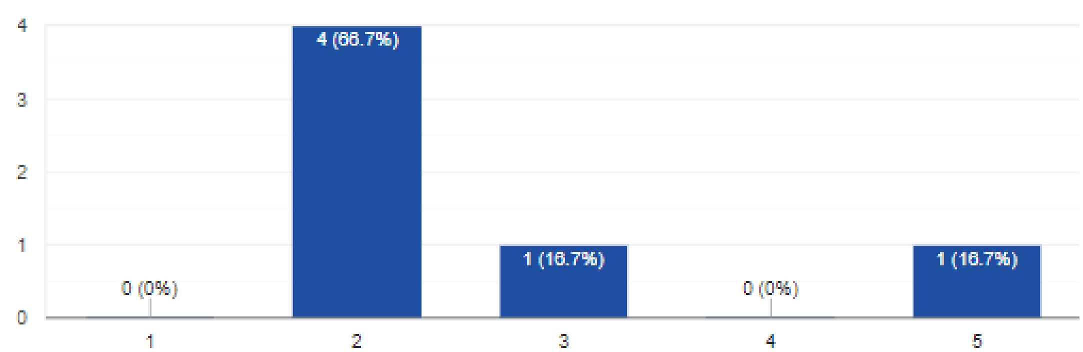
6 responses



AM weakens this capability because there is a limited availability of raw materials required for production. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



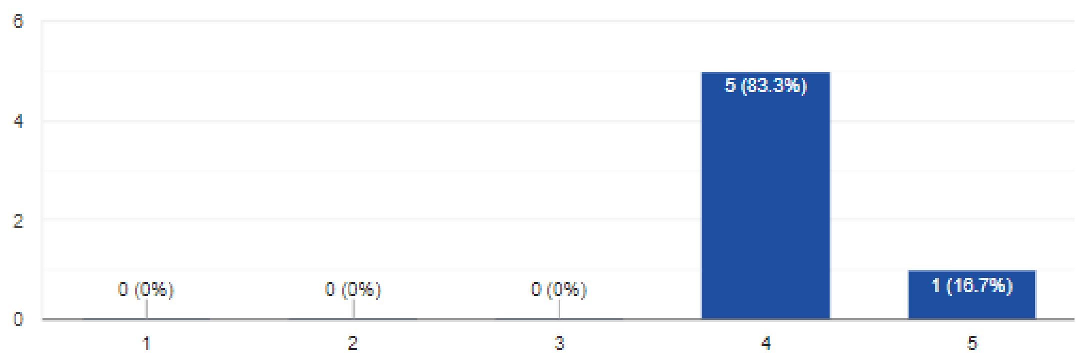
Questions Responses 6 Settings

C 8: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Market position" (see definition below)

AM strengthens this capability because it provides room for co-design of products with customers.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

6 responses



AM strengthens this capability because production is more customer-focused and customer relationships are improved as a result.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

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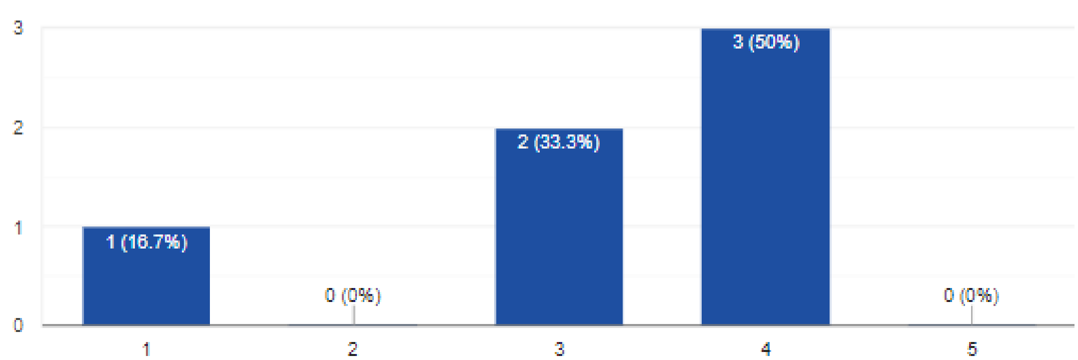
6 responses



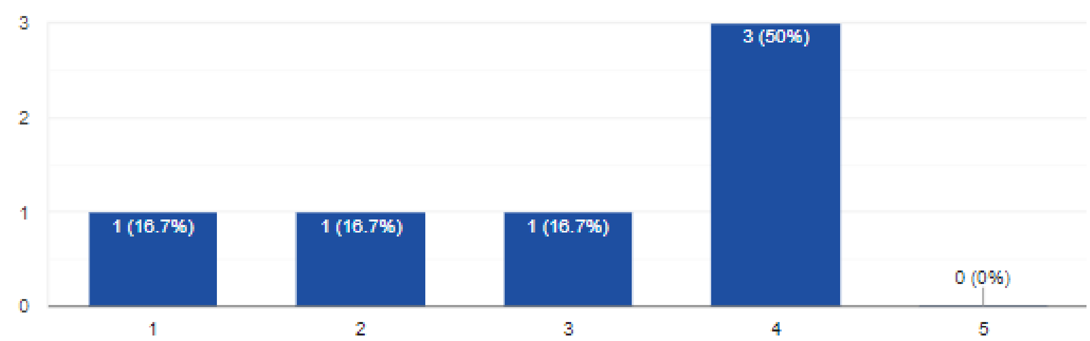
Questions Responses 6 Settings

C 9: Evaluate your agreement with the following statement on the impact of AM on the supply chain capability "Recovery" (see definition below)

AM strengthens this capability by enhancing the ability to outsource production in the event of capacity/distribution shortages. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses

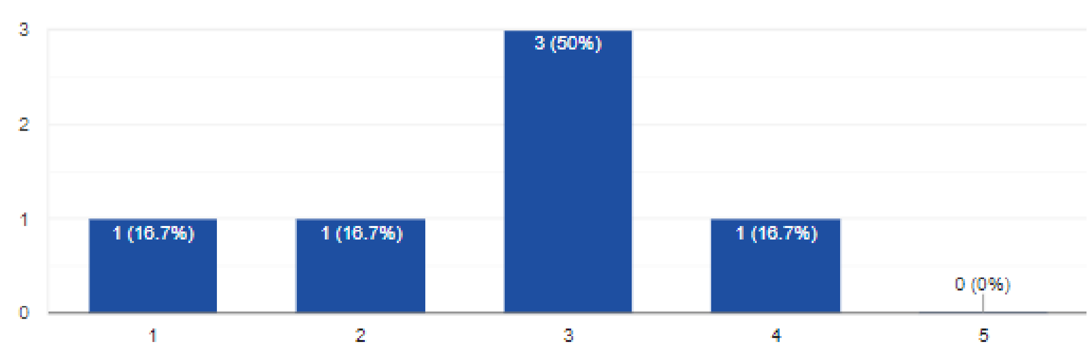


C 10: Evaluate your agreement with the following statement on the impact of AM on the supply chain capability "Visibility" (see definition below)

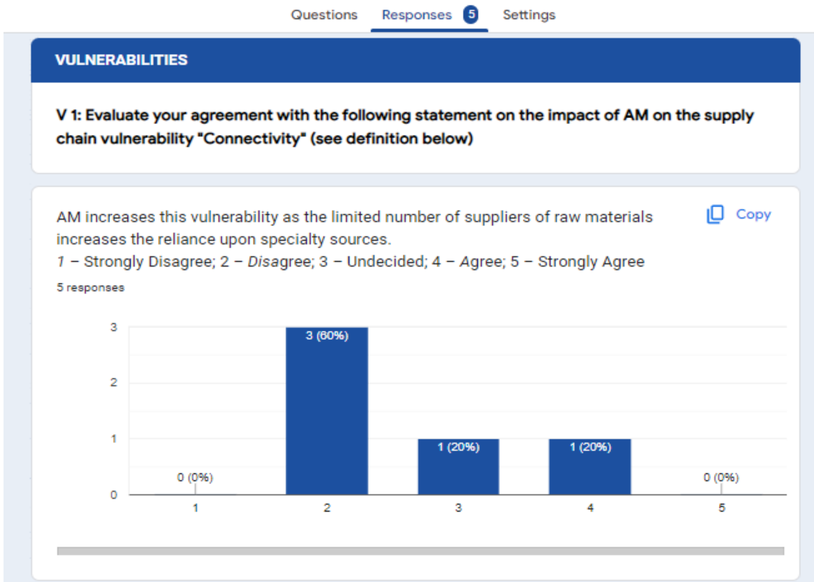
AM strengthens this capability because the reliance on ICT systems for information sharing helps in anticipating customer demands. Copy

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

6 responses



Round 2


Questions
Responses 5
Settings
VULNERABILITIES
V 1: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Connectivity" (see definition below)
AM increases this vulnerability as the limited number of suppliers of raw materials increases the reliance upon specialty sources.
1 – Strongly Disagree; 2 – Disagree; 3 – Undecided; 4 – Agree; 5 – Strongly Agree
Copy
5 responses
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3 (60%)
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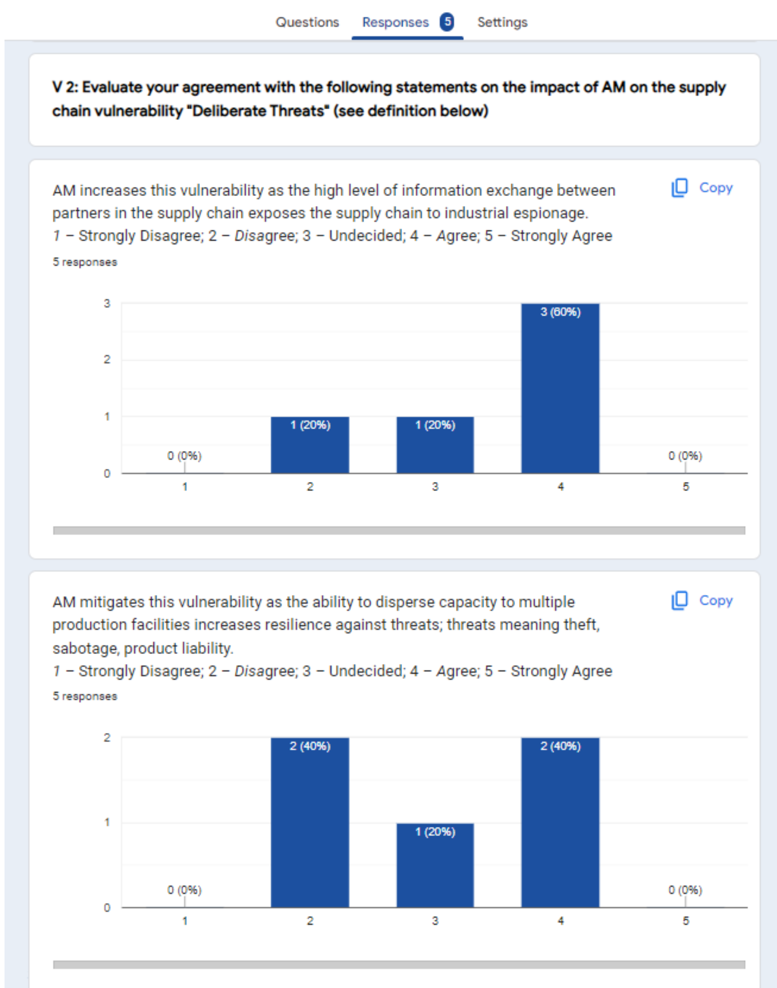
Questions
Responses 5
Settings
V 2: Evaluate your agreement with the following statements on the impact of AM on the supply chain vulnerability "Deliberate Threats" (see definition below)
AM increases this vulnerability as the high level of information exchange between partners in the supply chain exposes the supply chain to industrial espionage.
1 – Strongly Disagree; 2 – Disagree; 3 – Undecided; 4 – Agree; 5 – Strongly Agree
Copy
5 responses
0 (0%)
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3 (60%)
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AM mitigates this vulnerability as the ability to disperse capacity to multiple production facilities increases resilience against threats; threats meaning theft, sabotage, product liability.
1 – Strongly Disagree; 2 – Disagree; 3 – Undecided; 4 – Agree; 5 – Strongly Agree
Copy
5 responses
0 (0%)
2 (40%)
1 (20%)
2 (40%)
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Questions Responses 5 Settings

CAPABILITIES

C 3: Evaluate your agreement with the following statement on the impact of AM on the supply chain capability "Collaboration" (see definition below)

AM strengthens this capability by promoting an increase in collaborative information sharing between supply chain partners.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

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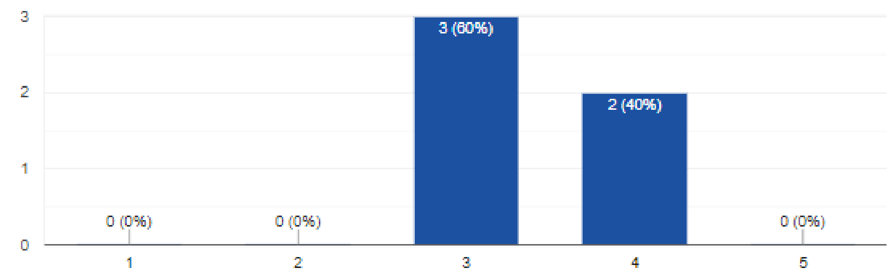
5 responses

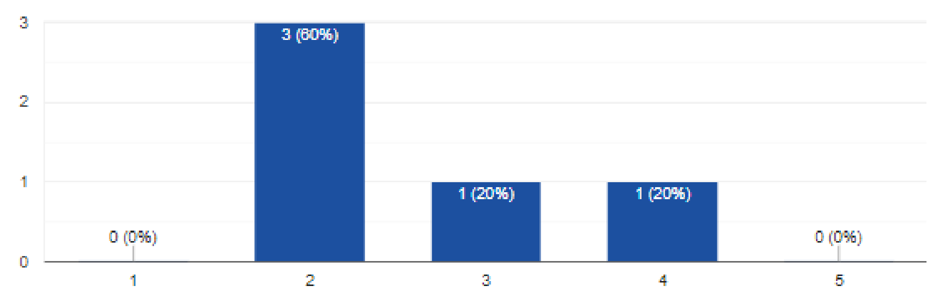


C 7: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "flexibility in sourcing" (see definition below)

AM weakens this capability because there is a limited availability of substitute suppliers.
1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

Copy

5 responses



Questions Responses 5 Settings

C 5: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Efficiency" (see definition below)

AM strengthens this capability because there is an extension of the product's life cycle.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

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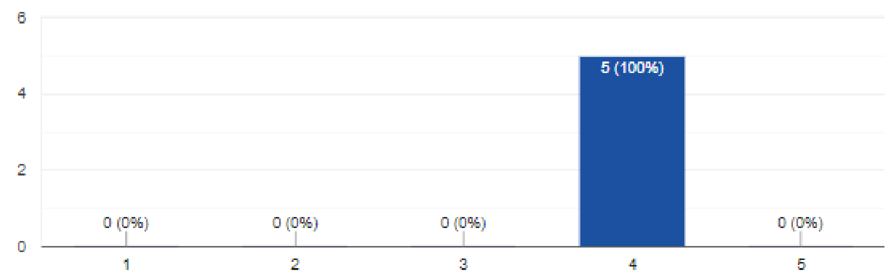
5 responses



AM strengthens this capability because production is on-demand according to customer orders.

1 – Strongly Disagree; 2 – *Disagree*; 3 – Undecided; 4 – *Agree*; 5 – Strongly Agree

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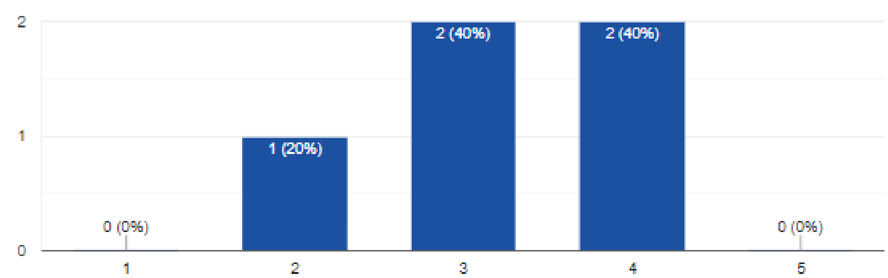
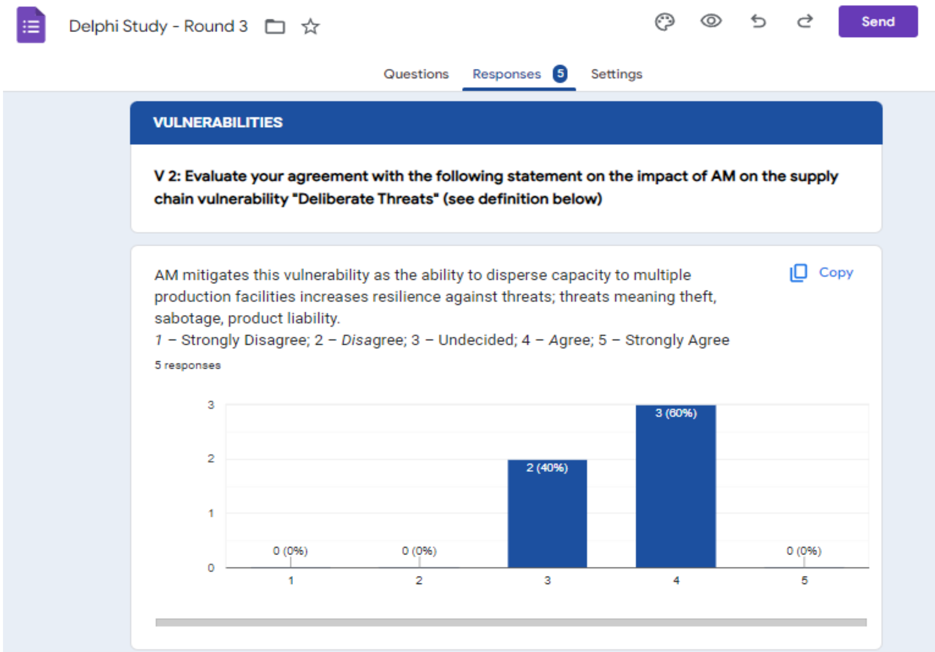
5 responses



Round 3


Delphi Study - Round 3
Send
Questions
Responses 5
Settings
VULNERABILITIES
V 2: Evaluate your agreement with the following statement on the impact of AM on the supply chain vulnerability "Deliberate Threats" (see definition below)
AM mitigates this vulnerability as the ability to disperse capacity to multiple production facilities increases resilience against threats; threats meaning theft, sabotage, product liability.
1 – Strongly Disagree; 2 – Disagree; 3 – Undecided; 4 – Agree; 5 – Strongly Agree
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5 responses
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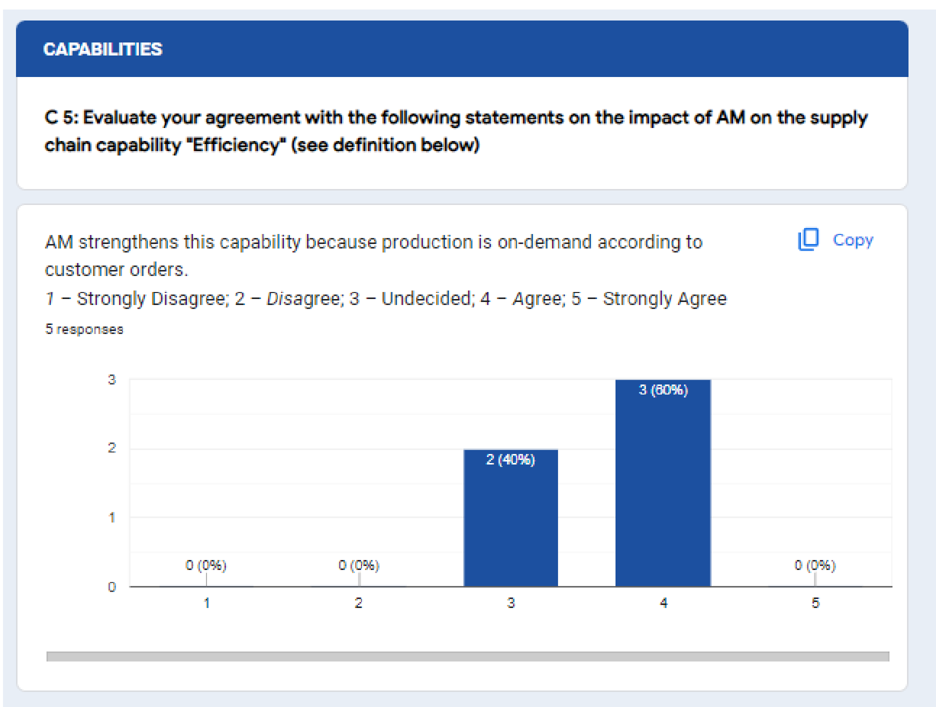
CAPABILITIES
C 5: Evaluate your agreement with the following statements on the impact of AM on the supply chain capability "Efficiency" (see definition below)
AM strengthens this capability because production is on-demand according to customer orders.
1 – Strongly Disagree; 2 – Disagree; 3 – Undecided; 4 – Agree; 5 – Strongly Agree
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5 responses
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Countermeasures

Delphi Study - Countermeasures All changes saved in Drive

Questions Responses 3 Settings

VULNERABILITIES

V2: High reliance on information flow which expose IT inadequacies

3 responses

Encryption and multiple fail safes

The information flow should be limited due to IP concerns.

Some countermeasures to for example avoid data security breaches could be to ensure that security is a top priority for IT in different companies. When your company shares information it can be many reasons why you have data breaches such as bad encryption of information or no encryption at all, outdated software with security breaches that have been patched in updates but as company did not update software they are still present.

Also scalability can be an issue as when a company grows maybe their IT infrastructure does not scale properly and the demand is greater than the offer IT infrastructure can give making bottlenecks, or crashes that will disrupt the information flow between parties.

V4: No regulation and standardization for AM materials and processes

3 responses

Close collaboration between research, policy, and industry.

There are/Will be standardization for AM Manufacturers, a specially for Aerospace suppliers.

For AM materials one of the issues we can have is that the material is inconsistent as it is quite new and for example the density if you use 3D printing in PLA can vary a lot. Humidity affects for example the quality of 3D printed parts with PLA. Having a controlled environment such a lab where temperature and humidity are controlled can be a countermeasure for this issue.

As of today I am not aware of material specifications for some AM materials and therefore companies can struggle to find standards that define material properties making unreliable to use one supplier for materials or another.

We have experienced that in Alva when ordering PLA from one supplier or another where we could see that the tension that one material coud resist from one material or the other for the same print was almost twice as much having exactly the same settings and the only change being the change of material supplier.

Delphi Study - Countermeasures All changes saved in Drive

Questions Responses 3 Settings

CAPABILITIES

C3: Insufficient information sharing in the supply chain

3 responses

Close collaboration between supply chain actors

Better collaboration between end user and manufacturer after the agreement is signed is a given.

One countermeasure could be to stablish collaborative platforms where supplier and customer exchange information and any update from any party is available to both parties. There are several tools to exchange information so the best would be to unify the solution preferrred by both parties.

Also transparency in the communication can be a countermeasure as you need to keep the communication as clean and efficient as possible in order to avoid miscommunication and issues when "delivering" or "ordering". An example can be when a supplier is not clear with leadtimes and they promise to deliver within 10 days but then they take 20 instead of 10. That will lead in insufficient information sharing making a disruption for the customer and also waste of time due to not good or transparent communication.

C3: Minimal collaborative demand forecasting in the supply chain

3 responses

Usage of Big Data and predictive algorithms

this will create a longer time line or increase the inventory levels for the manufacturer, something that will lead to higher price or longer lead times.

Implementing Real-time monitoring for sales for example can help the minimal collaborative demand where the information is updated in actor of the supply chain. With Real-time monitoring you could predict if your forecast is accurate or not as well as update in production and the delivery of raw materials and with a well integrated ERP you can basically run a smooth supply chain that requires little information share as everything is updated in the forecast.

Delphi Study - Countermeasures   All changes saved in Drive

Questions   Responses 3   Settings

C5: Limited capacity sharing in the supply chain

3 responses

Investing in alternative suppliers

This should not be an issue with in the agreement with the end customer, however, sharing between other supply chains will be an issue.

A possible countermeasure could be to pool among different actors in the same business in order to share resources such as sharing equipment or production lines. In Norway this can be a problem as the market is quite small and the capacity is also limited for most of the actors.

C10: Inadequate ICT structure for secure information sharing in the supply chain

3 responses

Investing in ICT infrastructure

Here the ICT must be in place, if not this will limited the manufacturer to deliver anything to Aerospace and defense customers.

To avoid having an inadequate ICT structure one possible countermeasure could be to pefrorm regular IT audits either internally or by hiring external consultants that can perform this service for us. This way you can address different security gaps and patch or fix them before they become an issue.

C: Propositions for supply chain capabilities

Capability factor	Definition (Pettit, et al., 2011)	Sub-factors (Pettit, et al., 2011)	Propositions
Adaptability	Ability to modify operations in response to challenges or opportunities.	Fast re-routing of requirements, Lead time reduction, Strategic gaming and simulation, seizing advantage from disruptions, Alternative technology development, Learning from experience.	AM adoption positively affects adaptability since short lead times and the possibility to reallocate production enables the supply chain to quickly respond to disruptions.
Capacity	Capability to have the necessary assets available to enable sustained levels of production.	Reserve capacity, Redundant assets.	AM adoption positively affects capacity since AM enables redundancy in production and facilitates production scalability by providing a buffer to address volatile demand.
Collaboration	Ability to work effectively with other entities for mutual benefit.	Collaborative forecasting, Customer management, Communications, Postponement of orders, Product life cycle management, Risk sharing with partners.	AM adoption positively affects collaboration since AM facilitates order postponement, collaborative information sharing and collaborative demand forecasting.
Dispersion	Broad distribution or decentralization of assets.	Distributed decision-making, Distributed capacity and assets, Decentralization of key resources, Location-specific empowerment, Dispersion of markets.	AM adoption positively affects dispersion since AM enhances the possibility to distribute capacity in multiple locations, also facilitating the dispersion of markets.
Efficiency	Capability to produce outputs with minimum resource requirements.	Waste elimination, Labor productivity, Asset utilization, Product variability reduction, Failure prevention.	AM adoption positively affects efficiency since AM allows minimum raw material consumption, capacity sharing, production of complex products in an easy way, tool-less manufacturing approach, reduced labour need, on-demand manufacturing, and the extension of the product's life cycle via in situ remanufacturing.
Flexibility in order fulfilment	Ability to quickly change outputs or the mode of delivering outputs.	Alternate distribution channels, Risk pooling/sharing, Multi-sourcing, Delayed commitment, Production postponement, Inventory management, Re-routing of requirements.	AM adoption positively affects flexibility in order fulfilment since AM facilitates on-demand production, order postponement and rerouting of production capacity to different facilities.

Flexibility in sourcing	Ability to quickly change inputs or the mode of receiving inputs.	Part commonality, Modular product design, Multiple uses, Supplier contract flexibility, Multiple sources.	AM adoption negatively affects flexibility in sourcing due to limited availability of substitute suppliers and limited raw materials for production.
Market position	Status of a company or its products in specific markets.	Product differentiation, Customer loyalty/retention Market share, Brand equity, Customer relationships, Customer communications.	AM adoption positively affects market position since AM features like co-design and customer-focused production allow close collaboration with customers which improve customer relationships.
Recovery	Ability to return to normal operational state rapidly.	Crisis management, Resource mobilization, Communications strategy, Consequence mitigation.	AM adoption positively affects recovery since AM facilitates outsourcing of production in the event of capacity or distribution shortages, breakdown of production equipment and geopolitical crisis.
Visibility	Knowledge of the status of operating assets and the environment.	Business intelligence gathering, Information technology, Products, Assets and People visibility, Information exchange.	AM adoption positively affects visibility due to the reliability on ICT systems by partners in the supply chain, this promotes information sharing across the SC and enables the supply chain better anticipate customer demands.

D: Propositions for supply chain vulnerabilities

Vulnerability factor	Definition (Pettit, et al., 2011)	Sub-factors (Pettit, et al., 2011)	Propositions
Connectivity	Degree of interdependence and reliance on outside entities.	Scale of network, Reliance upon information, Degree of outsourcing, Import and Export channels, Reliance upon specialty sources.	AM adoption positively affects connectivity since AM facilitates an increase in the degree of outsourcing of production to external entities due to the digital nature of AM technology. However, there is a negative impact since the high reliance upon information flow can create connectivity issues when adequate ICT infrastructures are missing. Similarly, the limited number of suppliers of raw materials increased the reliance upon specialty sources.
Deliberate threats	Intentional attacks aimed at disrupting operations or causing human or financial harm.	Theft, Terrorism/sabotage, Labor disputes, Espionage, Special interest groups, Product liability.	AM adoption positively affects resilience to deliberate threats since AM facilitates the dispersion of capacity to multiple facilities (redundancy in production). However, there is also a negative impact since the high level of information exchange exposes SC to industrial espionage.
Resource limits	Constraints on output based on availability of the factors of production.	Supplier, Production and Distribution capacity, Raw material and Utilities availability, Human resources.	AM adoption negatively affects resource limits due to its reliance on very few suppliers in the supply chain, causing an exposure to raw material and supplier unavailability.
Sensitivity	Importance of carefully controlled conditions for product and process integrity.	Complexity, Product purity, Restricted materials, Fragility, Reliability of equipment, Safety hazards, Visibility to stakeholders, Symbolic profile of brand, Concentration of capacity.	AM adoption negatively affects sensitivity due to problems on the reliability of equipment and utilization of limited materials, as well as the importance of their purity.
Supplier-Customer disruptions	Susceptibility of suppliers and customers to external forces or disruptions.	Supplier reliability, Customer disruptions.	AM adoption positively affects supplier-customer disruptions thanks to the possibility to reallocate production, distribute capacity and potential to reroute requirements.
Turbulence	Environment characterized by frequent changes in external factors beyond your control.	Natural disasters, Geopolitical disruptions, Unpredictability of demand, Fluctuations in currencies and prices, Technology failures, Pandemic.	AM adoption positively affects turbulence since AM facilitates lead time reduction and distributing capacity to different locations which promote the recovery of the supply chain from disruptions like unsteady customer demands and geopolitical upsets.

E: Specialization Project

NTNU
Norwegian University of Science and Technology

TPK4530 SPECIALIZATION PROJECT

Fall Semester

MANAGING SUPPLY CHAIN DISRUPTIONS WITH THE SUPPORT OF ADDITIVE MANUFACTURING

Author: Joseph Aguariavwodo
Supervisor: Mirco Peron

Department of Mechanical and Industrial Engineering

Norwegian University of Science and Technology

December 2022

Preface

This specialization project was written in the third semester of the Global Manufacturing Management master's degree Program at the Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

The theme of this project is of great interest to me and conducting this specialization project has given me motivation to pursue further research in this field.

I would like to thank my supervisor, Mirco Peron for his guidance and direction while conducting this research project, and the production management research group for their support and feedback throughout the semester. I would also like to express my thanks to my colleagues for their support and perspectives while conducting this project.

And finally, I would like to thank my friends and family for providing me with moral support and encouragement throughout the semester.

Joseph Aguariavwodo

Trondheim, Norway

20.12.22

Abstract

Research on supply chain disruptions had led to the development of strategies which companies can implement to make their operations more resilient and anticipate disruptions better. Supply chain resilience is gaining popularity today due to the collapse of many supply chains caused by the COVID-19 pandemic, but there is little research relating to supply chain resilience and the adoption impacts of additive manufacturing.

This specialization project addresses the need for empirical evidence that supports the adoption of additive manufacturing to enhance supply chain resilience in dealing with disruptions. In this specialization project, one major research question guides the research. This research question was further divided into two based on the constructs of supply chain resilience. The research questions are;

RQ 1: How does additive manufacturing affect supply chain resilience?

RQ 2: How does additive manufacturing affect supply chain capabilities?

RQ 3: How does additive manufacturing affect supply chain vulnerabilities?

In this project, three research areas are identified to identify the literature gap in the adoption impacts of additive manufacturing for supply chain resilience. The research areas are;

i. Supply chain disruptions
ii. Supply chain resilience
iii. Additive manufacturing

The research also combines the literature study on the two constructs of supply chain resilience to generate propositions as recommendations for managers in the industry. An agenda for future research is given as well. Future research could involve quantitative methods on how the flexibility of additive manufacturing enables firms respond better to customer demands. This specialization project sufficiently addresses the topic of supply chain disruptions & resilience, and it lays the foundation for future research in this field.

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List of Abbreviations

AM: Additive Manufacturing

AM-SCR: Additive Manufacturing-Supply Chain Resilience

CODP: Customer Order Decoupling Point

COVID-19: Coronavirus disease

PPE: Personal Protective Equipment

SC: Supply Chain(s)

SCM: Supply Chain Management

SCR: Supply Chain Resilience

SCRAM: Supply Chain Resilience Assessment and Management

1. Introduction

1.1 Background

Supply chain disruptions are generally seen as unintended and unexpected events that occur upstream in the supply chain, in the logistics network or further downstream that threaten the normal business operations of the focal organization (Messina, et al., 2020). Supply chains (SC) almost always prove to be vulnerable to disruptions. A recent example is the outbreak of the COVID-19 pandemic that caused significant reductions in the supply and availability of products spanning different industries on a global scale. Other examples of supply chain disruptions are natural disasters, transportation failure and delays like the crisis at the Suez Canal in 2021, price fluctuations, legal contract disputes, epidemics and pandemics, political crises, and cyber-attacks, all of which pose a great risk to the supply chain (Ivanov, 2021).

Disruption risks can be caused by several reasons such as; supply chain complexity due to increased globalization and outsourcing, disruptions at a supply base and increased specialization and geographical concentration of manufacturing which imply that a disruption at one or more points will affect almost all the points and links in the supply chain (Ivanov, 2021). These potential shortcomings drive supply chains to be more resilient to disruptions considering that most contemporary supply chains operate globally which makes them even more vulnerable to disruptions (Naghshineh & Carvalho, 2021)

Supply chain resilience has become popular in the last decade and is necessary for businesses in ensuring continuity and dealing with unexpected disruptions. Supply chain resilience has been defined by (Hohenstein, et al., 2015) as the supply chain's ability to be prepared for unexpected risk events, respond and recover quickly from potential disruptions, return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance. The concept of supply chain vulnerabilities and capabilities as constructs of supply chain resilience was introduced by (Pettit, et al., 2011) as an approach in risk management to enable a supply chain to survive unexpected disruptions.

New studies on supply chain resilience are carried out to ascertain that for supply chains to be resilient, it is vital for firms to build certain operational capabilities that must be aligned with supply chain partners to manage both expected, unexpected changes and aspects within the supply chain that would make it vulnerable to disruptions.

Part of these operational capabilities is the adoption of technologies like additive manufacturing which impacts the state and dynamics of the supply chain thereby influencing its capacity to be resilient to vulnerabilities and disruptions (Naghshineh & Carvalho, 2021). Supply chain capabilities are defined as attributes that enable an enterprise or organization anticipate and overcome disruptions, while supply chain vulnerabilities are defined as fundamental factors that make an enterprise susceptible to disruptions (Pettit, et al., 2011).

Additive manufacturing (AM) also known as 3D printing, rapid manufacturing, rapid prototyping, or digital manufacturing is a technology that enables the production of complex geometries and near-net shape components, its name stems from the fact that it builds a component, part or product from raw materials layer by layer, additively (Zijm, et al., 2019). This technology is becoming more popular in supply chains because of its potential to reduce inventory holding costs and allow on-demand production of customized products within a short time. This potential is seen as very important for enterprises in building capabilities to counteract vulnerabilities and ensure long-term survival. Additive manufacturing technology emerged as a mitigation tool to effectively manage disruptions caused by the COVID-19 pandemic and risks that affected supply chains. The adoption of AM impacts the state and dynamics of supply chains influencing their capacity to be resilient to SC vulnerabilities and disruptions (Naghshineh & Carvalho, 2021). The role of additive manufacturing in the medical industry during the pandemic was to stop the shortage of medical devices and personal protective equipment. As a result of the pandemic, companies, groups and individuals started to cooperate to supply people and hospitals that were facing items shortage (Longhitano, et al., 2021). One of the main reasons that medical device supply chains became resilient after this major disruption was the ability of 3D printers to rapidly produce specialized medical devices that complied with regulatory standards.

This research project aims to understand the possibilities for additive manufacturing to impact supply chain resilience while dealing with disruptions. The research is conducted through a systematic review of literature on the topic to identify gaps and develop the body of knowledge further.

1.2 Problem statement

Little research has been done on the link between supply chain resilience and supply chain digitalization using tools like additive manufacturing. To give more clarity, (Zouari, et al., 2020) concluded that supply chain resilience is positively impacted by the degree of digital maturity and the adoption of digital tools. However, the importance of additive manufacturing for supply chain resilience was not addressed. In more recent studies, (Naghshineh & Carvalho, 2020) and (Meyer, et al., 2022) proposed that additive manufacturing could be advantageous in dealing with supply risks and further identified proactive and reactive capabilities that will ensure a resilient supply system, but they didn't provide in-depth information on how additive manufacturing will ensure resilience in the supply chain. The publication by (Naghshineh & Carvalho, 2021) addresses how the adoption of AM influences the state of the SC and makes the supply chain more resilient. However, there is limited empirical evidence on how AM adoption improves resilience to SC disruptions. Therefore, this project aims to bridge that gap.

1.3 Research scope

The main objective of this project is to investigate supply chain resilience and additive manufacturing in dealing with disruptions. This research project will focus on generating propositions that will be used in a survey to get empirical evidence on how additive manufacturing can be a support system in dealing with disruptions and enhancing supply chain resilience. Existing literature on additive manufacturing for supply chain resilience don't explain in details how additive manufacturing can guarantee supply chain resilience. Although the paper by (Naghshineh & Carvalho, 2021) provides some insights on the adoption impacts of additive manufacturing in supply chains, it doesn't explicitly say how the adoption impacts of additive manufacturing will establish supply chain resilience. To develop a good understanding of this research area, three topics will be studied critically to identify the literature gap. These topics are:

- Supply Chain Disruptions: to highlight the causes of disruptions in supply chains and ways to deal with disruptions.
- Supply Chain Resilience: subfactors like supply chain capabilities and vulnerabilities will be evaluated and used to develop propositions.
- Additive Manufacturing: will be discussed to ensure a common understanding of the technology and its use in supply chains.

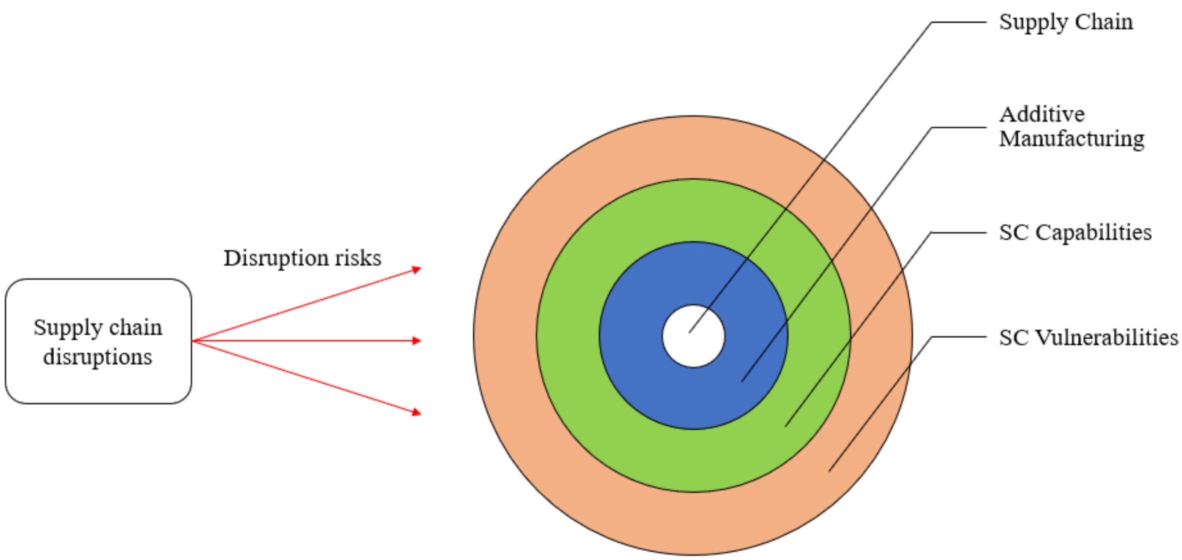


Figure 5: Research variables

Figure 1 shows the connection between the topics of this research project. Disruption risks affect the supply chain and become vulnerabilities when adverse effects occur which cause damages to the supply chain (Wu, et al., 2020). This project will determine if the adoption of additive manufacturing in the supply chain will enhance SC capabilities that will mitigate SC vulnerabilities to improve supply chain resilience. Research on these topics were carried out through a literature review to view contributions on the topics over the last few years.

1.4 Research questions

Based on the main objective of this research project, one main research question (RQ1) was defined to address the literature gap in additive manufacturing for supply chain resilience. The research question was divided into two RQs (RQ2 and RQ3) based on the two constructs of supply chain resilience developed by (Pettit, et al., 2011).

RQ 1: How does additive manufacturing affect supply chain resilience?

RQ 2: How does additive manufacturing affect supply chain capabilities?

RQ 3: How does additive manufacturing affect supply chain vulnerabilities?

To answer the research questions, I performed a systematic review of the literature that exists on the topic and developed propositions which will be discussed in detail later in this report. RQ1 will be answered in chapter 2, while RQ2 and RQ3 will be answered in chapter 4.

2. Theoretical background

This chapter presents theory on supply chain disruptions along with additive manufacturing and supply chain resilience to show the literature gap in the additive manufacturing for supply chain resilience topic. The chapter consists of three parts: an analysis of supply chain disruptions, discussion on supply chain resilience and its subfactors, and a review of additive manufacturing where the first research question will be addressed.

2.1 Investigating supply chain disruptions

As briefly described in chapter one, SC disruptions are unexpected events occurring in both the upstream and downstream parts of the supply chain which threaten normal operations of an organization. Most literature describe disruptions as a temporal occurrence with its causes emerging from the industry context, the focal organization context, specific problems and decision-making issues (Öberg, 2021). The various causes and effects of disruptions with related factors are shown in the table below.

<table>
<tr><th>Causes</th><th>Factors</th><th>Effect</th></tr>
<tr><td>Natural disasters</td><td>Globalized supply chains</td><td rowspan="6">Heightened demand, trade restrictions, raw material shortage, factory closures, product shortage, price inflation, production & supply chain bottlenecks.</td></tr>
<tr><td>Pandemics and epidemics</td><td>Specialized factories</td></tr>
<tr><td>Logistic failure and delays</td><td>Centralized distribution</td></tr>
<tr><td>Cyber-attacks</td><td>Increased outsourcing</td></tr>
<tr><td>Political instability</td><td>Reduced supplier base</td></tr>
<tr><td>Legal contract disputes</td><td>Increased demand volatility</td></tr>
</table>

Table 7: Causes and effects of disruptions (Ivanov, 2021; Petit, et. al., 2011)

It is understood that when disruptions occur in an industry, organization or in one part of the supply chain (upstream or downstream), the ripple effects spread to other parts of the supply chain which adversely impacts the performance of individual firms and networks. Ripple effect in a supply chain occurs when a disruption, rather than remaining contained to one part of the supply chain, cascades downstream/upstream and impacts the performance of the entire supply chain (Ivanov, 2021). To effectively deal with disruptions and prevent its ripple effect from affecting the entire supply chain, different strategies can be employed in the different phases of disruption that can make supply chains ready to tackle disruptions, respond to and recover after being affected by disruptions (Ali, et al., 2017). The phases are

1. Pre-disruption phase
2. During-disruption phase
3. Post-disruption phase

The phases and strategies employed would be discussed further in this chapter.

2.1.1 Pre-disruption phase

In this phase, proactive strategies such as anticipation are needed to enable supply chains prepare, resist and avoid disruption. (Ali, et al., 2017). Elements of this strategy are:

1. situation awareness which involves an understanding of supply chain vulnerabilities and planning for such events
2. robustness which is the ability of the supply chain to proactively anticipate change before it occurs and resist change by retaining its stability and functioning despite disturbances
3. security which protects the supply chain from deliberate attacks such as counterfeiting and can be improved by creating synergies with SC partners
4. visibility which can be enhanced by IT capabilities that can enable transparency through connectivity and integrated information sharing across the supply chain.

The pre-disruption phase is characterized by high uncertainty and unpredictability of the occurrence of disruptions, and the ability of organizations to mitigate disruption risks. In this light, (Das, et al., 2019) suggested that designing supply chains with a low need for "certainty" may be as important as proactive strategies. The challenges faced with disruption impact investigation are the consideration of "known events", the exclusion of "unknown events" and the attention to mainly the direct effects of disruptions rather than disruption propagation chains and the resulting indirect effects. They further stated that the ultimate objective of the low-certainty-need supply chains is for organizations to develop the ability to operate according to planned performance regardless of external changes.

2.1.2 During-disruption phase

After a disruption is discovered, organizations must take immediate action to cope with the impact, contain ripple effects, and restore operations in the supply chain as soon as possible

(Chen, et al., 2019). In this phase, concurrent strategies such as adaptability and responsiveness are required to enable supply chains cope with disruptions. (Ali, et al., 2017). Elements of these strategies are:

1. flexibility, which is the ability to adapt to disruptions and redeploy dedicated capacity and resources
2. redundancy, which entails maintaining excess capacity to respond to disruptions in the supply chain
3. collaboration, which involves responding to SC disruptions with partners through collaborative planning and information sharing
4. agility, which is the ability of the supply chain to adapt quickly to unexpected changes in demand or supply.

2.1.3 Post-disruption phase

Reactive strategies such as recovery and restoration are required to enable supply chains bounce back from disruptions and return to the original or desired state. (Ali, et al., 2017). The recovery strategy is concerned with supply chain stabilization and adjustments to the allocation of scarce resources to ensure process continuity. In this phase, organizations should prioritize operations preservation and contingency plan execution to stabilize resiliency, followed by adaptation and long-term impact minimization as primary elements for recovering from disruptions (Chen, et al., 2019). To properly recover from disruptions, that is from discovering disruptions to returning to a normal level of performance, (Chen, et al., 2019) state that organizations must consider some important factors in their management process which are; collaboration and coordination, formation of an emergency/crisis team and establishment of a standard of procedure. Implementation of these factors will ultimately lead to supply chain reconfiguration / redesign, resource reconfiguration, development of recovery plans, evaluation of financial strength and market position, improvement of customer relations, and knowledge management.

Supply chain resilience encompasses both proactive and reactive strategies in the different disruption phases, therefore an integration of pro- and reactive decisions is important for increasing SC resilience by utilizing the synergetic effects between mitigation and contingency policies (Das, et al., 2019).

2.2 Supply chain resilience

Supply chain resilience was first described as the ability of the supply chain to cope with unexpected disturbances (Christopher, 1992). In this publication, it was discovered that supply chains are vulnerable to disruptions due to organizations seeking out low-cost solutions, developing leaner supply chains and in consequence there is an increased risk in business continuity. In achieving supply chain resilience, it is necessary to understand what makes supply chains more vulnerable, assess the risk profile to effectively mitigate and manage those risks. The term was introduced again by (Christopher, et al., 2003) as a term in mitigating supply chain risks, from which a strategic approach in creating a resilient supply chain was developed. This approach denotes that supply chain resilience requires recognition when strategic decisions are taken in an organization, such as relocating facilities or changing sources of supply.

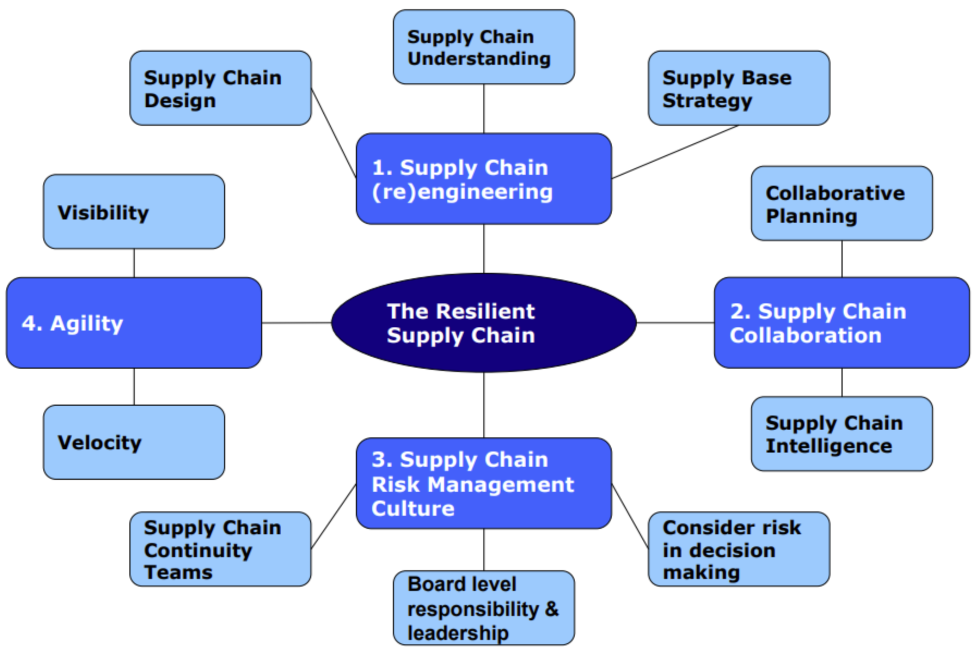


Figure 6: Strategic approach to create SC resilience

Figure 2 highlights agility and collaboration as requirements that must be in place to improve resilience in the supply chain. Agile supply chains are characterized by the ability of firms to continuously monitor and interpret demand and supply in a volatile market and maintain communication with suppliers and customers (Rahimi, et al., 2019). Aspects like visibility (the capability of the company to see all the information regarding the flow of products and finances both downstream and upstream along the supply chain), flexibility (capability to quickly readapt production) and velocity (time required for moving goods along the supply chain, measured in lead times) which are directly linked to SC agility also affect supply chain resilience (Ambrogio, et al., 2022). The agility of a company is also dependent on the agility of all the actors involved in the supply chain, as such a company's resilience is significantly affected by its customers' and suppliers' ability to anticipate and respond to disruptions (Pettit, et al., 2019). This is in contrast to antifragile supply chains that embrace disruptions and disorders and see disruptions as an opportunity to learn and grow (Priyadarshini, et al., 2022).

As mentioned in chapter 1, supply chain resilience depends on two constructs; capabilities and vulnerabilities, and these constructs will be explained further in detail.

2.2.1 Capabilities and vulnerabilities

Supply chains must be designed in a way to withstand disruptions i.e., the supply chain should exhibit low vulnerability and recover from disruptions quickly at minimal cost (Ivanov, 2021). Supply chain resilience looks at maintaining some levels of desired performance despite disruptions. With the use of some proactive capabilities i.e., inventory, flexibility, a supply chain can absorb negative disruption impacts for example, supply unavailability without performance degradation. However, if proactive capabilities do not help, performance can decline. Therefore, balancing vulnerabilities and capabilities is a major concern in supply chain resilience management (Ivanov, 2021). The need for balancing capabilities and vulnerabilities is to reduce disruption risks and improve supply chain performance.

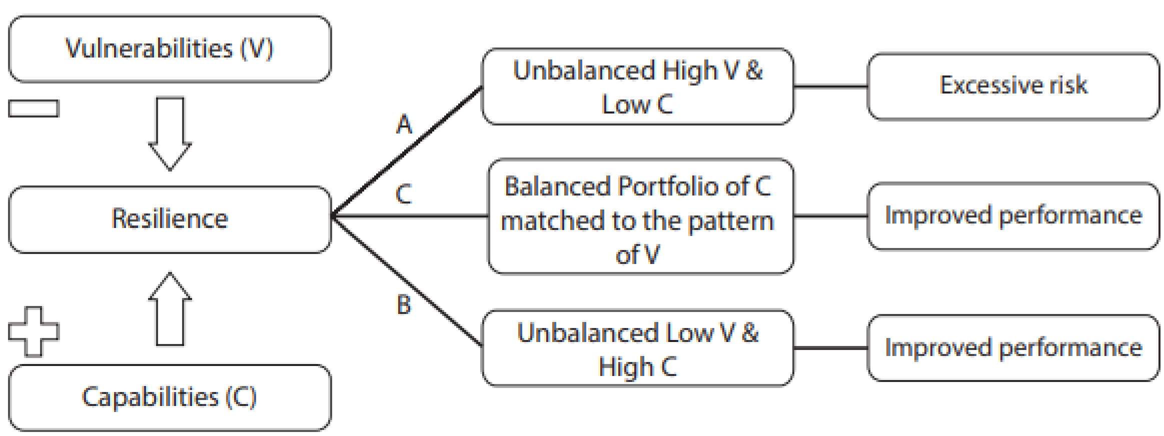


Figure 7: Balancing vulnerabilities and capabilities (Pettit et al., 2011)

Existing research on supply chain resilience is built on the framework developed by (Pettit, et al., 2011), which proposed that: supply chain resilience increases as capabilities increase and vulnerabilities decrease; linkages exist between each vulnerability and a specific set of capabilities that can directly improve balanced resilience. For example, a supply chain with high vulnerability in ‘connectivity’ can face severe consequences if capabilities in ‘visibility’ and ‘collaboration’ are poor.

Capabilities and vulnerabilities emerged as two constructs of the SCRAM framework, and the link between both constructs is based on the logic that capabilities are developed by firms to mitigate vulnerabilities and improve resilience in the supply chain. The supply chain resilience framework has potential to provide managers insights regarding their strengths, weaknesses, and priorities (Pettit, et al., 2011). By identifying highly rated capabilities, managers will have detailed information regarding the strength of the company and what can be done to gain competitive advantage. Examples for the two SCR factors ‘capabilities’ and ‘vulnerabilities’ were detailed in the SCRAM framework which are shown in table 2. These examples will be referred to as ‘sub-factors’ and will be used in outlining propositions which will serve as the main outcome of this report. A detailed description of examples of the two SCR factors ‘capabilities’ and ‘vulnerabilities’ is given in the appendix of this report.

Vulnerabilities	Capabilities
Turbulence, Deliberate threats, External pressures, Resource limits, Sensitivity, Connectivity, Supplier/Customer disruptions	Flexibility in sourcing, Flexibility in order fulfilment, Capacity, Efficiency, Visibility, Adaptability, Anticipation, Recovery, Dispersion, Collaboration, Organization, Market position, Security, Financial strength

Table 8: Examples of vulnerabilities and capabilities (Petit, et al., 2011)

The gap that exists in supply chain capabilities and vulnerabilities is such that limited information is available on the examples (and their relevance in industry) highlighted in the SCRAM framework, and only a specific company in one industry and its global supply chain was used in developing the SCRAM framework, and thus the examples given may be subjective. To expand on this framework, companies in several industries need to be focused on which may give rise to more examples within the two constructs of supply chain resilience.

2.3 Theory on additive manufacturing

As briefly mentioned in chapter one, additive manufacturing is the process of joining materials to make objects from 3D model data layer upon layer. AM can make efficient use of raw materials and produce minimal waste while reaching satisfactory geometric accuracy. In AM, a design in the form of a computerized 3D solid model can be directly transformed to a finished product without the use of additional fixtures and cutting tools. This opens up the possibility to produce parts with complex geometry that are difficult to obtain using material removal processes i.e., subtractive manufacturing (Huang, et al., 2013). Additive manufacturing technology consists of three basic steps:

1. A computerized 3D solid model is developed and converted into a standard AM file format

2. The file is sent to an AM machine where it is manipulated, e.g., changing the position and orientation of the part or scaling the part

3. The part is built layer by layer on the AM machine

Different AM methods build and consolidate layers in different ways using different materials, a summary is shown in figure 4 which is adapted from (Ngo, et al., 2018).

Methods	Materials	Applications	Benefits
Fused deposition modelling	Continues filaments of thermoplastic polymers Continuous fibre-reinforced polymers	Rapid prototyping Toys advanced composite parts	Low cost High speed Simplicity
Powder bed fusion (SLS, SLM, 3DP)	Compacted fine powders Metals, alloys and limited polymers (SLS or SLM) ceramic and polymers (3DP)	Biomedical Electronics Aerospace Lightweight structures (lattices) Heat exchangers	Fine resolution High quality
Inkjet printing and contour crafting	A concentrated dispersion of particles in a liquid (ink or paste) Ceramic, concrete and soil	Biomedical Large structures Buildings	Ability to print large structures Quick printing
Stereolithography	A resin with photo-active monomers Hybrid polymer-ceramics	Biomedical Prototyping	Fine resolution High quality
Direct energy deposition	Metals and alloys in the form of powder or wire Ceramics and polymers	Aerospace Retrofitting Repair Cladding Biomedical	Reduced manufacturing time and cost Excellent mechanical properties Controlled microstructure Accurate composition control Excellent for repair and retrofitting
Laminated object manufacturing	Polymer composites Ceramics Paper Metal-filled tapes Metal rolls	Paper manufacturing Foundry industries Electronics Smart structures	Reduced tooling and manufacturing time A vast range of materials Low cost Excellent for manufacturing of larger structures

Figure 8: Summary of method, materials, application, benefits of AM (Ngo, et al., 2018)

Additive manufacturing has emerged in recent years as a technology that has great potential to replace traditional or subtractive manufacturing technologies. This is due to the ability of additive manufacturing to eliminate the need for large bulk inventory thus reducing costs of inventory holding & logistics and allow on-demand production of small batch sizes of highly customized products thus reducing production lead time and improving process flexibility (Alkahtani & Abidi, 2019). This ability makes additive manufacturing a good solution for dealing with disruptions in the supply chain.

Traditional supply chain	AM influenced supply chain
High transport costs	Lesser transportation costs
High level of required inventory	Decrease in required inventory
Long lead times	Shorter manufacturing lead time
Push supply chain	Pull supply chain
Complex distribution networks	Reduced inventory
Lengthy response to customer demand	Quick response to customer demand
Manufacturing far away from point of use	Manufacturing closer to point of use
Challenging management of demand uncertainty	Easier management of demand uncertainty
Supply chain disruptions-broken machines, regional turmoil, or shipping delays	Hedge against disruption

Table 9: Traditional SC vs. AM influenced SC (Alkahtani & Abidi, 2019)

In comparison to conventional supply chains, it can be seen that the major impacts of additive manufacturing on supply chains are: a change in the supply chain structure where the need for multi-level production planning decreases along with the associated risks and costs, reduction of both raw material & finished goods inventory due to strong digitalization of the manufacturing process, decentralized manufacturing, reductions in transportation time & overall lead time, and increased customer responsiveness by shifting the customer order decoupling point (CODP) more upstream the supply chain (Zijm, et al., 2019). For manufacturers, AM's most useful role may turn out to be more in enhancing supply chain capabilities or innovations in different sections of the supply chain rather than in creating new products. However, there is still a research gap in designing and operating a proper framework for supply chain for additive manufacturing (Alkahtani & Abidi, 2019).

2.3.1 Additive Manufacturing for Supply Chain resilience

Resilient supply chains are characterized by the design of the supply chain network (provision of multiple sourcing alternatives, shorter SC length, how agile the SC is), nature of relationships between actors in the supply chain which is described by the degree of collaboration & information sharing, and design of processes, taking flexibility, capacity and redundancy into consideration (Wicher & Lenort, 2012). To achieve a resilient supply chain in the face of disruptions, additive manufacturing plays a role in building capabilities in the supply chain which make the SC less vulnerable and less prone to disruptions. A balanced mix of proactive and reactive capabilities are required to mitigate disruption risks and must be considered before disruptions. (Meyer, et al., 2022). The proactive capabilities should absorb the disruptions and the organization should execute a planned, adaptive reactive capabilities to re-establish the original supply source.

Resilience capabilities	Proactive	Reactive	Impact of AM
Decentralization	x	x	AM enables decentralized manufacturing, providing a local supply source.
Product postponement/substitution	x	x	AM enables easy modification based on CAD data digitally.
Capacity pooling	x	x	AM requires no tooling; therefore, demands of distinctive organisations can be sourced via the same 3D printer and thereby allows the pooling of capacities.
Use of lead time reserves		x	AM requires no tooling; therefore, manufacturing is frictionless by solely using CAD data minimizing setup and changeover times and thus provides the possibility for lead time reduction.

Geographical diversification	x		CAD data can be sent via information technology and divide sourcing to several locations.
Insourcing	x	x	AM enables organizations produce the demands of consumers in emergencies.
Multiple sourcing / buffer capacity	x	x	As any potential 3D printer can manufacture demands, more supply sources become available, which can be assigned and utilized in the short-term.
Risk-mitigation inventory	x		AM saves CAD data virtually and thereby provides a ‘digital warehouse’ on which physical goods can be retrieved ‘on-demand’

Table 10: Impact of AM on resilience (Meyer, et al., 2022)

From the table above, it is seen that capabilities like decentralization, capacity pooling and product postponement are both necessary in anticipating and recovering from disruptions, therefore it can be said that additive manufacturing affects supply chain resilience by acting as a secondary/alternative supply source and minimizing demand risks but potentially increasing supply risks as little or no inventory is held during sourcing (Meyer, et al., 2022). However, achieving resilience in the supply chain leads to increased costs. Since research on the impact of AM on supply chain resilience is limited, organizations must apply economic decision making regarding these resilience capabilities.

3. Methodology

This project was conducted through a systematic review of literature on additive manufacturing for supply chain resilience. This was done to adequately answer the research questions. The research questions were addressed by analysing the literature and relevant findings. The review of literature was carried out through a systematic process where the key words were defined, classified into three categories, searched and critically reviewed. An in-depth detail of the research methodology in this project are as follows.

3.1 Systematic literature review

Conducting a systematic literature review or mapping review involves mapping out and categorizing existing literature from which to commission further reviews or research by identifying gaps in the research literature (Grant & Booth, 2009). In this project, a systematic literature review was conducted to identify and critically analyze relevant research in a transparent and reproducible way. The systematic literature review followed the approach highlighted by (Tranfield, et al., 2003) which is shown in the table below. Activities in the three phases were performed sequentially.

Phase 1: Planning the review	• Established the need of this review and its contribution. • Review panel or audience determined. • Highlighted research questions this systematic review will address. • Established the search strategy for this systematic review.
Phase 2: Conducting the review	• Established a practical plan for selecting articles. • Documented the search process and selection. • Pre-determined a criterion by which the articles were analysed and selected for final review.
Phase 3: Reporting and dissemination	• Clearly communicated the motivation and the need for this review. • Clearly presented and explained the results. • Clearly communicated the contribution of this review.

Table 11: Literature review process

3.1.1 Planning the review

Considering the research questions and the main theme of this project, three criteria were applied to guarantee a structured and systematic approach to identify relevant literature: time period, database selection and keywords definition.

In this decade, additive manufacturing emerged as a promising technology with numerous benefits in the supply chain (Abidi & Alkahtani, 2019), therefore an 11-year timeline with publications from 2011 to 2022 were considered to understand the applications of additive manufacturing in supply chains. The search was carried out using Scopus which gives a broad information base in topics like management. The keywords were defined by referring to the primary keywords used by (Naghshineh & Carvalho, 2021) which include "additive manufacturing", "supply chain". "resilience", "capabilities" and "vulnerabilities". Related to supply chain disruptions, keywords such as "risk", "agility", "robust" and "disruptions" were also included. The search strings were developed using a combination of these keywords and their synonyms. A visual representation of this is given below.

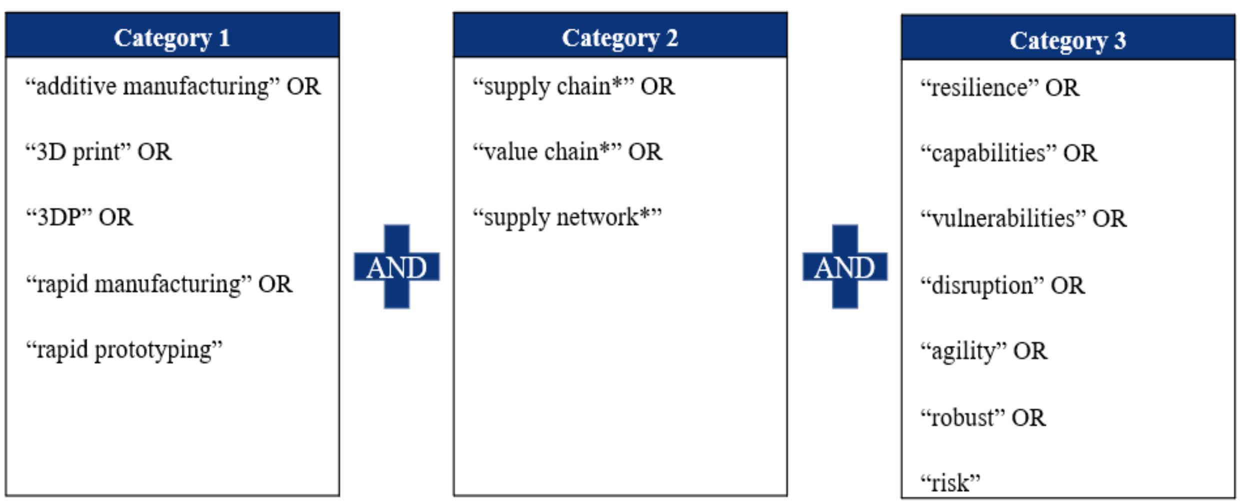


Figure 9: Applied search string

3.1.2 Conducting the review

After an initial search, a total of 376 articles were found. To further validate the search, only journal articles published in the English language and articles in the subject areas of ‘engineering’, ‘business, management and accounting’, ‘computer science’, decision sciences’ and ‘economics’ were considered. This reduced the publications found to 239. After reading through the title and abstracts of these publications, only papers dealing with additive manufacturing and supply chain disruptions, resilience or agility were selected to ensure relevance.

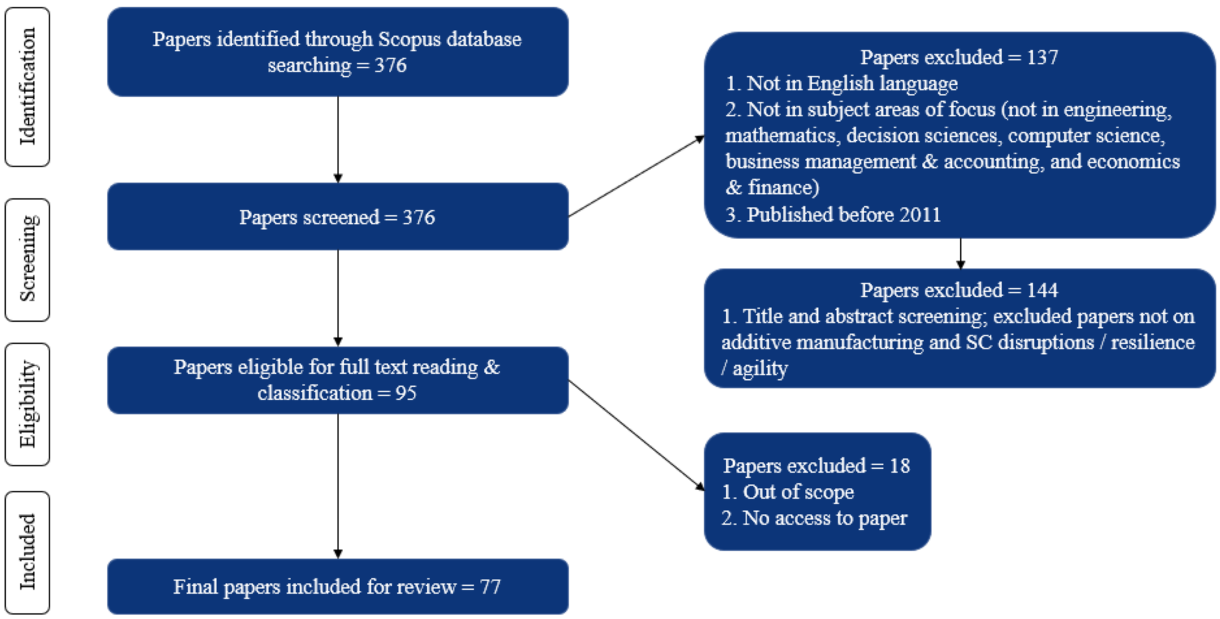


Figure 10: Article selection and evaluation process

Next, a full text reading of the papers accepted was conducted after screening and classify them based on relevant topics like resilience, supply chain capabilities and vulnerabilities using the “AM-SCR” framework developed by (Naghshineh & Carvalho, 2021) to have a structured approach in answering the research questions. The “SCRAM” framework developed by (Pettit, et al., 2011) in defining supply chain capabilities, vulnerabilities, and their subfactors was compared with the AM-SCR framework used by (Naghshineh & Carvalho, 2021) in defining the adoption impacts of additive manufacturing in the supply chain. This comparison was done to develop an understanding of supply chain capabilities and vulnerabilities, and to identify the link between them.

3.1.3 Reporting and dissemination

The last phase in the review process involved documenting the literature study, generating propositions, and summarizing findings into categories related to the two constructs of supply chain resilience which are capabilities and vulnerabilities.

The generation of propositions is regarded as the main outcome of this systematic literature review as described by (Grant & Booth, 2009). 15 sets of propositions were suggested that show the relationship between the research variables in figure 1.

4. Descriptive analysis and content analysis

This chapter will present the literature findings related to additive manufacturing and supply chain resilience in dealing with disruptions. The findings are presented in two stages; a descriptive analysis which shows the distribution of the literature and a content analysis which summarizes the findings into different categories where the second and third research questions will be addressed.

Although the time horizon for the identification of papers for this research project was from 2011 to 2022, an article by (Tuck, et al., 2007) discuss the impacts of rapid manufacturing for an agile supply chain and also discuss concepts like flexible manufacturing and mass customization. Figure 7 shows that most articles on additive manufacturing for supply chain resilience were published between 2020 and 2022 which confirms that the body of literature on this topic is growing, especially in response to the disruptions caused by the Covid-19 pandemic. There is incresing interest in topics like flexibility, decentralization and adaptability compared to topics like cyber-security threats and material shortage which have minimal research interest.

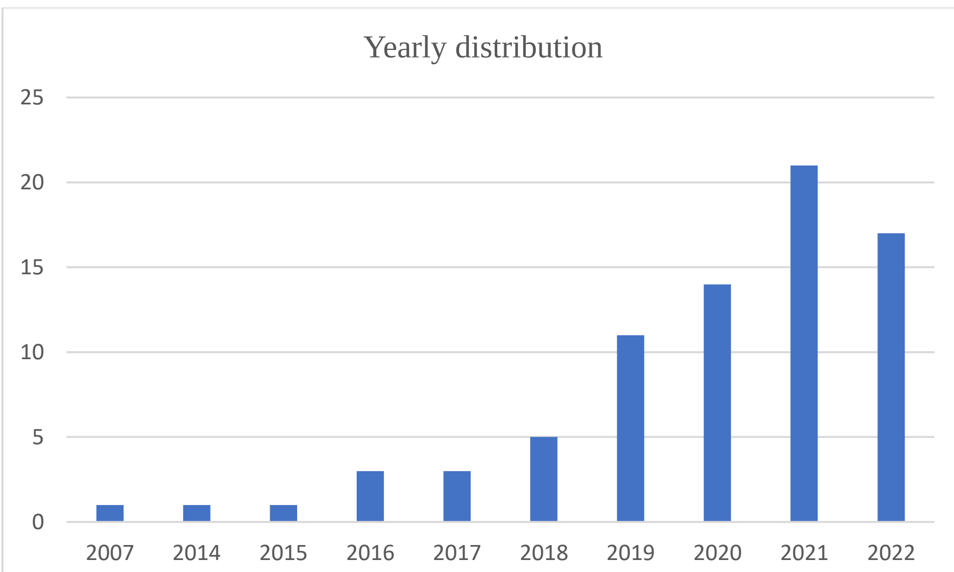


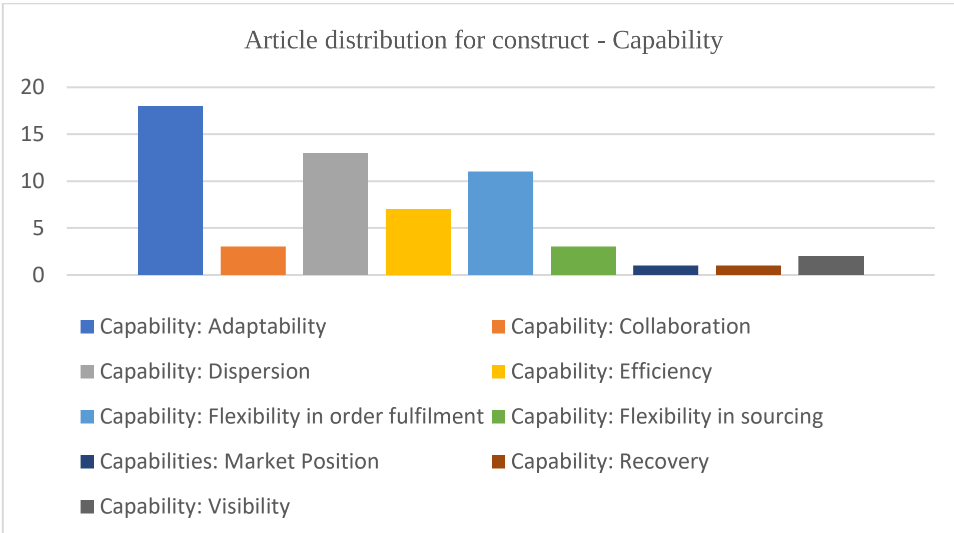
Figure 11: Distribution over the years

The 77 articles selected for review were published within 32 interdisciplinary academic journals as shown in table 6. The highest number of articles in these journals were published in the *Journal of Manufacturing systems* and *Journal of Computers and Industrial Engineering*. The diversity of the journals' research themes (i.e business logistics, food science and technology, manufacturing technology management, bioengineering and biotechology, operations management research, and SCM) affirms the multidisciplinary nature of this research topic and its increasing attention in various research communities.

Academic Journal	Count
Journal of Manufacturing Science and Technology	2
Journal of Applied Sciences	2
Computers and Industrial Engineering	4
Concurrent Engineering: Research and Applications	1
Frontiers in Bioengineering and Biotechnology	1
Industrial Management and Data Systems	1
International Journal of Advanced Manufacturing Technology	1
International Journal of Food Science and Technology	1
International Journal of Industrial Engineering and Production Research	1
International Journal of Integrated Supply Management	1
International Journal of Operations and Production Management	1
International Journal of Physical Distribution and Logistics Management	2
International Journal of Production Economics	2
International Journal of Production Research	1
International Journal of Services and Operations Management	1
International Journal of Systems Science: Operations and Logistics	1
Journal of Business Logistics	2
Journal of International Entrepreneurship	1
Journal of Manufacturing Systems	4
Journal of Manufacturing Technology Management	3
Journal of Purchasing and Supply Management	1
Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers, Series A	1
Operations Management Research	2
Production Planning and Control	1
Progress in Additive Manufacturing	1
Rapid Prototyping Journal	1
Supply Chain Forum	1
Supply Chain Management	2
Sustainable Production and Consumption	1
Technology in Society	1
Virtual and Physical Prototyping	1
Vision: The Journal of Business Perspective	1
Others	30

Table 12: Distribution of articles in academic journals

After considering the research questions, an inductive approach was used in this review to categorize the relevant papers into relevant sub-factors of supply chain cpabilities and vulnerabilities as highlighted by (Naghshineh & Carvalho, 2021). Figure 7 shows how the 77 articles are categorized into the relevant sub-factors. The findings on these sub-factors are discussed and used to develop propositions which will be useful for future research on this topic.



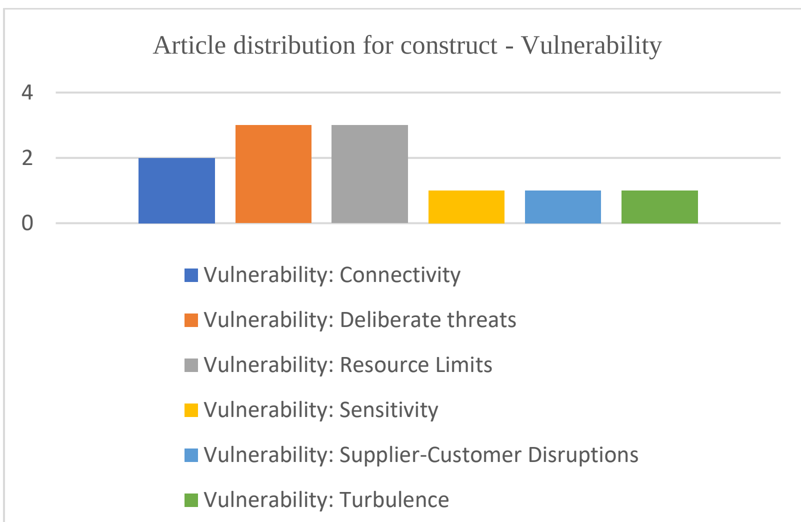


Figure 12: Article distribution per resilience constructs

4.1 Supply chain capabilities

This section gives insight on how additive manufacturing enhances supply chain capabilities in anticipation of supply chain disruptions. The findings from research on SC capabilities show that the adoption of additive manufacturing in the supply chain will lead to more on-demand manufacturing, more flexibility/postponement of orders, increased collaboration between partners in the SC and improved transparency in the supply chain. A common consensus in the research is the reduction of production and delivery lead times by the adoption of additive manufacturing which improves a firm's relationship with its customers. Future research on the use of AM technology in enhancing supply chain capabilities can be on how AM adoption affects procurement practices and logistics multisourcing.

4.1.1 Adaptability

Adaptability is the capability of a firm to adjust operations to respond to challenges or opportunities (Naghshineh & Carvalho, 2021). In the medical and automotive spare parts supply chains, customers are highly sensitive to lead times, therefore the adoption of additive manufacturing leads to shorter lead times in production, sourcing and delivery of the final product to the customer (Ivanov, et al., 2019, Sabarish, et al., 2021). However, these supply chains are exposed to external risks if a disruption happens in the upstream SC since there is no intermediate inventory in between the stages because of AM's capability to eliminate inventory. The need to optimize manufacturing operations also led to the adoption of additive manufacturing as a technology due to AM's functionality in creating complex parts, and thus enables a distributed production of components in a make-to-order strategy (de Brito, Filipe M, et al., 2019).

Proposition: AM adoption in the supply chain leads to lead time reduction and has potential to revamp operations.

4.1.2 Collaboration

This capability indicates how effectively a firm works with other firms i.e., in the same supply chain for mutual benefit (Naghshineh & Carvalho, 2021). The adoption of additive manufacturing technology increases the need for close collaboration between the suppliers of the machines and material, and also the manufacturers of the product/parts, because the materials and machines for AM need to be compatible with each other to achieve optimal outcomes (Oettmeier & Hofmann, 2016). As a result of the COVID-19 pandemic, data and information sharing rapidly increased between companies and individuals due to the increased demand for medical devices and items. AM emerged as an important tool during the COVID-19 pandemic in supplying medical items because companies and individuals that own a 3D printer could easily access 3D printable files from open-design repositories and quickly produce parts (Longhitano, et al., 2021).

The integration of AM technology with sensors, data integration, predictive analysis, innovation, vertical and horizontal collaboration can develop sensing and seizing capabilities which will benefit the supply chain by ensuring a simplified supply chain and on-time production of high-quality products at a viable cost (Belhadi, et al., 2022). Collaborative design challenges the boundaries between firms. The use of data in collaboration enables greater specification of value propositions and pushes the power shift further towards consumers. The use of AM and enhanced information flows in the supply chain will lower inventory and quicken customer response which is an exhibit of agility (Christopher & Ryals, 2014).

Proposition: AM adoption improves collaboration between the SC partners which will lead to better forecasting of customer demands and lowering of inventory.

4.1.3 Dispersion

This capability indicates how effectively a firm can distribute production assets in different geographical locations and sell products to customers in those locations. The adoption of additive manufacturing can provide an alternative to production facilities by enabling distributed ways of manufacturing and allow manufacturers have access to geographically dispersed facilities which aids in quickly rerouting manufacturing capacity requirements in case of disruptions (Naghshineh & Carvalho, 2021). The adoption of AM leads to distributed manufacturing which allows a decentralized supply chain strategy to be implemented and this moves the finished product closer to the different points of sale (Sisca, et al., 2016). Distributed manufacturing improves responsiveness i.e., shorter repair times, shorter time to market, faster product availability and reduced transportation costs. However, in contrast to centralized manufacturing, distributed manufacturing locations may have limitations in economies of scope in terms of equipment utilization, raw material purchasing, labor, and knowledge (Verboeket, et al., 2021).

Proposition: AM adoption can influence the reallocation of production requirements & capacity in different locations and markets in the face of disruptions.

4.1.4 Efficiency

This is the capability to generate outputs with minimal resource/asset requirements (Naghshineh & Carvalho, 2021). Additive manufacturing adoption can increase production efficiency because it can reduce the number of obsolete products and minimize manufacturing waste using less raw materials during production and simplified production operations. AM adoption also improves internal operational performance measures like production complexity, production flexibility, lean manufacturing and logistics efficiency (Franco, et al., 2020). Additive manufacturing uses a limited and specific type of input materials for production, this also makes materials requirement planning more efficient.

AM adoption can improve the structural flexibility of a supply chain by asset sharing i.e., sharing of capacity, materials, machines and labour by different partners in the supply chain. AM technology limits the number as well as the type of materials required to build products. Therefore, this can facilitate asset sharing in terms of both capacity and inventory. (Mashhadi, et al., 2015).

Proposition: AM improves production efficiency combining the use of minimal input requirements for production as well as asset sharing.

4.1.5 Flexibility in order fulfilment

This is the capability to promptly adjust outputs or the mode of delivering outputs. It includes reallocation of production, production postponement, logistics multisourcing, inventory management and having alternate distribution channels (Naghshineh & Carvalho, 2021). The adoption of AM can help manufacturing firms to be flexible respond to changes in customer requests that may come in the form of increasing, decreasing, cancelling, or changing the timing of orders. This flexibility can be achieved due to the unique characteristics of AM such as lack of tooling, on-demand production and freedom of geometry (Alogla, et al., 2021). The adoption of AM in production can support very high degrees of postponement which enables firms to potentially become proactive in predicting production difficulties. This means that it is possible for firms to postpone product differentiation until a customer order is received (Delic & Eyers, 2020). AM's flexibility to produce on demand means that parts can be produced as required rather than hold inventories of stock in anticipation of future demand (Eyers, et al., 2018). This would lead to effective management of inventories and reduction of the associated costs. Distributed manufacturing as an outcome of AM also leads to improved flexibility in job order fulfilment

(Sisca, et al., 2016). Having multiple production units/facilities that adopt AM increases flexibility in meeting customer demands in case of disruptions.

Proposition: AM adoption enhances flexibility in fulfilling customer requests by supporting postponement of orders and allowing on demand production.

4.1.6 Flexibility in sourcing

This is the capability to promptly adjust inputs or the mode of receiving inputs by engaging multiple suppliers for sourcing and having multiple methods for production (Naghshineh & Carvalho, 2021). The adoption of AM allows for alternate sourcing of required components, overcoming sourcing issues in the supply chain. For example, in the medical industry, ventilator components used in hospitals like valves, tubing connectors and adapters can be replaced with 3D printed alternatives when necessary (Narayan, et al., 2022). Moreover, sourcing from two or several suppliers instead of one would enable the focal firm to reduce its ordering costs (Tang & Tomlin, 2008). The adoption of AM enables suppliers to quickly modify and introduce new products into the market by allowing the suppliers operate at different level of production volume and variety (Delic & Eyers, 2020). Additionally, as sourcing large quantities of products of components with AM may be costly, a firm can configure its sourcing process differently by using "AM insourcing" by maintaining its own AM capabilities, such as printers and raw material (Meyer, et al., 2021).

Proposition: AM adoption enhances flexibility in sourcing for alternate raw materials for production.

4.1.7 Market Position

This capability indicates how well a firm can maintain its position in specific markets and maintain strong long-term relationships with customers. Additive manufacturing features like engineer/make to order production, mass customization, customer-centric production, co-creation/co-design, and production postponement allow manufacturers closely collaborate with customers enabling them to effectively deal with the unpredictability in customer demands as well as potential customer disruptions. These AM features strengthen customer relationships and gives manufacturers a strong market position by allowing them deal with erratic customer demands (Naghshineh & Carvalho, 2021). When adopted in supply chains, AM can enable increased interaction between a firm and its customers and form new partnerships in customizing products. Additive manufacturing has the potential to impact networking activities of suppliers by influencing the relative power distribution along the supply chain (Hannibal, 2020). Since the present potential of AM lies in quick customization of tailor-made products that match the customers specifications, quick inspection of finished products and fast implementation of change requests will improve relations between suppliers, firms and customers.

Proposition: With the adoption of AM, customer relations can flourish by increased customization and co-design capabilities.

4.1.8 Recovery

Recovery enables a production system or supply chain to quickly return to the normal state of operations after being disrupted (Naghshineh & Carvalho, 2021). Most firms believe that they have a highly resilient supply chain, but in reality, the resilience of a supply chain cannot fully be measured unless it has faced disruptions, recovered from disruptions and then developed preventive measures against disruptions. Additive Manufacturing can play a crucial role in making the supply chain more resilient and less vulnerable to disruption. Moreover, it helps in reducing the recovery time of the supply chain to a significant level. The adoption of AM technology in a spare parts supply chain for example helps build a rigid system that would help a firm survive unexpected disruptions (Muthukumarasamy, et al., 2018).

Proposition: AM positively influences the recovery of a SC from disruptions by acting as a buffer between raw material sources and distribution centers, thus enabling the manufacturing of products near the customer’s geographical location and in turn achieving maximum customer satisfaction.

4.1.9 Visibility

Visibility gives firms knowledge about the supply chain environment as well as the status of operating assets (Naghshineh & Carvalho, 2021). These assets may include inventories, demand, and supply conditions, as well as production and purchasing schedules (Christopher & Peck, 2004). The adoption of AM will improve information exchange among the supply chain partners which will ultimately make inventory management more efficient, make the supply chain more transparent, make collaborative forecasting easier and allow the SC partners anticipate customer demand better and also anticipate customer/supplier disruptions (Naghshineh & Carvalho, 2021).

Proposition: AM adoption enhances transparency in the SC by improved information sharing which has a positive effect in anticipating customer demands.

4.1.10 Discussion on Capabilities

The findings on supply chain capabilities show that the adoption of additive manufacturing has some positive impacts on supply chain performance. Using additive manufacturing, a firm can adapt operations in times of disruptions to have even shorter production lead times in responding to erratic customer demands. In achieving shorter production lead times, facilities can be decentralized and located close to the customer in various geographical locations. Decentralization will lead to increased collaboration and transparency between the different partners in the supply chain. From the literature, additive manufacturing is said to also enhance flexibility in the supply chain which can have an influence on the recovery of the supply chain from disruptions. In choosing to adopt additive manufacturing in production operations, managers and firms must decide which capability best fits their supply chain needs to adequately handle disruptions.

4.2 Supply chain vulnerabilities

This section gives insight on how to best reduce vulnerabilities and manage disruptions better in the supply chain. The findings from research on SC vulnerabilities point that the adoption of additive manufacturing in the SC will lead to more complex and vulnerable information systems, although the number of suppliers may be reduced. Issues like use of sensitive materials for AM which may lead to material shortage also pose a threat to the supply chain.

A consensus in the research is that although the introduction of additive manufacturing in the supply chain makes the SC less vulnerable to unpredictable customer demands, it also makes the SC vulnerable to cyber attacks that can cause catastrophic effects.

Future research on the use of AM technology in addressing supply chain vulnerabilities can be on how AM adoption affects customer disruptions, distribution networks and how secure IT platforms can be established in the supply chain with the introduction of AM.

4.2.1 Connectivity

This vulnerability refers to the degree of interdependence of a firm or supply chain on external entities or partners (Naghshineh & Carvalho, 2021). Increased vulnerabilities in the SC arise from the complexity of interconnected systems and complex information flows. The adoption of AM enables companies transition towards an on-demand supply chain, this significantly reduces the number of suppliers that must be consolidated for production (Ivanov, et al., 2019), hereby reducing complexity of information flow and exchange, thus making the supply chain less vulnerable to disruption risks and more in control of production (Rahman, et al., 2021). However, having fewer suppliers in the SC might increase vulnerability to disruptions like the COVID-19 pandemic and global material shortage required for AM, but when the focus is strictly on the concept of resilience to cyber disruptions, fewer suppliers and less information flow is more desirable.

Proposition: AM adoption reduces the number of suppliers in the supply chain and makes information exchange easier, but reduced suppliers mean more vulnerabilities to global disruptions.

4.2.2 Deliberate Threats

This vulnerability refers to deliberate attacks that can cause financial harm or disrupt operations. With the adoption of AM in supply chains, there will be increased information sharing between the SC partners, however IT may not be as reliable and this creates cybersecurity threats and knowledge leaks that may cause industrial espionage (Naghshineh & Carvalho, 2021). The types of attacks (Gupta, et al., 2020) that could make the SC vulnerable are:

- Printer hardware attacks by malware or interference
- Raw material attacks causing shipment delay/damage
- Design-file attacks by IP theft or file corruption

Therefore, secure IT requirements need to be in place before proceeding with information sharing and exchange in the SC.

Proposition: IT inadequacies limit AM adoption and makes the SC more vulnerable to cyber-attacks.

4.2.3 Resource Limit

This refers to output constraints caused by the unavailability of production factors like production capacity, supplier capacity and raw material availability. Additive manufacturing enables the possibility to outsource production processes to external entities which facilitates the quick reallocation of production and rerouting of requirements in case of distribution or production capacity shortages (Naghshineh & Carvalho, 2021). In the spare parts supply chain, AM can increase the availability of spare parts and change the SC configuration by moving closer to user locations (Xu, et al., 2021). Sourcing with the use of an adaptable AM supply chain is also beneficial for small demand quantity of products like medical supplies under high supply risks (Glas, et al., 2022). However, the fact that AM requires a secondary supply chain for raw material and printer procurement gives the supply chain its own vulnerability against risks (Parikh, et al., 2018).

Proposition: AM adoption positively hedges against material shortage & unavailability in the SC.

4.2.4 Sensitivity

This vulnerability refers to the reliance of manufacturing on carefully controlled conditions for process and product integrity. AM adoption can increase sensitivity to problems concerning the reliability of equipment, utilization of scarce materials and product purity as AM processes become more standardized (Naghshineh & Carvalho, 2021). However, supply chains might still be vulnerable, especially humanitarian aid supply chains, as 3D printers are not usually mobile and tough enough to operate in many different environments (Lipsky, et al., 2019). Specifications like portability, durability, and ability to print off-grid need to be addressed in the context of additive manufacturing in supply chains.

Proposition: Equipment and material issues may inhibit the adoption of AM in the SC.

4.2.5 Supplier-Customer disruptions

This refers to the vulnerability of customers and suppliers to disruptions which in turn can make the entire supply chain vulnerable. The adoption of additive manufacturing in a production setting as well as the use of collaborative information sharing and exchange among the partners in the supply chain will enable the SC partners better anticipate customer/supplier disruptions (Naghshineh & Carvalho, 2021). However, the introduction of AM to a supply chain may disrupt several supply chain positions. Machinery and raw material producers in traditional manufacturing processes become wiped out as manufacturing becomes internalised and localised by the introduction of AM, hence sub-suppliers, logistics firms and manufacturing tools for traditional production gradually become obsolete (Öberg, 2021). This suggests how suppliers and other partners in a conventional manufacturing SC become vulnerable by the introduction of AM.

Proposition: AM adoption enhances anticipation of supplier/customer disruptions in the SC.

4.2.6 Turbulence

Turbulence refers to reoccurring changes in external factors that are beyond the focal firm's control (Naghshineh & Carvalho, 2021). In the manufacturing and distribution processes, supply chain vulnerability arises from product diversity, repeated changes in demand, shorter product life cycles, complex global distribution markets and logistics network relationships (Wu, et al., 2020). Due to its high degree of production flexibility, additive manufacturing can shorten delivery times of products in times of uncertain demand and meet diverse product needs through personalized manufacturing (Ivanov, et al., 2019).

Proposition: AM adoption reduces production lead times and allows for postponement of customer orders in times of uncertain demand.

4.2.7 Discussion on Vulnerabilities

The findings on supply chain vulnerabilities show that the adoption of additive manufacturing will highlight more complexities in the supply chain concerning materials and information systems. The use of additive manufacturing in dealing with turbulent supplier/customer disruptions will allow for reduction in production lead times and postponement of orders, but challenges lie with the reliability of AM processes on scarce materials and with the security of AM files in the supply network. In adopting additive manufacturing to prepare for and respond to disruptions, firms must ensure that potential issues with materials and cybersecurity are resolved first to avoid issues later.

4.3 Propositions

The propositions outlined in the table below serve as guidelines for supply chain managers looking to adopt additive manufacturing in their business operations.

SCR sub-factor	(Proposition)
Capability: Adaptability	AM adoption in the supply chain leads to lead time reduction and has potential to revamp operations.
Capability: Collaboration	AM adoption improves collaboration between the SC partners which will lead to better forecasting of customer demands and lowering of inventory.
Capability: Dispersion	AM adoption can influence the reallocation of production requirements & capacity in different locations and markets in the face of disruptions.
Capability: Efficiency	AM improves production efficiency combining the use of minimal input requirements for production as well as asset sharing.
Capability: Flexibility in order fulfilment	AM adoption enhances flexibility in fulfilling customer requests by supporting postponement of orders and allowing on demand production.
Capability: Flexibility in sourcing	AM adoption enhances flexibility in sourcing for alternate raw materials for production.
Capability: Market position	With the adoption of AM, customer relations can flourish by increased customization and co-design capabilities.
Capability: Recovery	AM positively influences the recovery of a SC from disruptions by acting as a buffer between raw material sources and distribution centers, thus enabling the manufacturing of products near the customer's geographical location and in turn achieving maximum customer satisfaction.

Capability: Visibility	AM adoption enhances transparency in the SC by improved information sharing which has a positive effect in anticipating customer demands.
Vulnerability: Connectivity	AM adoption reduces the number of suppliers in the supply chain and makes information exchange easier, but reduced suppliers mean more vulnerabilities to global disruptions.
Vulnerability: Deliberate threats	IT inadequacies limit AM adoption and makes the SC more vulnerable to cyber-attacks.
Vulnerability: Resource limits	AM adoption positively hedges against material shortage & unavailability in the SC.
Vulnerability: Sensitivity	Equipment and material issues may inhibit the adoption of AM in the SC.
Vulnerability: Supplier-Customer disruptions	AM adoption enhances anticipation of supplier/customer disruptions in the SC.
Vulnerability: Turbulence	AM adoption reduces production lead times and allows for postponement of customer orders in times of uncertain demand.

Table 13: Propositions

5. Conclusion

In this specialization project, the adoption impacts of additive manufacturing in the supply chain as a means to address disruptions have been analysed. This was done by answering the research question that cover this research. The research questions were answered using a systematic literature review where the literature study and relevant findings were analysed.
The answer to RQ1 is: Additive manufacturing affects supply chain resilience by building capabilities in the supply chain which make the supply chain less vulnerable to disruptions.
The answer to RQ2 is: Additive manufacturing affects supply chain capabilities by allowing on-demand manufacturing, more flexibility in postponing customer orders and increased transparency which allows for better collaboration between the partners in the supply chain.
The answer to RQ3 is: Additive manufacturing affects supply chain vulnerabilities by making the supply chain less vulnerable to unpredictable customer demands but creating more complex and vulnerable information systems.

In this research, the two constructs of supply chain resilience which are capabilities and vulnerabilities were investigated with respect to the adoption of additive manufacturing. The main objective of this research was achieved as the propositions generated show that in using additive manufacturing to ascertain supply chain resilience, firms must implement a secure IT platform for information exchange and collaboration with other partners in the supply chain, select relevant suppliers and look to address challenges with demand and supply. For the master thesis, the propositions generated would be presented to managers in different industries to validate how the adoption impacts of AM are seen in practice.

A limitation of this project is the lack of a quantitative approach in the content analysis as the research was conducted using a qualitative approach. This research could also have benefitted from a case study of a medical firm which adopts the use of additive manufacturing in its operations after encountering disruptions caused by the COVID-19 pandemic, to show better the business impacts before and after the pandemic.

Future research on this topic could be on how the flexibility of additive manufacturing enables firms to respond better to customer demands. This specialization project sufficiently addresses the topic of supply chain disruptions & resilience, and it lays the foundation for future research in this field.

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Appendix

A: Supply chain capability examples (Pettit, et al., 2011).

Capability Factor	Definition	Sub-Factors
Flexibility in sourcing	Ability to quickly change inputs or the mode of receiving inputs	Part commonality, Modular product design, Multiple uses, Supplier contract flexibility, Multiple sources
Flexibility in order fulfillment	Ability to quickly change outputs or the mode of delivering outputs	Alternate distribution channels, Risk pooling/sharing, Multi-sourcing, Delayed commitment, Production postponement, Inventory management, Re-routing of requirements
Capacity	Availability of assets to enable sustained production levels	Reserve capacity, Redundancy, Backup energy sources and communications
Efficiency	Capability to produce outputs with minimum resource requirements	Waste elimination, Labor productivity, Asset utilization, Product variability reduction, Failure prevention
Visibility	Knowledge of the status of operating assets and the environment	Business intelligence gathering, Information technology, Products, Assets and People visibility, Information exchange
Adaptability	Ability to modify operations in response to challenges or opportunities	Fast re-routing of requirements, Lead time reduction, Strategic gaming and simulation, Seizing advantage from disruptions, Alternative technology development, Learning from experience
Anticipation	Ability to discern potential future events or situations	Monitoring early warning signals, Forecasting, Deviation and Near-miss analysis, Contingency planning, Preparedness, Risk management, Business continuity planning, Recognition of opportunities
Recovery	Ability to return to normal operational state rapidly	Crisis management, Resource mobilization, Communications strategy, Consequence mitigation
Dispersion	Broad distribution or decentralization of assets	Distributed decision-making, Distributed capacity and assets, Decentralization of key resources, Location-specific empowerment, Dispersion of markets
Collaboration	Ability to work effectively with other entities for mutual benefit	Collaborative forecasting, Customer management, Communications, Postponement of orders, Product life cycle management, Risk sharing with partners
Organization	Human resource structures, policies, skills and culture	Learning, Accountability and Empowerment, Teamwork, Creative problem solving, Cross-training, Substitute leadership, Culture of caring
Market position	Status of a company or its products in specific markets	Product differentiation, Customer loyalty/retention Market share, Brand equity, Customer relationships, Customer communications
Security	Defense against deliberate intrusion or attack	Layered defenses, Access restrictions, Employee involvement, Collaboration with governments, Cyber-security, Personnel security
Financial strength	Capacity to absorb fluctuations in cash flow	Insurance, Portfolio diversification, Financial reserves and liquidity, Price margin

B: Supply chain vulnerability examples (Pettit, et al., 2011).

Vulnerability Factor	Definition	Sub-Factors
Turbulence	Environment characterized by frequent changes in external factors beyond your control	Natural disasters, Geopolitical disruptions, Unpredictability of demand, Fluctuations in currencies and prices, Technology failures, Pandemic
Deliberate threats	Intentional attacks aimed at disrupting operations or causing human or financial harm	Theft, Terrorism/sabotage, Labor disputes, Espionage, Special interest groups, Product liability
External pressures	Influences, not specifically targeting the firm, that create business constraints or barriers	Competitive innovation, Social/Cultural change, Political/Regulatory change, Price pressures, Corporate responsibility, Environmental change
Resource limits	Constraints on output based on availability of the factors of production	Supplier, Production and Distribution capacity, Raw material and Utilities availability, Human resources
Sensitivity	Importance of carefully controlled conditions for product and process integrity	Complexity, Product purity, Restricted materials, Fragility, Reliability of equipment, Safety hazards, Visibility to stakeholders, Symbolic profile of brand, Concentration of capacity
Connectivity	Degree of interdependence and reliance on outside entities	Scale of network, Reliance upon information, Degree of outsourcing, Import and Export channels, Reliance upon specialty sources
Supplier/Customer disruptions	Susceptibility of suppliers and customers to external forces or disruptions	Supplier reliability, Customer disruptions

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