Master's degree thesis

LOG950 Logistics

Additive Manufacturing in the Healthcare Supply Chain

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Molde University College
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Preface

This thesis serves as the culmination of my two-year Master of Science program in Logistics with a specialization in Supply Chain Management at Molde University College. The project was conducted between January 2023 and May 2023, and has provided me with a deeper understanding of logistics and supply chain management through the literature review and research.

I am grateful for the participation of the interviewees, whose input has been invaluable to the thesis and has provided significant insights to support my research.

Additionally, I would like to express my appreciation to my supervisor, Morten Svindland, as well as my family and girlfriend for their support throughout my studies.

Bergen, 21.05.2023

Anders Rostbakken

Abstract

This thesis investigates the effects of additive manufacturing on supply chain risk and resilience in the healthcare sector. The research explores the implementation of AM and its impact on risk levels and resilience capabilities. Through a qualitative approach, including a literature review and interviews with industry experts, the study uncovers valuable insights.

The literature review deals with central themes from previous research and literature to shed light on the research question that has been chosen for the thesis. The themes in the literature review are supply chain management and strategy, centralizing and decentralizing, and supply chain risk and resilience. Furthermore, it deals with additive manufacturing with a comparison against traditional manufacturing, and additive manufacturing in the health sector. The literature review emphasizes the importance of flexibility, waste reduction, and supply chain design in building resilient supply chains. Risk management strategies, such as robustness and resilience, are also discussed. The literature suggests that AM can address these challenges by minimizing waste, enabling flexibility, and expanding production capacity. Semi-structured interviews with four healthcare industry experts provide further understanding. The findings reveal that AM reduces waste, enables agile supply chains, and enhances transparency and visibility. It allows in-house production, reduces dependency on external suppliers, and expands localized manufacturing capacity.

In conclusion, this research demonstrates that AM has the potential to decrease supply chain risk and enhance resilience in the healthcare sector. By minimizing waste, improving flexibility and agility, and decentralizing production capacity, AM enables proactive responses to disruptions.

Table of Contents

List of Tables

List of Figures

Abbreviations:

AM – Additive manufacturing

BTO – Build-to-Order

CAD – Computer-aided design

ECR – Efficient Consumer Response

JIT – Just-in-time

SCM – Supply Chain Management

TM – Traditional manufacturing

3D-printing – Three-dimensional printing

1.0 Introduction

Advancements in internet-based communication and advanced logistics have made it possible to create increasingly lengthy and intricate multi-layered supply chains, which have been cost-effective, so far (Aggarwal & Bohinc, 2011). At the same time supply chain disruptions have become a large problem for many organizations, and supply chains all over the world suffer from events like the Covid-19 pandemic, the war in Ukraine, climate change, political regulations, terrorism, and geopolitical influences. As a result of the pandemic, a chain of occurrences in the world markets, like supply and transportation constraints, delay in development of infrastructure and a slowdown in manufacturing operations happened all at once. Supply chain upheaval is affecting all industries and sectors (Facts&Factors, 2022).

Supply chain leaders were asked to identify the vulnerabilities which were exposed during the pandemic in a study. The findings were that 58% of the leaders answered alternate supply sources and 56% answered raw material and inventory shortages. One of the research findings from this study was that less than 10% of the interviewed leaders rated their supply chain as highly resilient on a score of 1 to 5 (Berman, 2022). This clarifies the need for research and development in this area. According to a survey conducted by the World Economic Forum in 2013, over 80% of companies expressed concerns about the resilience of their supply chains. Furthermore, the concept of enhancing supply chain resilience to address disruptions has garnered significant academic support in recent times (Tukamuhabwa et al., 2015).

Mitigating risk and disruption and enhancing resilience has become a topic of great importance. Innovation in technology and manufacturing methods may be one way to solve this. Additive manufacturing (AM) technologies have seen a significant increase in usage across various industries in recent years. In the 20th century, the introduction of the moving assembly line by Henry Ford enabled mass production of identical products. Nowadays, additive manufacturing is allowing production of moderate to large quantities of customized products, creating new opportunities in production paradigms and manufacturing possibilities. Overall, additive manufacturing is providing exciting prospects for innovation and production possibilities (Attaran, 2017b).

The technology is still in development and is not utilized to a very high degree to date. There is still a greater potential for the use of the technology in many industries, such as the healthcare sector, considering the disruptions in this supply chain in recent years. During the pandemic the health sector suffered huge disruptions in the supply chain for medical supply (Spieske et al., 2022). The Covid-19 pandemic has presented unprecedented challenges to global supply chains due to the exponential increase in the number of patients requiring medical attention (Manero et al., 2020). This lays the foundation for the need for research into how to create more resilient supply chains in this sector. The thesis will explore if additive manufacturing is the answer to mitigating risk and creating supply chain resilience in the Healthcare sector.

The thesis will explore if additive manufacturing is the answer to mitigating risk and creating supply chain resilience in the healthcare sector.

1.1 Motivation and Background for the Thesis

A lot of studies have addressed how additive manufacturing can be used in companies and different industries, and some have researched the effects on risk and resilience, and how it can create supply chain resilience. Studies have been conducted on various industries, such as healthcare, automotive, aircraft, food etc. in both the additive manufacturing and supply chain literature. According to the authors knowledge, this may be the first research on what effects additive manufacturing has on risk and resilience in the Norwegian health care supply chain. What this research will bring forth of new knowledge is what effects the technology has on risk and resilience the Norwegian healthcare supply chain. What makes the research problem interesting and relevant is the backdrop, which is the disruptions of supply chains all over the world during the pandemic and other disruptive events, and the potential which additive manufacturing inhabits. By studying this research problem, one could find interesting results about the effects of additive manufacturing on risk and resilience in the healthcare supply chain, but also how it can be utilized to create more resilient supply chains in the health care sector, but also applications to other industries.

1.2 Research Problem

Based on the introduction and the background, the thesis will try to answer the following research problem:

What are the effects of Additive Manufacturing in the Healthcare Supply Chain on Supply Chain Risk and Resilience?

The thesis´ problem statement establishes the main theme of this research, which involves examining supply chain risk and resilience and additive manufacturing in a specific industry through literature review and empirical investigation. By defining key concepts such as supply chain management, risk, resilience, and additive manufacturing, the groundwork is laid for exploring the case of additive manufacturing in the Norwegian healthcare sector.

1.3 Structure of the Thesis

The thesis is structured in a standard way based on the guidelines from Molde University College.

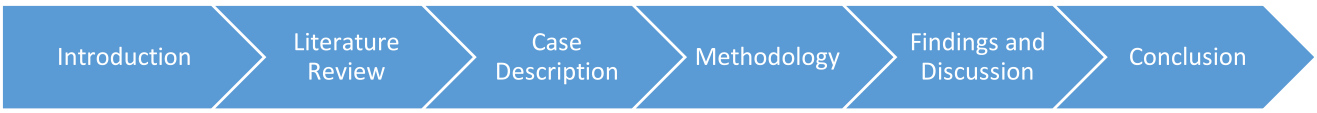

Figure 1: Structure of the Thesis.

2.0 Literature review

The literature review will provide a comprehensive analysis of the existing literature on supply chain strategy, risk and resilience and additive manufacturing, drawing on relevant research from academic books and research papers on the topics. The objective for this review is to identify best practices for the topics and gaps in the literature. Later on, how the proposed research will address these gaps.

2.1 Supply Chain Management

This section will begin with explaining the fundamentals of supply chain management (SCM) and supply chain strategy with focus on lean and agility, followed by the trade-off between centralization and decentralization, before moving on to the concept of supply chain risk, where risk assessment and mitigation is highlighted.

Supply chain management are defined in many ways. Christopher (2005, p. 5) defines SCM as: *"The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole"*. Figure 2 shows a model of a traditional supply chain concept which visualizes the definition of SCM. Each player in all these processes is a part of the network, which together makes up the supply chain.

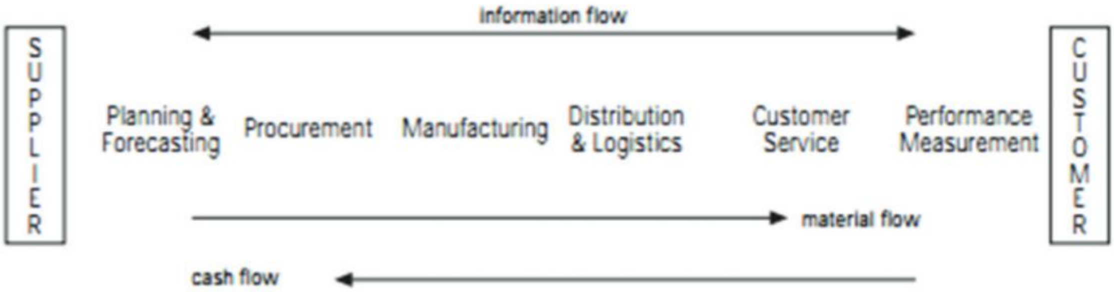

Figure 2: Supply Chain Concept (Christopher, 1999).

The supply chain comprises four main elements: purchasing, operations, distribution, and integration. Purchasing involves the identification of product suppliers, while operations involve demand planning, forecasting and inventory management. Distribution focuses on the movement of products, while integration aims to create an efficient supply chain system. By reducing the need for these activities, costs can be minimized. The effective management of supply chains has contributed to the success of some large businesses and retailers. For example by leveraging technology to streamline inventory tracking and restocking processes, leading to reduced costs (Thomas & Gilbert, 2014).

Supply chain management has evolved from Oliver and Webber (1982) early identification of the concept, to meet the challenges with today's modern economy. It has become a huge concern for organizations due to globalization with the continuous focus on increasing efficiency and optimization of more complex supply chain networks to maximize profits under normal circumstances (Pires Ribeiro & Barbosa-Povoa, 2018). To handle all these factors, it is important to have a good supply chain strategy.

2.1.1 Supply Chain Strategy

Supply chain strategy involves a collaborative effort by all firms in the supply chain to address market demand by coordinating the delivery of products and services to the end customer. The strategy is typically shaped by the type of product, demand patterns, customer needs, and any related risks that could potentially cause delays in supply chain delivery. Examples of such strategies are lean, agile, “leagile” and customized, which the thesis will into more detail under (Johnsen et al., 2018).

The concept of lean is centered around achieving more with less. Initially, it was introduced to enhance manufacturing performance by emphasizing material flow, pull-strategy by reacting to customer demand, and defining value according to the customer. However, it is also employed to eliminate waste in processes in the business. The ultimate objective of lean is to eradicate all forms of waste in the workplace (Johnsen et al., 2018). Types of waste are overproduction, waiting, transporting, inappropriate processing, unnecessary inventory and motions, and defects. These are all activities that consumes resources instead of adding value (Harrison et al., 2019). Central to lean thinking is the zero-inventory and just-in-time (JIT) method of delivery which is used to minimize inventory accumulation in the supply chain, and an approach to managing the supply chain (Johnsen et al., 2018). Four principles are involved in the lean virtuous improvement cycle: Specifying value, identifying the value stream, making value flow and pull scheduling. These principles all build on the overall goal of striving for perfection by eliminating waste (Harrison et al., 2019).

Establishing a lean supply chain requires more collaborative buyer-supplier relationships. The concept of lean supply partnerships has gained momentum as part of a transition towards collaborative relationships that foster procurement and logistics efficiency and effectiveness. Firms enter into closer long-term commitments and trust-based relationships all across the supply chain due to the opportunity to contribute and benefit from process improvements (Johnsen et al., 2018). A question that has been raised is whether a lean strategy is still suitable or adequate for industries experiencing escalating levels of turbulence and volatility in the market (Johnsen et al., 2018).

An agile supply chain can adapt to the evolving market needs as product life cycles shorten, and global economic and competitive factors cause uncertainty, requiring a high level of maneuverability. An agile supply strategy embodies the focus on time-based competition, where the ability to respond promptly to customer demands is deemed a competitive advantage (Christopher, 2000). Supply chain agility is the ability to swiftly adapt to unforeseen changes in supply or demand. Key components of agility are visibility and velocity. Visibility entails having a clear view of upstream and downstream inventories, demand, supply chain conditions, production, and purchasing, as well as internal visibility through clear communication and agreements. This requires close collaboration with customers and suppliers, as well as internal integration. Velocity, on the other hand, is the distance over time, which refers to the end-to-end pipeline time which is the time it takes to move products and materials from one end of the supply chain to the other. To improve velocity, time must be reduced through streamlined processes, reduced in-bound lead times, and non-value added time reduction (Christopher & Peck, 2004).

Flexibility is also a crucial characteristic of agile organizations and supply chains. Supply chain flexibility is composed of four factors: (1) System: Redundancy in capacity and inventory, and multiple sourcing, (2) Coordination and integration of systems and outsourcing, (3) Modularization/standardization of product and postponement (4) Process: Flexible and real-time based production/warehousing systems (Ivanov et al., 2014). It has its roots in flexible manufacturing systems as a business concept. These systems use cutting-edge machine technology that can provide a wide range of product variety to fulfill customer demands, e.g. additive manufacturing and other technologies (Johnsen et al., 2018). The capability to customize products at a local level implies that a greater degree of variety can be provided at a reduced overall cost, making it feasible to adopt "mass-customization" strategies (Christopher & Towill, 2000). Agile supply chains must have the ability to handle fluctuations in demand over time. Agility enhances the supply chain's ability to respond to actual customer demand rather than relying solely on forecast-based information. Inventory in an agile supply chain should be kept in a generic form, such as standard or semi-finished products, until the final customer requirements and order destination are determined. This approach is known as postponement or final configuration (Christopher, 2000).

The restricted visibility of actual demand is a significant challenge for many supply chains. Because there are multiple levels of inventory between the production point and the end market, these supply chains are often driven by forecasting instead of actual demand. The decoupling point, where the market pull meets upstream push, is the level where actual demand enters the supply chain. This concept was formerly known as the order penetration point. The concern lies not in the extent of order penetration, but in the level of visibility for actual demand (Christopher & Towill, 2000).

Supply chains are now constructed as a federation of partners connected as a network, resulting in a new form of market competition known as "network competition". In the current competitive global markets, sustainable and competitive advantage can be achieved by utilizing the unique strengths and capabilities of network partners to improve responsiveness to market demands. Electronic Data Interchange (EDI) and the Internet have allowed network partners to access and use the same data on real demand, resulting in the creation of virtual supply chains. Rather than being inventory-based, virtual supply chains rely on information sharing facilitated by information technology. However, to fully benefit from shared information, process integration is required. This involves collaborative work between buyers and suppliers, joint product development, common systems, and shared information (Christopher & Towill, 2000).

The characteristics discussed over are essential to an agile supply chain, as shown in the figure below.

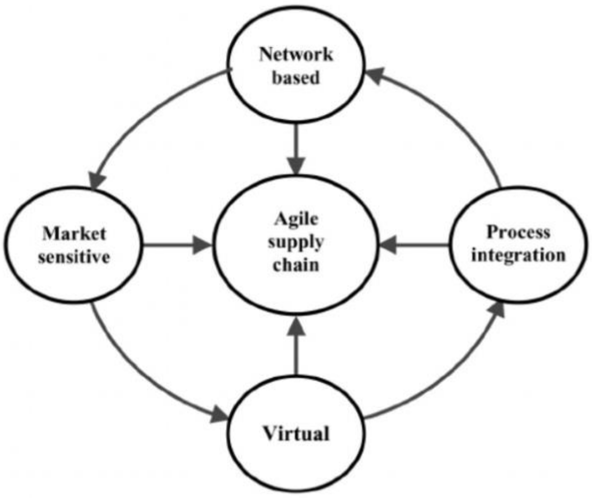

Figure 3: The Information Based Agile Supply Chain (Harrison et al., 1999).

A significant distinction between the two is that a lean strategy is related to level scheduling, while an agile strategy involves reserving capacity to handle volatile demand. Some argue that leanness is an element of agility in some circumstances (Christopher & Towill, 2000). A concept that has emerged from these two strategies is called “leagile”. Instead of looking at the supply chain as lean or agile in isolation, one can see it as a blended or hybrid strategy, combining elements from both approaches. A “leagile” strategy implies that the supply chain is agile enough to respond to the actual demand, with product availability and short delivery lead times, supported by information transparency, serves as a crucial market advantage (Christopher & Towill, 2000).

The Pareto principle, or 80/20 rule, says that 80% of the total volume is generated from 20% of the products. The principle can be used to determine the supply chain strategy, blending lean and agile. The way the top 20% of products by volume are handled should differ from managing the remaining 80%. Generally, the top 20% is more predictable, while the 80% tends to be less predictable. Thus, lean manufacturing and distribution principles are more applicable to the top 20%, while the remaining 80% needs a more agile management approach (Christopher & Towill, 2001).

2.1.2 Centralized or Decentralized Purchasing

When it comes to the organizational design of purchasing, or the purchasing strategy, a crucial consideration is whether to prioritize centralization or decentralization. Centralization emphasizes global coordination, integration, and synergy across various organizational units, while decentralization emphasizes flexibility and adaptability to local conditions (Johnsen et al., 2018).

By implementing a centralized purchasing function, organizations can realize synergies across multiple business units. These purchasing synergies refer to the performance improvement that results from combining forces, information, knowledge, and functional resources from two or more purchasing units. Consolidating expenditures and suppliers can lead to improved deals through increased economies of scale and scope. In addition, organizations should strive to standardize product components and parts to enable economies of scale. By merging fragmented purchases, many organizations have created value and achieved significant savings (Johnsen et al., 2018).

Decentralized purchasing can leverage knowledge of local supply market conditions. Local sourcing has the potential to decrease transaction and transportation costs, while also having a positive impact on sustainability by reducing environmental effects. In situations where an organization has a wide range of purchase categories and is naturally decentralized, there may be reluctance to centralize power as local units possess superior knowledge of local supply markets and can often make better deals themselves. However, a decentralized purchasing organization can lead to competition for resources between units instead of collaboration and synergy (Johnsen et al., 2018). The table under shows advantages and disadvantages of decentralized purchasing.

Advantages	**Disadvantages**
• Less bureaucracy and more streamlined purchasing procedures • Accountability for profit centers • Alignment with local requirements and suppliers • Motivation of local buyers • Improved ability to respond to local conditions	• Decreased bargaining power due to lack of economies of scale • Inconsistent strategies, policies, and codes of conduct between business units • Limited synergy and knowledge exchange • Duplicate efforts resulting in wastage of resources

Table 1: Advantages and Disadvantages of Decentralized Purchasing (Johnsen et al., 2018).

Ultimately, the decision to prioritize one approach over the other depends on the specific needs and goals of the organization. Advantages and disadvantages of centralization and decentralization of manufacturing in the healthcare context will be presented in more detail later in the paper.

2.1.3 Supply Chain Risk

Businesses are constantly surrounded by risk, both internally and externally. It is how the company deals with risk that is decisive for the effect it has on operations and its supply chain. As the thesis covered in the introduction, today's companies experience risks from factors such as natural disasters, pandemics, market-related conditions, war, political sanctions, trade wars and many other factors. Risk can come in the form of disruptive events for companies that cause unrest in operations and supply chain. If the company has not taken steps to prepare for risk, it will most likely be vulnerable to such disturbances, and it will therefore have a much greater impact on the company.

In recent decades, supply chain risk management has received increased attention due to several factors. Globalization has increased the length and complexity of supply chains, and thus their exposure and vulnerability to risk. Various industry trends have also made the topic of managing risk become increasingly important, such as firms' high dependence on outsourcing, reliance on suppliers for specialized capabilities, and the growing use of information technology to coordinate and manage the extended supply chain (Narasimhan & Talluri, 2009). In addition, the Lean management philosophy has been adopted to a large extent in SCM, which has made supply chains more vulnerable during unwanted incidents due to the reduction of redundancies. Pettit et al. (2010) argues that globalized supply chains, specialized factories, centralized distribution, increased outsourcing, reduced supplier base, increased volatility of demand, and technological innovations are factors contributing to potential disruptions. We have also seen that close and strategic buyer-supplier relationships in some cases are no longer enough to ensure supply in times of crisis (Behzadi et al., 2017).

A traditional risk management process involves a continuous cycle of hazard identification, risk assessment, control analysis, selection and implementation of measures and review. While risks can often be quantified using historical data, evaluating risks involves making assumptions based on subjective information. Building a holistic supply chain risk management program that encompasses supply, products, demand, and information management by integrating risk management techniques could be a good solution. However, applying this approach to every link in a global supply chain for all potential disruptive causes would be a huge task (Pettit et al., 2010).

Assessing risk is crucial in the uncertain era of the global economy, where supply chain design must account for demand unpredictability. Demand uncertainty can pose two types of risks: the risk of failing to meet unexpected demand on time, and the opposite risk of overestimating demand, leading to excessive inventory costs. Apart from demand risks, other general risks like unreliable vendors, delayed shipments, and natural disasters must also be considered (Zsidisin & Ritchie, 2009). There are two main categories of risks that affect SCM, which is internal and external risk. The first category pertains to coordinating supply and demand, such as issues with inventory control and stock-outs. The second category relates to disruptions and delays to regular supply chain activities, such as natural disasters, civil unrest, and ethical issues in the workforce (Kleindorfer & Saad, 2005). In risk assessment, it is crucial to identify the types of risks involved, their impact, and probability of occurrence, and to determine their significance to the overall business (Johnsen et al., 2018).

A standard way to assess risk is to use a risk matrix, which categorizes the identified risks in terms of impact and probability. This is a tool for assessing each risk factor so that managers can rank them and visualize what the biggest vulnerabilities for the supply chain is, evaluate them, and put in place action plans to take steps before the problem occurs. Mathematically, risk is the product of the likelihood of an event occurring and the potential severity of its impact. Where likelihood refers to the probability or chance that an event will occur, and severity refers to the degree of harm or damage that would result from the event. By combining these two factors, we can measure the overall level of risk associated with a particular event or situation. The higher the likelihood and severity of an event, the greater the risk, and the more vulnerable the system or entity is to that event (Pettit et al., 2010). Establishing a community within the supply chain is crucial to mitigating supply chain risks by facilitating information exchange between its members, according to Christopher and Peck (2004).

As pointed out earlier in the thesis, supply chain risk can be categorized into internal and external risk, but Christopher and Peck (2004) divides external risk into two categories, external to the firm and external to the supply chain. This builds on Christopher's statement that it is now supply chains that compete, not individual companies. The three categories can be sub-divided into a total of five categories: Internal risk, which includes process and control risk, external risk to the firm which includes demand and supply, and external risk to the network which includes environmental risks (Christopher & Peck, 2004). Risk can further come from a variety of reason and sources as seen in the figure below which shows supply chain risks and their drivers.

Category of Risk	Drivers of Risk
Disruptions	▪ Natural disaster ▪ Labor dispute ▪ Supplier bankruptcy ▪ War and terrorism ▪ Dependency on a single source of supply as well as the capacity and responsiveness of alternative suppliers
Delays	▪ High capacity utilization at supply source ▪ Inflexibility of supply source ▪ Poor quality or yield at supply source ▪ Excessive handling due to border crossings or to change in transportation modes
Systems	▪ Information infrastructure breakdown ▪ System integration or extensive systems networking ▪ E-commerce
Forecast	▪ Inaccurate forecasts due to long lead times, seasonality, product variety, short life cycles, small customer base ▪ "Bullwhip effect" or information distortion due to sales promotions, incentives, lack of supply-chain visibility and exaggeration of demand in times of product shortage
Intellectual Property	▪ Vertical integration of supply chain ▪ Global outsourcing and markets
Procurement	▪ Exchange rate risk ▪ Percentage of a key component or raw material procured from a single source ▪ Industrywide capacity utilization ▪ Long-term versus short-term contracts
Receivables	▪ Number of customers ▪ Financial strength of customers
Inventory	▪ Rate of product obsolescence ▪ Inventory holding cost ▪ Product value ▪ Demand and supply uncertainty
Capacity	▪ Cost of capacity ▪ Capacity flexibility

Table 2: Supply Chain Risks and their Drivers (Chopra & Sodhi, 2004).

Supply chain disruptions have been defined as *"unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain"* (Macdonald & Corsi, 2013, p. 2). In the context of healthcare, disruptions can be defined as unexpected events that have the potential to hinder the provision of healthcare services to patients (Mandal, 2017). Mitigation, preparation and management of supply chain disruptions is especially important in the healthcare supply chain, because of the consequences for human lives and safety if it fails (Spieske et al., 2022). The way risk and disruptions propagate in the supply chain is called the Ripple Effect. The Ripple Effect is described as the effect of a disruption on supply chain performance, as well as its propagation through the structural design and planning parameters of the chain (Ivanov et al., 2014). The Ripple Effect is interesting for understanding how risk and disruptions works, and thereby how to manage the risk.

There are several classifications, frameworks and models offering ideas for risk mitigation strategies. One of the simplest and most effective ways to "buy time" in the event of a supply chain disruption is to increase the level of inventory. For predictable lower value products, decentralizing inventory has the benefit of spreading the risk across multiple production locations. However, for more complex products, holding more inventory may not be cost-effective, and alternative options must be explored (Johnsen et al., 2018):

- Increasing supplier redundancy through multi-sourcing is an effective way to reduce the risk of disruption in the supply chain. Multi-sourcing involves having backup suppliers to rely on in case of any disruption in the regular supply chain.
- Expanding production capacity is a long-term solution that requires additional investment in the supply base. Decentralized capacity with low costs should be prioritized for predictable demand, while centralized capacity should be established for more unpredictable demand.
- When market unpredictability grows, pooling or aggregating demand can be a useful strategy. This enables suppliers to leverage economies of scale where possible and apply smoothing techniques over time to balance production.
- To improve supply chain responsiveness due to system delays, companies can implement strategies like Efficient Consumer Response (ECR) and Build-to-Order (BTO). This requires better coordination between suppliers and manufacturers, as well as investing in integrated IT systems. Flexibility can be increased by reducing the time needed for suppliers to switch from one product to another based on customer demand. This is especially crucial for low-volume, unpredictable items.

The figure under shows how various mitigation strategies works on the different categories of risk as presented earlier.

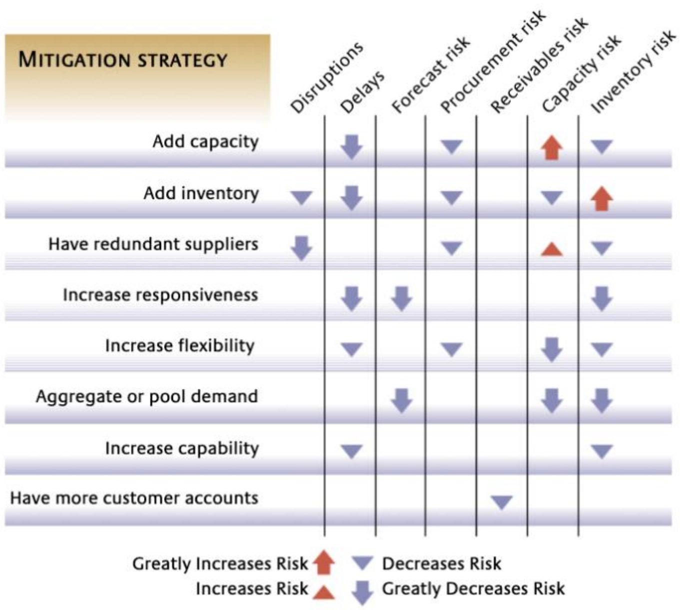

Figure 4: Assessing the Impact of Various Mitigation Strategies (Chopra & Sodhi, 2004).

Even with precise assessment tools and good strategies, it is not certain that one will always be able to maneuver away from all the risks that the supply chain faces. As we have seen with the pandemic, we cannot prepare for all disruptions. We do not simply know everything that is going to happen in the future, and the business environment is rapidly changing. Therefore, companies must prepare for the unknown, or the black swan scenarios. Traditionally, black swan supply chain events have been linked to improbable, rare or unlikely occurrences that often comes without a warning, that can have significant, and sometimes even catastrophic, impacts on businesses (Aggarwal & Bohinc, 2011). Black swans are scenarios like the Covid-19 pandemic, or the blockage of the Suez Canal for six days in March 2021 by the Ever Given, a container ship that run aground in the canal. Both events disrupted the global supply chain. The latter caused major delays in the global trade, huge costs, and affected various businesses all over the world. The cost of the blockage was estimated at $9.6 billion to the global economy (Lee & Wong, 2021). It is therefore important to think beyond risk assessment and mitigation and focus on building robust and resilient supply chains that can withstand disruptive events such as black swan scenarios. Thus, the thesis will describe and explore the concept of supply chain resilience in the next segment.

2.2 Supply Chain Resilience

This chapter will focus on defining supply chain resilience, its importance, and characteristics and frameworks for enhancing resilience.

As the thesis described in the previous chapter, managing and mitigating risk is of great importance for businesses in today’s turbulent and volatile markets. But, the conventional risk assessment approach is insufficient to address unforeseeable events. The concept of supply chain resilience can bridge these gaps and complement the current risk management programs and business continuity planning methods, making it possible for a supply chain to withstand unexpected disruptions and gain a competitive advantage (Pettit et al., 2010). Christopher and Peck (2004) also argues that creating more resilient supply chain may be the answer to overcoming these obstacles. Since the 2000´s supply chain resilience has been studied on a larger scale in the scientific literature (Tukamuhabwa et al., 2015). Some crucial episodes, from both the economic and industrial point of view account for some of the reason for this trend (Bevilacqua et al., 2019).

There are many definitions of supply chain resilience in the scientific literature. A common view of the term resilience refers to the capacity to endure and bounce back from disruptions, as well as the capacity to adjust to shifting circumstances. Christopher and Peck (2004, p. 2) defines resilience in a short and precise manner as: *"The ability of a system to return to its original state or move to a new, more desirable state after being disturbed".* A more detailed definition, which also takes into account the supply chain perspective is: *“The adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption”* (Tukamuhabwa et al., 2015, p. 1). Instead of bouncing back to an “old normal” after disruption, Ivanov (2022), like the definitions, argues that firms can adapt Supply Chain Viability, which involves adaptation to a “new normal” to survive in radically changed conditions. Common for the definitions is the terms “disturbed” or “disruption”. These terms are essential in the study of resilience because it is what creates the need to build resilient supply chains.

Risk management strategies can be divided into two categories, either robust or resilient. A robust supply chain can withstand disturbances, retain its original structure, and remain functional in the face of uncertainties. Whereas a resilient supply chain can quickly return to its original condition, or to a new and more preferred state after it has been disturbed (Behzadi et al., 2017). Both robustness and resilience are key capabilities for successful supply chain risk management (Ivanov et al., 2014).

Several articles highlight different characteristics that are important to develop to create resilience in the supply chain. Christopher and Peck (2004) argues that resilience involves flexibility and agility, and its effects go beyond merely redesigning processes to making critical choices on procurement and forming more cooperative supply chain partnerships that are built on enhanced transparency of data. Patel et al. (2022) mentions three capacities that are central for a resilient supply chain. These are absorptive, adaptive, and restorative capacity. Redundancy, collaboration, and robustness are highlighted as important characteristics of resilience in another study (Zamiela et al., 2022). Collaboration is a recurring subject, as the concept of collaborative supplier relationships was mentioned earlier in the thesis. Scholten and Schilder (2015) highlights efficiency, redundancy, collaboration, flexibility, velocity, and visibility as reoccurring terms in their review of literature that deals with supply chain resilience. However, it is a trade-off between efficiency, flexibility, and resilience, which is highly relevant in practice as it is challenging to create resilience at the same time as maintaining efficiency and keeping costs down (Ivanov et al., 2014). This trade-off is also discussed by Christopher and Peck (2004). Traditionally, having excess capacity was viewed as wasteful and undesirable. However, strategically placing additional capacity and inventory at critical points can be highly advantageous in building supply chain resilience.

Traditionally SCM has been focused on Design-for-Efficiency and Responsiveness. On the other hand, the Design-for-Resilience approach involves designing supply chains and operations to withstand severe and unforeseen disruptions, and to recover quickly when faced with such disruptions. The Design-for-Resilience approach primarily focuses on three key resilience assets or capabilities: Redundancies, which include measures such as risk-mitigating inventories, backup supply and transportation infrastructure, and subcontracting capacities. Furthermore, real-time monitoring and visibility systems that rely on data-driven insights are important. Lastly, flexibility and contingency recovery plans that can help organizations respond effectively to disruptions and rapidly recover from them (Ivanov, 2022).

Christopher and Peck (2004) have established a framework for building a resilient supply chain consisting of four principles: (1) Firms can proactively incorporate resilience into a system before a disruption occurs through supply chain engineering. (2) Risk identification and management require close collaboration among stakeholders. (3) Agility is necessary to have quick responsiveness to unexpected events. (4) Creating a risk management culture is crucial. Secondary factors like availability, efficiency, flexibility, redundancy, velocity, and visibility are also considered as significant characteristics, and are factors that help to influence these four principles. The main findings of Christopher and Peck (2004), that supply chain resilience is achieved by focusing on combining a lean strategy with agility and flexibility, is backed up by multiple studies, among others by Mensah and Merkuryev (2014).

Pettit et al. (2010) have also developed a framework for supply chain resilience, as seen in the figure below. They identified 14 capabilities that enhance the resilience of a supply chain. These include sourcing and order fulfillment flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, organization, market position, security, and financial strength.

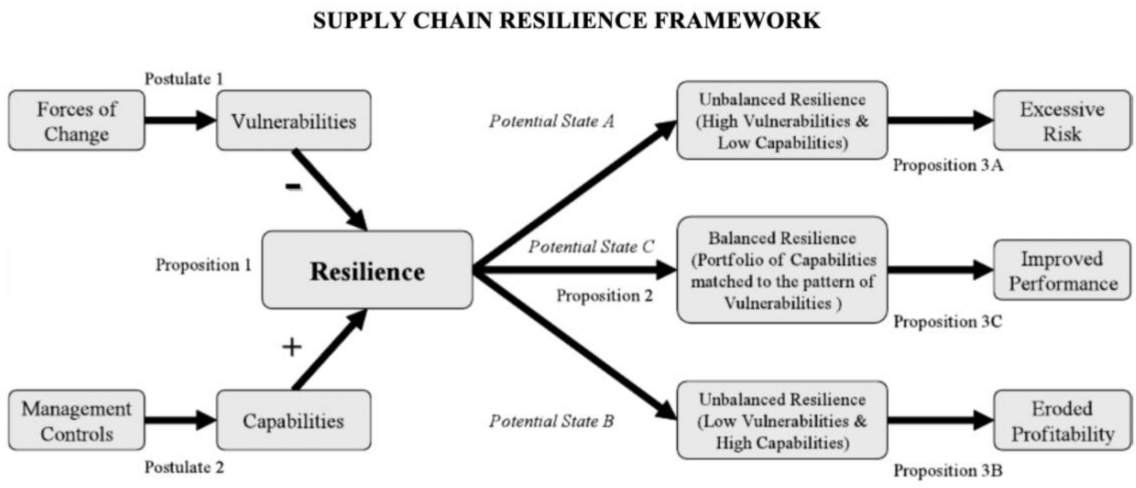

Figure 5: Supply Chain Resilience Framework (Pettit et al., 2010).

In the framework it is laid down as a premise that as the capabilities of a supply chain increase and vulnerabilities decrease, the level of resilience increases. Here, supply chain capabilities refer to the qualities that enable a business to anticipate and effectively manage disruptions. These capabilities may prevent a disruption from occurring, such as implementing security measures. They may also mitigate the effects of a disruption, e.g. by having emergency supplies readily available. Finally, these capabilities may enable a business to adapt and recover quickly in the aftermath of a disruption. As sees in the figure, there are three potential states with each its own results. Two of them leads to “unbalanced resilience”, while one leads to "balanced resilience". The state of "balanced resilience", or the “zone of resilience” can be achieved by developing capabilities that effectively address the vulnerabilities in a specific supply chain, while also considering the level of investment required and associated risks. “Balanced resilience” results in improved performance for the supply chain (Pettit et al., 2010).

Ivanov et al. (2014) have made a framework for resilience that consists of four focus areas, two in pre-disruption state and two in post-disruption state. The focus areas before disruption includes preparedness with risk monitoring and control, and mitigation by creating structural and parametric robustness. After disruption the focus in on stabilization with operation preservation and contingency plan execution, and recovery through adaptation and long-term impact minimization. All focus areas are operationalized through use of business processes, supply chain models and IT.

There are three primary dimensions of supply chain resilience, according to Naghshineh and Carvalho (2022). Namely proactive capability, supply chain design, and reactive capabilities. Additive Manufacturing can enhance supply chain readiness and improve responsiveness by accelerating product time-to-market or manufacturing speed. The deployment of AM systems to locations requiring emergency supplies with shorter turnaround times can further improve supply chain agility. Additionally, supply chain complexity can be reduced through effective supply chain design, which can boost a company's supply chain resilience by reducing vulnerability. Utilizing additive manufacturing can also lead to reduced dependence on suppliers of complex components.

A multi-layered protection framework has been developed to ensure resilience in medical product supply chains. The investment in measures is considered crucial to safeguard patients from the adverse effects of medical product shortages, and thereby ensure public health during both regular and emergency situations. Incorporating resilience into medical supply chains is a complex and challenging reliability problem as there are multiple available resilience options that interconnect in intricate ways (NASEM, 2022). This complexity can be attributed to three key factors:

Medical supply chains involve numerous components, including people, processes, technologies, and policies, making them complex systems. Thus, enhancing resilience can be achieved through various approaches that target different aspects of the supply chain (Hopp et al., 2022). Employing multiple protection layers is an effective way to improve reliability, as stated by The Redundancy Principle. (Hopp & Lovejoy, 2013). Additionally, measures to increase resilience can be implemented at various stages in the timeline since disruptive events and their consequences evolve over time.

The framework initially consists of three protective layers, which are categorized as mitigation, preparedness, and response. These phases align with the standard emergency response phases defined by FEMA (2021). Mitigation is carried out before an emergency and aims to prevent future emergencies or minimize their impact. Measures for mitigation include hardening and diversification. Preparedness measures are also implemented before an emergency and aim to prepare for handling an emergency. Relevant measures for preparedness include inventory stockpiling, capacity buffering, contingency planning, and readiness. Response measures take place during an emergency and focus on responding safely to the emergency (FEMA, 2021). It includes reducing demand and/or increasing supply, and prophylaxis activities such as front-line, last-mile measures that immediately resolve the issue to protect human lives during a shortage. The development of such solutions exploded during the pandemic (NASEM, 2022). During the early stages of the Covid-19, 3D-printed components were used to modify ventilators, allowing multiple patients to share a single machine, as a demand reduction measure (Ayyıldız et al., 2020).

A fourth phase is also included in the framework, recovery, which is measures after the emergency (FEMA, 2021). However, recovery has been replaced with awareness, which serves as the foundation for the three layers of defense described earlier. It is believed that awareness is crucial for building resilience in a medical product supply chain. It involves having the necessary information for assessing, mitigating, preparing, and responding to risks by the right individuals. The effectiveness of mitigation measures determines whether a potential trigger event will lead to an actual supply chain disruption. If the multiple layers of protection fail, a disruptive trigger event can cause harm to the patients (Hopp et al., 2022).

Identifying which medical products are critical to the supply chain is crucial as it determines where to emphasize necessary resilience measures. It is essential to note that there is no universal approach to enhancing supply chain resilience for all medical products. Different product supply chains, markets, and risk profiles require tailored interventions. The critical challenge lies in selecting cost-effective measures that match each product. Allowing the market to provide actions enables market competition and innovation to generate optimal solutions, making research on the role of additive manufacturing in this context significant (NASEM, 2022).

The popularity of the resilience subject has not has not become any less after Covid-19, as supply chains worldwide has seen the importance of preparing for disruption. Ivanov (2022) have developed a framework for “Lean resilience” called the AURA framework (Active Usage of Resilience Assets), which is a framework for post Covid-19 supply chain management. The AURA framework redefines resilience as an active and value-generating component of operations management, rather than a passive defense against rare and disruptive events. The framework is divided into five main areas: Plan, source, make, deliver, and return. The plan area involves supply network design with consideration of structural shifts, disruption analytics and the use of digital platforms. Next, the source phase involves active integration of backup suppliers in everyday business, product substitution, and supplier collaboration platforms. The make phase includes using capacity agility, e.g. flexible lines, for resilience, using postponement for resilience, and adapting Industry 4.0 and additive manufacturing. The deliver area involves decentralized logistics structures, omni-channel distribution, and the use of blockchain and tracking technologies for resilience. Last, the return phase includes contingency sourcing with recycled materials, and closed-loop supply chain as a resilience asset (Ivanov, 2022).

By comparing the literature, it is clear that flexibility, agility, and visibility are essential for achieving supply chain resilience for an organization. Companies need to develop a comprehensive understanding of how the entire supply chain functions before any unforeseen events occur in order to build resilience into their operations and systems. Successful supply chains rely on transparency of supply and demand information (Johnsen et al., 2018). Technology such as Enterprise Resource Planning (ERP) systems, blockchain technology and radio frequency identification (RFID) enables a higher degree of supply chain visibility. Although supply chain technologies have advanced to a point where companies are expected to have good visibility of their goods throughout the supply chain, the complexity of global supply networks means that in reality, firms do not have anywhere near perfect visibility. The consequence of this is that companies lose sight of critical issues such as the origin of the products and what it actually contains (Johnsen et al., 2018).

2.3 Additive Manufacturing

This chapter defines additive manufacturing, highlights the main technology with its characteristics, comparing it to traditional manufacturing, explores its impact on the supply chain, and identifies advantages and limitations. Further it explores AM in the healthcare context and its implementation challenges in this industry.

Additive manufacturing (AM) is defined by ISO/ASTM, which makes international industry standards, as the *"process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing technologies"* (ISO/ASTM, 2021, p. 1). The terms additive manufacturing and 3D-printing are often used interchangeably in the industry, where AM is the broader and more comprehensive term. They both refer to the technology of creating a final three-dimensional object from the bottom up by adding layers of material upon each other (Attaran, 2020). The printers commonly use a movable inkjet print head to distribute material over a build area, which allows for the creation of various products and services for customers (Harrison et al., 2019). Various materials such as polymers, metals, plastics, resins, rubbers, composites, ceramics, concrete, and even organic substances can be used in AM. To achieve this, most commercial 3D printers use computer-aided design (CAD) to translate the design into a three-dimensional object, where the CAD serves as a guide for the 3D printer (Attaran, 2020).

According to ISO/ASTM International standard, there are seven categories of AM processes:

1. Binder jetting is an AM process that involves selectively depositing a liquid bonding agent to join powdered materials (ISO/ASTM, 2021). This process can be utilized with a broad range of high-productivity powders and successfully processed materials such as metals, polymers, and ceramics. Nonetheless, creating printing and post-processing techniques that optimize part performance is still a challenge (Ziaee & Crane, 2019).
2. Direct energy deposition employs focused thermal energy to melt and fuse materials during deposition. The energy source, which can be a laser, electron beam, or plasma arc, is concentrated to melt the materials being deposited (ISO/ASTM, 2021). This method typically uses metals in either wire or powder form and is the second most widely used among different metal printing technologies (Dutta, 2020).
3. Vat photopolymerization involves selectively curing liquid photopolymer in a vat using light-activated polymerization (ISO/ASTM, 2021). Photopolymerization is categorized into three groups based on the curing methods: cured with a laser (Stereolithography (SLA)), cured with a projector (Digital Light Processing (DLP)), and cured with LEDs and oxygen (Continuous Digital Light Process (CDLP) / Continuous Liquid Interface Production (CLIP)) (Pagac et al., 2021)
4. Material jetting involves selectively depositing droplets of build material, such as photopolymer and wax (ISO/ASTM, 2021). This technology is widely employed across various industries as it can produce parts relatively quickly. Material jetting can print parts with higher accuracy in relation to dimensions and lower surface roughness compared to other polymeric material printing technologies such as FDM and SLA (Gülcan et al., 2021).
5. Material extrusion involves dispensing material selectively through a nozzle or orifice (ISO/ASTM, 2021). It is the second most widely used AM process. Material extrusion is a fast and cost-effective method for producing parts using a wide range of materials, including commodities, engineering materials, high-performance thermoplastics, composites, and functional materials. It is not well-suited for producing intricate or miniaturized parts (Hsiang Loh et al., 2020).
6. Powder bed fusion is an process where thermal energy selectively fuses specific regions of a powder bed (ISO/ASTM, 2021). This process is suitable for polymers and metals, and less to ceramics and composites. The most promising area for

research and development in this field is laser-based powder bed fusion with metals. Laser-based powder bed fusion has a higher cooling rate and produces better surface finishes compared to other AM processes (Sun et al., 2017).

7. Sheet lamination involves bonding sheets of material to create an object (ISO/ASTM, 2021). While it was among the first AM techniques to be commercialized, it has not gained widespread success in the market. One of the drawbacks of this method is that each layer requires a full sheet of material, which can result in high material waste if the build volume is not fully utilized (Gibson et al., 2021).

The emergence of AM technology has begun to disrupt the traditional processes of product design, manufacturing, and distribution, as it offers a financially feasible option for decentralized production. This technology also enables customers to participate in the design and manufacturing process at the point of consumption. For instance, hospitals are utilizing bio-printing to offer bone engineering services in-house, which simplifies the medical supply chain and enhances the success rate of surgical procedures (Harrison et al., 2019).

Initially, the primary advantage of the first 3D printing machines was the decreased time required for product development of prototypes. However, current advancements in this technology have enabled the creation of complete products or parts, assisting multiple industries in minimizing production time, improving efficiency, and cutting costs. AM can now be integrated into various stages of the conventional supply chain, and streamline operations by producing more complex components in close proximity to the end customer (Attaran, 2020).

The vast range of printers and materials available in AM has resulted in a wide range of shapes, sizes, and applications. It is possible to print objects as small as microscopic structures or as large as aircraft wings or even entire houses. The versatility of the technology has led to numerous applications for AM, each with unique implications for agile manufacturing: Prototyping, spare parts (equipment and components), low-volume products, and customized products (Harrison et al., 2019).

AM also causes significant changes in how supply chains deliver value. A variety of industries, such as aerospace, healthcare, automotive, military, and food, are actively utilizing the technology to gain a competitive advantage, despite being relatively new to many businesses. The flexibility, speed, and relatively lower cost of producing small quantities with AM is supporting the shift of the customer order decoupling point upstream, leading to reduced production time and enables customized solutions. AM also supports the production of more complex products with fewer components than traditional manufacturing methods, resulting in reduced inventory costs and the number of suppliers needed. Suppliers of previously outsourced parts gets displaced with vendors of printers and printing material when bringing the manufacturing in-house (Harrison et al., 2019).

2.3.1 Traditional Manufacturing vs. Additive Manufacturing

Traditional, or conventional, manufacturing (TM) methods involve reducing an object through cutting, milling, and turning to create a final product, which can be called subtractive manufacturing (Harrison et al., 2019). This is an energy- and resource-intensive manufacturing processes that often leave behind a good deal of unused material and waste in the process (Peng et al., 2018). However, this manufacturing process is usually much faster and cheaper in mass production (Haleem & Javaid, 2020). Additive manufacturing builds objects up from scratch, layer by layer, which in turn reduces the amount of material required in the supply chain and leaves very little excess material and waste (Peng et al., 2018). Haleem and Javaid (2020) also argues that AM has less energy consumption and less material waste in production.

The design process for an AM product does not require any tools or fixtures. With proficient computer skills, the design and development time is typically shorter than TM, the responsiveness between design and product increases, and the manufacturer can easily make modifications to the product. However, skilled human resources are typically required for designing products and operating AM machines. Interruptions during the production process are generally not feasible, as any breakage can lead to damage and waste of the parts being printed (Haleem & Javaid, 2020).

AM technology allows for cost-effective production of small batches and provides opportunities for cost-effective customization of products and parts. On the other hand, the manufacturing expenses for each item may be significantly higher since the materials used could be expensive and lack the benefits of economies of scale. Additionally, post-processing can further contribute to the overall cost of the product (Haleem & Javaid, 2020). Experts generally agree that AM is not a direct competitor but rather a complementary approach to high-volume manufacturing in various sectors. The high output per hour and low unit costs of mass production is hard to match (Harrison et al., 2019).

The following figure provides a comparison between TM supply chain and AM supply chain. In TM, material resource providers supply materials to part and component manufacturers, who then pass on these parts to an assembly plant. The final product is then sent to retailers or distributors. Any disruptions during the manufacturing or assembly process could lead to delays in delivering products to retailers or distributors, unless the system has redundancy built in. In contrast, AM with localized production is less vulnerable to such disruptions. Firstly, there may not be any need for assembling parts or components. Secondly, a disruption in the manufacturing process does not affect all retailers or distributors. The utilization of AM can potentially lead to significant changes in the manufacturing supply chain, resulting in decreased dependence on SCM. By bringing production closer to consumers, the number of links in the SC can be reduced (Thomas & Gilbert, 2014).

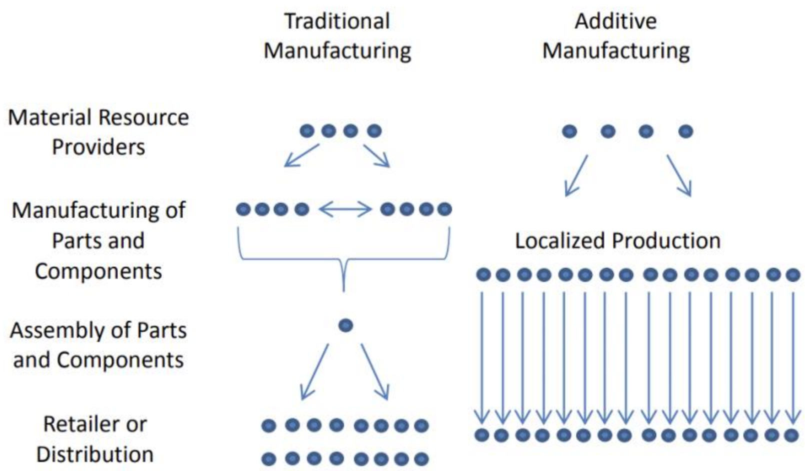

Figure 6: Traditional Manufacturing Compared to Additive Manufacturing Supply Chain (Thomas & Gilbert, 2014).

If AM is used to reduce the number of supply chain links and bring production closer to consumers, it could decrease the vulnerability to disasters and disruptions. In any product's supply chain, every factory and warehouse present a potential point where a disruption could delay or halt production and delivery. A shorter supply chain with fewer links implies fewer points of potential disruption. Furthermore, if production is decentralized and brought closer to consumers, it may result in several facilities manufacturing a few products rather than a few facilities producing many products. Disruptions in the supply chain may then only have local impact rather than regional or national effects (Thomas & Gilbert, 2014).

Multiple studies show that AM has the potential of altering supply chains and logistics (Attaran, 2017a; Chen, 2016; Kubáč & Kodym, 2017). Some common factors in the literature shows that AM can reduce inventories, safety stocks, lead time, waste, and complexity. Inventory and safety stock can be reduced or eliminated by building up digital storage of designs instead of having expensive warehouses with a lot of inventory. This greatly reduces costs for warehouses and inventory, as all parts and products can be stored digitally and be produced with AM when needed, i.e. on-demand. Furthermore, it can impact supply chains by increasing the speed of product development and production flexibility, reducing economic lot size, and decreasing material waste (Attaran, 2017a). AM has the potential to reduce supply chain- and logistics complexity in various ways (Kubáč & Kodym, 2017). One significant benefit of the technology is consolidating multiple components into a single product, resulting in reduced inventory complexity. AM can also eliminate the need for assembly and pre-assembly steps, reducing the number of suppliers and processes needed. Additionally, product customization through 3D printing can lead to cost reduction and increased profits by engaging customers in the design and production stages, providing tailored offers to each customer, and quickly adapting to changes in the market (Attaran, 2017a).

The impact of AM has the potential to be very disruptive on the setup of global supply chains. The technology can eliminate the need for high volume production facilities and low-level assembly workers, which can dramatically reduce supply chain costs. Manufacturing can occur almost anywhere at the same cost, making it financially inefficient to transport products across the globe. This is at the same time somewhat contradictory to the fact that mass production is difficult to match economically, as previously pointed out. As a result, manufacturing reflow and supply chain transformation can lead to a reduction in global freight volume, significantly affecting the logistics industry (Chen, 2016).

The figure under shows advantages and disruptions with additive manufacturing in the supply chain.

Advantages	**Disruptions**
• Industrial Efficiency: The use of AM enables consumers to print parts to fix their items, transforming them into micro-manufacturers. This has the potential to improve industrial efficiency. • Component Manufacturing: Industries that require small quantities of components that must meet precise specifications can benefit from AM. • Printing Complete Systems: With the multi-material capability of AM, it is possible to print complete systems or subsystems. This feature is especially useful as most finished products are made from more than one material. • Quality Improvement: The potential for quality improvement is a key advantage of AM. Companies can also enhance their aftermarket services as consumers become producers. • Modifications and Redesigns without Penalties: 3D printing facilitates design and innovation without time or cost penalties. Engineers can try multiple	• Mass Customization: AM supports production of customized products, which can enhance customer satisfaction while minimizing waste. • Disruptive Market Entry: The benefits of AM can potentially reduce the cost of market entry for new competitors. • Decentralized and Localized Production: AM permits localized production, reducing reliance on centralized supply chains. This enables products to be manufactured on-site or nearby, lowering lead times, transportation costs, and the risk of supply chain disruptions. The efficacy and efficiency of localized supply chains were demonstrated during the Covid-19 pandemic. • On-Demand Manufacturing: AM facilitates on-demand production, allowing for products to be manufactured only when needed. This minimizes the need for large inventories that are costly and time-consuming to manage.

iterations simultaneously with minimal additional costs. • Increased Supply Chain Efficiency: The real-time visibility to production and receipt of parts provided by 3D printing can minimize general manufacturing time and cost, leading to increased supply chain proficiency.	• Reduced Lead Times: AM can significantly decrease lead times to produce spare parts, replacement components, and obsolete parts. This ensures that products can be repaired or maintained quickly, reducing downtime and increasing product availability. • Environmentally Sustainable Practices: AM leaves a smaller environmental footprint by minimizing waste as only necessary materials are used.

Table 3: Advantages and Disruptions of AM (Attaran, 2017b; 2020)

In conclusion, AM has the potential to enhance resilience in SCM by minimizing the risk of supply chain disruptions, cutting lead times, and enhancing overall efficiency and effectiveness. Nevertheless, it is worth noting that AM does not provide the perfect solution to these problems, and there are still obstacles to be overcome, including quality control, regulatory compliance, and cost-effectiveness (Attaran, 2020). It exists several obstacles in adopting AM in a manner that would enable its substantial and rapid expansion. Size restrictions, slow production time, high cost of printing equipment, regulation implications, and the high need for post-processing are some of them (Attaran, 2017b). There is also implications in adaptation of new technology for many organizations (Holmström & Gutowski, 2017).

2.3.2 Additive Manufacturing in Healthcare

The healthcare sector has significant potential for transformation, and the utilization of AM in the medical field is expected to expand. AM is already being employed in manufacturing of medical products. While this market is still in its early stages, there is high anticipation of successful implementation in the medical industry. In 2012, the AM market in the medical segment was valued at $11 million. As the technology becomes more affordable with time, it is projected to reach $1.9 billion by 2025 (Attaran, 2017b).

The medical field has discovered innovative ways to utilize AM, and one of the initial transformations that AM brought to the medical industry was the creation of custom implants like hearing aids and prosthetics (Berman, 2012). With the aid of computer-aided design software and AM, practitioners can now scan a patient, manufacture a personalized implant or prosthetic, and fit the patient with a customized component that meets their specific needs (Attaran, 2017b). AM is being used in a variety of applications in the medical field. For example, medical models, implants, tools, instruments and parts for medical devices, medical aids, supportive guides, splints and prostheses, and biomanufacturing. Selecting the appropriate printing technology is crucial for manufacturing medical devices using AM. Among the most used AM processes for medical devices are stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM) for plastic parts, while direct metal laser sintering (DMLS) and selective laser melting (SLM) are preferred for metal parts (Salmi, 2021).

With AM, replacement parts can be easily manufactured on-demand, and improved preventive maintenance can be achieved with 3D printed spare parts. The technology enables local distributors and service providers in remote locations to print parts, removing restrictions on goods delivery. This shortens the supply chain and increases cost savings, as there is no longer a need for inventory shipping and stockpiling. The need for large bulk inventories become unnecessary as this technology enters the mainstream medical industry (Attaran, 2017b).

In the medical field, where each patient or customer is unique, AM has considerable potential in developing small quantities of personalized and customized solutions with relatively low costs compared to other manufacturing processes (Berman, 2012). A literature review done by Salmi (2021) shows that the benefits of AM in medical fields are many of the same as the literature depicts for general supply chains. Additionally, the medical field reaps benefits like improved medical outcome, decreased radiation exposure, digital storage, reduction of manual work, fully automated and digitized manufacturing, enablement of surgeon as designer, innovation potential, and the ability to use different materials and make complex geometries. Attaran (2017b) also mentions reduced surgery time and cost, reducing the risk of post-operative complications, and reduced lead-time as benefits of AM in healthcare. The potential for AM to enhance the design and development of medical parts and products is significant. AM technology can improve design accuracy, reliability, and ease while also enhancing the performance of medical parts through the use of innovative and unique designs and high-quality materials (Haleem & Javaid, 2020).

It also exists significant barriers in the adoption of AM in medical supply chain. The most critical barriers are lack of a variety of materials, lack of education and training to workers and designers, and limitations in production technology. The findings are useful insight because it portrays significant barriers in in the adoption of AM in the sector of the thesis. The results from the study suggests that the managers should emphasize the technological and organizational barriers more (Choudhary et al., 2021).

Ensuring that AM products meet the required quality and regulatory standards remains a significant challenge in the healthcare sector. To overcome this challenge, rigorous testing and validation processes are necessary to ensure the safety and efficacy of products intended for use in clinical settings. To ensure compliance with regulatory guidelines, it must establish a quality management system (QMS) for 3D printed medical devices. This system includes a set of policies, procedures, forms, and work instructions, along with the necessary resources (Haleem & Javaid, 2020).

Despite these challenges, the use of AM in the healthcare supply chain has the potential to revolutionize the design, production, and distribution of medical devices. However, additional research and development efforts are necessary to unlock the full potential of this technology in the healthcare industry.

Hospitals can incorporate AM into their ecosystem either with centralized or decentralized manufacturing. By facilitating the production line, a hospital can go from a customer to a manufacturer (Terkaj & Tolio, 2019). In a centralized model, hospitals depend on external suppliers to provide them with the required products. Relevant personnel place orders for the necessary items, which are then manufactured and delivered to the hospitals. This approach does not require any investment in manufacturing facilities, and suppliers handle the regulatory approval process. However, there are some drawbacks to this method. Hospitals lose control and rely on suppliers, which can lead to increased lead times and higher final costs for the products and parts (Pettersson et al., 2019).

A decentralized manufacturing model involves having production facilities and equipment located within the hospital. Studies have demonstrated that integrating AM technology with a multidisciplinary team possessing valuable experience and clinical knowledge can lead to fast response times. However, achieving desired outcomes would depend on having trained personnel within the hospital who can operate AM technology. Additionally, the hospital would need to take responsibility for obtaining regulatory approvals for printed parts (Calvo-Haro et al., 2021). A decentralized production system offers several potential benefits, such as reduced inventory management and logistical information system needs (Khajavi et al., 2018).

The Covid-19 pandemic highlighted the importance of distributed production in the healthcare system, marking a paradigm shift in the industry (Perez-Mañanes et al., 2021). In the event of a global crisis or other unexpected events, localized production reduces the risk of supply chain disruption. However, a successful in-house 3D capacity is dependent on satisfactory economics as a key factor. The costs of buying AM machines of the needed quality for manufacturing of medical parts can be significant (Haleem & Javaid, 2020).

An alternative option is to leverage the existing local production capacity. Currently, there are numerous external entities possessing 3D printers with the ability to produce medical equipment on demand. Many of these entities are organized in clusters, where they exchange knowledge and experiences while benefiting from being part of the group. Utilizing the capacity of these clusters and AM-companies could provide a solution for generating the necessary capacity to produce medical equipment in times of crisis, thus aiding in the preparedness of the healthcare supply chain and increasing its resilience. However, obtaining approvals and qualifications and regulating the process to ensure patient safety in hospitals remain a challenge.

3.0 Case Description

Several Norwegian healthcare organizations are now using 3D printing as an aid in various forms of surgery. The medical technical department at Haukeland University Hospital in Bergen has used 3D printing since 2015, as the first to use it in the Norwegian health sector. Oslo University Hospital, Rikshospitalet, Helgeland Hospital, Lærdal hospital and other hospitals have recently also purchased 3D printers (Stormo, 2021).

The Norwegian health sector is divided into four health organizations, according to geographical division, hence Health South-East, West, Mid-Norway, and North. The case for the research is the implementation and use of AM in two different regions, specifically in the regions Health South-East and West, which is the regions with the most users. The two biggest hospitals in Norway are located in these regions, which is Haukeland University Hospital and Oslo University Hospital. In 2021, Haukeland University Hospital had around 984,000 patient encounters, 40,000 operations were performed, and they have around 13,000 employees in 229 occupational groups (Helse-Bergen, 2022). Oslo University Hospital carries out around 1,2 million patient treatments a year, and with its 24,000 employees it is the largest hospital in Europe, and one of the largest in the world measured by the number of employees (Oslo-universitetssykehus, 2023). The research will study the use of AM in the regions, and the perceived benefits, limitations, and implications of the technology as the effects.

3.1 The Healthcare Sector

The healthcare sector is a rather unique industry due to its nature, which is to treat people with illnesses, injuries, or other ailments in the best possible way, and as effectively as possible. This creates a great need for all equipment to always be in place, which in turn creates pressure on the supply chain. There are both private and public health clinics, but in Norway it is most relevant to talk about the public sector because that is where the majority of medical treatment takes place in Norway. Compared to a normal business, public hospitals stand out in that the purpose is not to make as much money as possible, but to treat all patients effectively and in a good way. However, it is worth noting that they also have a financial responsibility for their operations. This means that the starting point for running a hospital, with associated operations such as managing the supply chain, is different from running a commercial business. Because of the criticality in a hospitals function, on could argue that the importance of the healthcare supply chain to work is even bigger than of a commercial business.

There are unique challenges and considerations in the healthcare sector. The literature notes that the healthcare supply chain is characterized by a high degree of complexity, uncertainty, and interdependence. Planning how many people need treatment in the various areas is very difficult, and it is therefore challenging to forecast demand for the hospital's services (Landry & Beaulieu, 2013). The visualization displayed below depicts a healthcare supply chain with the external and internal chain, however, it can often be a lot more actors and links than what is shown here.

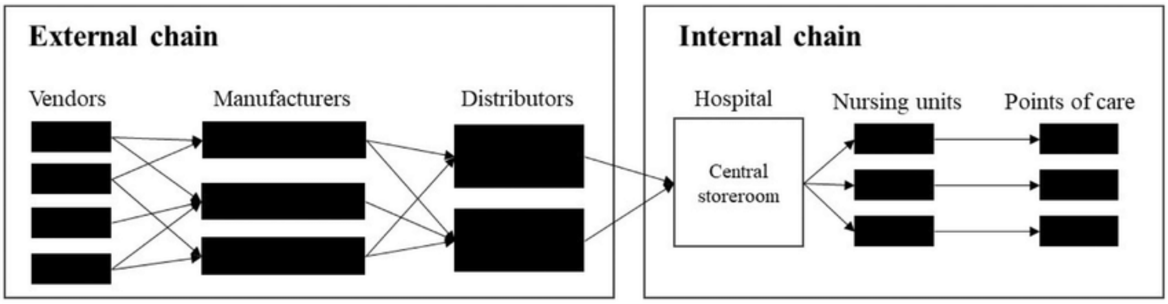

Figure 7: Healthcare supply chain design (Landry & Beaulieu, 2013).

The medical sector is a huge buyer and customer for many supplier firms. Norway's healthcare system spent approximately NOK 387 billion in 2020, of which 49% was spent on medical treatment and rehabilitation, and 11% was spent on medicines and medical consumables (Monsrud, 2021). Sykehusinnkjøp HF is the organization that provides procurement for the Norwegian healthcare institutions above a certain value limit and works as a centralized purchasing function. The organization is owned by the four health organizations, Health South-east, West, Mid-Norway and North. In its strategic plan for 2020-2023, it states, among other things, that the organization must ensure delivery capability and security of supply as one of the purchasing areas of focus. However, this is not explicitly clear in the report from which this information is taken. The reason for this is probably that the strategy report was made and published before the Covid-19 pandemic hit Health Norway (Sykehusinnkjøp-HF, 2020).

4.0 Methods and Data

In this chapter, the methodological approach used in this paper is outlined, including the framework and concepts employed to address the research problem. Information regarding data collection and the qualitative approach taken is also presented. The research strategy, design, approach, methodological choices, and data collection techniques are all selected based on their suitability for the thesis and research question.

4.1 Methodology

The research problem lays the foundation for which methods to choose, and the "who, what, when, where and how" approach guides the choices for how to carry out the research. The research strategy acts as the underlying philosophy and framework for the entire research process, while the research design is the roadmap that connects the philosophical beliefs to particular methods. The choices of methods leads to specific techniques used for gathering and analyzing data (Saunders et al., 2016).

4.1.1 Research Strategy

A research strategy outlines the general approach for conducting business research. Two main approaches are commonly used: quantitative and qualitative research. In a quantitative research strategy, data is collected and analyzed through quantification. It relies on deductive reasoning to connect theory and research and considers social reality as objective, external, and independent of social actors. In contrast, a qualitative research strategy focuses on words rather than numbers when collecting and analyzing data. It utilizes inductive reasoning to connect theory and research and perceives social reality as inherently dynamic and constantly evolving due to social interactions (Bell et al., 2018).

The aim of this study is to investigate the impact of AM on risk and resilience in the supply chain of hospitals, and the research problem is more suitable for qualitative methods. The goal of this study is not limited to confirming the existing literature, but also to reveal new findings, aligning with the inductive research approach. As the study relies on participants' interpretations of their experiences and observations of AM use, a qualitative research strategy is appropriate for gaining deep insights and understanding of the phenomenon.

4.1.2 Research Design

The framework for collecting and analyzing data is described by the research design, which reflects the decisions made regarding the research process. There are five types of research design: experimental design, cross-sectional design, longitudinal design, case study design, and comparative design (Bell et al., 2018). Research design can also be categorized into three types: exploratory, descriptive, and explanatory studies. An exploratory study is conducted to gain a better understanding of a problem. A descriptive study aims to provide a detailed profile of events, persons, or situations, and is often a component of an explanatory study. Finally, an explanatory study seeks to identify and explain the relationship between variables (Saunders et al., 2016).

In this study, the comparative design is selected as the primary research design. Since respondents in the two regions, or cases, will have distinct perceptions and experiences with the implementation and use of AM, it is interesting to compare different cases and evaluate what is unique and what is common among them. The comparison logic suggests that contrasting cases help in better understanding social phenomena (Bell et al., 2018).

4.1.3 Sampling

To obtain a comprehensive understanding of the different aspects and perspectives, a non-probability sampling technique is suitable for selecting the appropriate participants, instead of a probabilistic sampling method. Purposive sampling, a non-probability sampling technique, is used to identify participants for data collection. Purposive sampling is a method that involves selecting samples based on the subjective judgment of the researcher rather than random selection. Because the research has a clear objective, strategic selection of participants that are qualified is seen as necessary to gather the required data to answer the research question. The research question and the amount of people who has insight into this topic is rather limited, so it is not that many respondents to choose from. The sampling method is appropriate to use when the research is time-limited, such as the work on the master's thesis (Bell et al., 2018).

The target population for this research consists of individuals who are involved with AM technology or work within the supply chain of a hospital in one of the selected regions in Norway, and the selection of informants is based on this criterion. This allows the research to obtain data both from those who work specifically with AM in the hospitals, and those who work closely with the supply chain and see the challenges there.

A total of four respondents is selected for this research. Two from each of the health organizations Health South-East and West. The interviewees were both found and contacted through online research based on the target population and the criteria set for the selection. Through their role from working with AM in a hospital or within the supply chain, they have valuable knowledge and insights which makes them qualified to give insights for the research. Respondents are kept anonymous in order to comply with data protection rules in accordance with the GDPR, and throughout the process, privacy is taken into account. The participants are listed in the table below.

Respondent	**Region**	**Role**
1	West	Supply Manager
2	West	Engineer
3	South-East	Doctor in specialization
4	South-East	Engineer

Table 4: List of Participants.

4.1.4 Data collection

Interviews are a widely used technique for collecting qualitative data. They allow researchers to gather information about individuals' beliefs, feelings, and motivations. There are three types of interviews: structured, semi-structured, and unstructured. For qualitative research, semi-structured and unstructured interviews are appropriate. In an unstructured interview, there are usually no prepared questions, and the interviewee guides the conversation in any direction they seem relevant. In a semi-structured interview, the researcher provides an interview guide with some prepared questions on the topic. However, the interviewee can rearrange the order of the questions and add additional ones if they feel it is appropriate (Bell et al., 2018). Both types of interviews offer flexibility during the process. The main difference is that data analysis from unstructured interviews can be challenging since the data can vary significantly across interviews. Therefore, for comparative research, it is better to follow a guide to some extent to ensure that the researcher obtains comparable data (Saunders et al., 2016).

The study's primary data was obtained by conducting semi-structured interviews with the chosen participants. Prior to the interviews, an interview guide comprising of 10 questions was created, drawing upon the literature review and theoretical framework. The interview guide facilitates structure and enables the interviewees to prepare adequately to answer the questions. Due to the unavailability of some interviewees for a physical meeting and the long distances involved, the interviews were conducted online via video. Moreover, with the increasing use of video meetings, it no longer poses a significant obstacle for execution of the interviews and the quality of the data. Follow-up questions were asked during the interviews based on the interviewees' answers. The process of the interviews and data processing are all following the current data protection rules in accordance with the GDPR. After the interview process were finished, the interviews were transcribed.

In the case of this study, there was some uncertainty as to whether the processing of information in the interviews could be considered processing of personal data or not. In GDPR Article 4 no. 1, personal data is defined as *"any information about an identified or identifiable physical person [...], an identifiable physical person is a person who can be directly or indirectly identified"* (Personopplysningsloven, 2018). Information that can identify a person directly, for example name, age, and social security number, had no impact on the results of this study. Thus, it was not necessary to collect such data. However, the uncertainty fell on whether the information that needed to be collected could in any way identify a person in an indirect way. The information about which region the interviewees work in and what role they have is not enough to identify them, and therefore safeguards the anonymity of all respondents.

In order to provide participants with an understanding of the study, the interview began with a brief overview of the thesis and the main context of the interview. The interview guide consists of an introductory question, structured questions on the various topics supply chain risk, resilience and AM, and some finishing questions. The introductory questions aimed to gain insight into the participants' background and experience with AM or the healthcare supply chain. The questions were categorized based on the different topics in the thesis.

4.1.5 Data Analysis

Qualitative data analysis is a systematic process where researchers organize and transform collected information to interpret and comprehend the studied phenomenon. Information collected through interviews often contains in-depth text that is rich in content. However, identifying analytical paths in all the data can be challenging. Coding is a crucial process adopted by most qualitative data analysts for interpretation and transformation. One of the most widely used methods for qualitative data analysis is thematic analysis (Bell et al., 2018).

Thematic analysis is a systematic approach used to identify, organize, and provide insights into patterns of meaning within a dataset. The method's accessibility and flexibility are its main advantages. Thematic analysis can be applied to both inductive and deductive approaches, allowing for the extraction of sufficient details from complex data and the exploration of various perspectives. For this thesis, inductive thematic analysis is the appropriate method for identifying perceived experiences and observations of AM technology's hospital use and its impact on risk and resilience. The six steps of inductive thematic analysis include familiarizing oneself with the data, generating initial codes, searching for themes, reviewing potential themes, defining and naming themes, and producing the report. The data analysis for this research follows this method (Braun & Clarke, 2012).

4.1.6 Validity and Reliability

Validity and reliability are essential aspects of all types of research. However, in qualitative research, the researcher's subjectivity can often cloud data interpretation, making these aspects even more critical (Brink, 1993).

Validity in research refers to the accuracy and truthfulness of scientific findings. A valid study should reflect what actually exists. Researchers verify and check data, analysis, and interpretations to ensure their accuracy. To test the validity of the research, four commonly used tests are construct validity, internal validity, external validity, and reliability (Saunders et al., 2016).

Construct validity involves identifying the specific operational measures for the concepts under study. To ensure that the research satisfies construct validity, the concept must be defined in a manner that enables comparison with existing literature, which is done in this study (Saunders et al., 2016).

Internal validity refers to the accuracy of research findings in reflecting reality, without any influence of extraneous variables (Brink, 1993). To ensure internal validity in this research, the findings of the study are evaluated by the respondents themselves through respondent validation, which involves checking the research results after conducting interviews. The research is also peer-reviewed, as it has been regularly followed up by an academic supervisor.

External validity concerns generalization and the legitimacy of applying these reflections of reality across groups (Brink, 1993). For this study, the concepts and purpose are well defined, but it is still a narrow area and few respondents from just two areas. Therefore, the outcome may be completely different elsewhere, which may contribute to making the research less transferable. Qualitative research can be contextually unique and research-oriented, making it challenging to achieve high external validity. Consequently, the study's limitations include a small sample size and a limited number of respondents.

Reliability is related to the consistency, stability, and repeatability of the informant's accounts, as well as the investigator's capability to accurately collect and record information. Reliability indicates that the data gathered in a study can be duplicated with consistent outcomes (Brink, 1993). Recording the entire process in an accessible manner ensures that it can be reviewed by peers for auditing purposes (Bell et al., 2018). This study must be free from any researcher or participant errors or biases. The setup ensures that participants can respond to questions freely and that the interview environment is secure. Furthermore, the researcher has no vested interest in pointing the research towards any particular direction. Additionally, the content of this study will be reviewed consecutively by the supervisor, and by graders through a written submission and an oral presentation at the end of the work.

5.0 Results and Discussion

The following chapter will present the results from the qualitative interviews and the data that is gathered in the research and discuss it against the literature presented earlier in the thesis. The discussion is based on trying to answer the research question for the thesis. The results and discussion chapter are divided according to the thematic analysis of the data, and it is presented according to the topics in the literature. The order of the topics has nevertheless been changed to make the discussion flow more naturally, and it starts with additive manufacturing, and moves on to risk and resilience, before gathering the threads at the end with a summary.

It is worth noting that the role and field of the respondents are quite different, which means they have different areas of expertise and knowledge. Interviewee 1 is a supply manager and works with supply and preparedness, so it is natural that this person has more insight into the supply chain field, which is highly relevant for the field of the thesis. The others have more specific knowledge about the medical field and the use of AM in the healthcare sector.

5.1 Additive Manufacturing

Additive manufacturing is mostly applied for production of customized models, tools and equipment, and special parts and spare parts in both healthcare regions. Protective equipment, valve parts and various objects for the hospital's operation are other popular areas of use according to several of the interviewees. Interviewee 3 told that "*it is especially used for parts where there are problems getting them, or it is extremely expensive, mostly out of warranty period, so there is no risk in producing ourselves".* Both regions utilize the AM capacity for a broad range of products, and the scope of the use is increasing. New solutions are constantly being developed, and those involved are becoming increasingly competent at designing and producing new components. Medical personnel around the various departments are also becoming increasingly aware of what AM can be used for, which reinforces the field of use. "*It is the understanding of what it can be used for, and the cooperation between the medical personnel and the AM technical personnel which is the biggest force driving this forward"* reported interviewee 4. Collaboration seems to be a key factor in the development of AM in the two regions.

During the pandemic, the South-East region had a lot of personal protective equipment (PPE) produced by private individuals with 3D printers, which was a great help when they could not get this equipment delivered from their regular suppliers, which usually is from low-cost manufacturing companies in China or other Asian countries. They also used some of their own capacity to produce this equipment. The West region, on the other hand, did not utilize this solution to the same extent. Interviewee 1 says that the capacity they had in-house, and the materials in-stock was not sufficient to produce enough quantity. They investigated the possibility of having protective equipment produced by local AM companies, but they priced the components very high. However, region West was better equipped to face the pandemic with better preparedness plans and inventory holding. This shows that with insufficient capacity and material in inventory, AM will not be of much help in the production of products that are suitable for mass-manufacturing when the crisis occurs. However, protection equipment is rather cheap to hold because it is inexpensive and has long shelf life, and interviewee 1 points out that this is not where measures for local production has its biggest advantage. Furthermore, the respondent highlights the fact that implementing an AM capacity is not a sufficient solution in itself. "*With 3D printing, you can focus on holding the raw material and having the capacity. You need to make sure you have electricity and material to print".* At Haukeland University Hospital they have built up preparedness for power supply in the form of battery capacity, and they have even installed two aircraft engines in the mountains to supply the hospital with energy in the event of a power cut. They also have large warehouses with the ability to hold a lot of inventory, like raw material for AM. The interviewee said the following about the solution: "*A brilliant solution to contingency planning. It strengthens the case for having in-house capacity by ensuring internal supply, as this is a brilliant solution if a crisis arises".*

A majority of the interviewees report several similar benefits about the use of AM in the hospital. The recurring advantages are that AM provides better opportunities to prepare for operational situations and diagnose injuries by printing out models of injuries. Furthermore, it is easy to create customized solutions for patients, and tools and spare parts can easily be repaired or replaced, which saves the hospital a lot of time. In the South-East region, one area of focus is personalized surgery. This area can save the healthcare sector enormous sums, where AM is the key to this field according to Interviewee 3: *"We have AM technology "in house" which can quickly 3D print models of the individual patient's injury or surgical disease condition, and customized surgical tools. It makes it much easier to provide specialized surgery".* The models the hospitals need for specialized surgery are often ordered from other countries with a delivery time of several weeks, which therefore makes emergency use not feasible. With their own AM capacity, the hospitals can print these models themselves, which enables better personalized surgery and emergency use. In the literature, Salmi (2021) pointed out that the medical field reaps benefits like improved medical outcome from AM, which seems to coincide with the data from the interviews. A commonality among the interviewees is that the AM capacity in the hospitals is run by enthusiasts with limited resources. It does not seem to be a large investment area, although the benefits and possibilities seem to be almost unlimited.

5.1.1 Lead-time

Multiple studies show that AM has the potential to reduce lead times in production of spare parts, replacement components, and obsolete parts (Attaran, 2017a; Chen, 2016;

Kubáč & Kodym, 2017). AM ensures that products can be repaired or maintained quickly, reducing downtime, and increasing product availability. Furthermore, decentralized and localized production enabled by AM reduces reliance on centralized supply chains. This allows for products to be manufactured in-house or nearby, lowering lead times, transportation costs, and the risk of supply chain disruptions. The efficacy and efficiency of localized supply chains were demonstrated during the Covid-19 pandemic (Attaran, 2017b; 2020). Both regions' interviewees agree that using AM significantly reduces lead times for parts and components. Interviewee 3 mentioned that they now produce surgical tools with AM that were previously unavailable. In the past, they relied on foreign companies for printing, which took several weeks for delivery. However, now they can easily produce them in less than a day. Interviewee 2 also confirms the reduction in lead time, stating that: "*Incredibly more efficient with internal and local production. Lead time is extremely shorter"*. Thereby the literature and the findings coincide with the reduction of lead time. However, this is limited to the current use in the healthcare sector.

5.1.2 Costs

Multiple articles used in the literature points out that a central benefit of AM is reduced costs, which is also, to some extent, backed up by the data from the research (Chen, 2016; Harrison et al. 2019; Attaran, 2020). Interviewee 4 said that: *"We were given the opportunity to establish this service [AM] internally, which allows us to build up expertise, and in the long term save millions each year".* Interviewee 3 mentions the following: *"Previously, we relied almost exclusively on outside print vendors for prototypes. Today, we are running four 3D printers, and the impact has been big [...]. Our rate of 3D printing has doubled, and cost has been reduced by 70 percent".* The cost reductions seem to be significant in the cases that AM is utilized in a manner where it is found as a suitable manufacturing method for the particular product or part. Nevertheless, as interview 3 pointed out, the costs have been reduced as the rate of AM has increased, which is an interesting find.

The literature discusses the cost implications of AM compared to mass production. Interviewee 1 highlighted that the cost per unit of locally produced AM equipment, such as protective gear, was much higher than mass-produced equipment imported from low-cost countries like China. This finding suggests that mass production is more cost-effective for standard parts.

According to Chen (2016) and Harrison et al. (2019), AM has the potential to dramatically reduce supply chain costs by eliminating the need for high-volume production facilities and assembly workers. It allows manufacturing to take place almost anywhere at the same cost, reducing the need for global transportation. However, the literature also acknowledges that the manufacturing expenses for each item may be significantly higher with AM due to expensive materials and the lack of economies of scale. The traditional mass production process is typically faster and cheaper in comparison, as experienced in the West region during the pandemic (Haleem & Javaid, 2020). Experts generally agree that AM is not a direct competitor to mass production but rather a complementary approach, particularly in sectors requiring high-volume manufacturing (Harrison et al., 2019). Chen (2016) suggests that production can happen anywhere at the same cost, but this contradicts other literature indicating that AM is a complementary approach and that the cost implications are significant.

Interviewee 2 emphasized the cost implications of AM beyond small-scale customized parts: *"I also see some cost implications, especially for production beyond small-scale customized parts. There are high machine and material costs, but also a lack of robustness and quality has a significant impact on costs due to quality assurance costs after printing. Complex geometries and small batch sizes are distinctive features of AM which make it challenging to post-process and automate production. Therefore, post-processing makes up a significant proportion of the total sub-costs".* The high costs of machines, materials, and the need for post-processing and quality assurance all contribute to the overall cost of AM production. Attaran (2017b) and Haleem and Javaid (2020) also highlight obstacles to the adoption of AM, including size restrictions, slow production time, high equipment costs, regulatory implications, and the substantial need for post-processing. These factors further increase the overall cost of AM products.

Overall, the literature and interviews suggest that while AM offers advantages in terms of supply chain efficiency and decentralized production, it may not always be cost-effective compared to mass production, especially for standard parts. The cost implications of AM, including expensive materials, lack of economies of scale, and the need for post-processing, pose challenges to its widespread adoption and expansion. However, for customized parts and products, AM can be a cost-effective production method which can enable mass-customization strategies with the rights capacity.

5.1.3 Localized Production

The literature highlights the benefits of localized production through AM in reducing supply chain vulnerabilities and improving efficiency. Thomas and Gilbert (2014) suggest that a shorter supply chain with fewer links can decrease the risk of disruptions, as each factory and warehouse in a supply chain presents a potential point of disruption. Decentralized production closer to consumers can result in several facilities manufacturing a few products, minimizing the impact of disruptions to local areas rather than having regional or national effects.

The interview findings support the theory that localized production with AM reduces supply chain risks. Interviewee 1 emphasizes the efficiency and reduced supply shortage risks associated with internal and local production, stating, *"Incredibly more efficient with internal and local production, and it reduces the risk of supply shortage".* The same interviewee also highlights that "*if we were able to produce ourselves, we would disrupt simple supply chains, cut out procure-to-pay, eliminate the entire procurement and purchasing process for the relevant parts".* Interviewee 3 reinforces the positive attitude towards in-house and localized production, stating that *"we are no longer dependent on suppliers for all possible parts we use. A hospital has a lot of parts and components".*

Attaran (2017a) argues that AM can eliminate the need for assembly and pre-assembly steps, reducing costs and the number of suppliers required. This aligns with the earlier discussion on the cost implications of AM. It is acknowledged that AM can reduce costs and supply chain complexity before and during manufacturing but may incur increased costs for post-processing. Additionally, localized production enabled by AM reduces reliance on centralized supply chains, leading to lower lead times, transportation costs, and the risk of supply chain disruptions. The Covid-19 pandemic demonstrated the efficacy and efficiency of localized supply chains (Attaran, 2017b; 2020).

The literature suggests that localized production is particularly beneficial for specialized and customized products that are difficult to source, out of production, have long delivery times, or high costs. In times of global crises or unexpected events, localized production reduces the risk of supply chain disruption. However, the successful implementation of in-house AM capacity depends on satisfactory economics, as the costs of acquiring high-quality AM machines and raw material for medical part manufacturing can be significant (Haleem & Javaid, 2020). Interviewee 2 acknowledges that "*The use of AM may increase the cost of medical devices and implants a little in the short run due to investment in the equipment and materials. However, in the long run, it will hopefully save us costs by reducing the need for inventory and reduced lead times".* The literature also highlights the potential for reducing inventory and safety stock by having digital storage of parts and products, and producing on-demand with AM. This approach can significantly reduce warehouse and inventory costs. However, it is important to recognize that AM is not a fit-for-all solution for every supply chain risk-related problems, and it is essential to maintain visibility and agility in the supply chain. The literature on agility says that an agile supply chain must have the visibility to produce on-demand, which is a flexible capacity. Agility, flexibility, and visibility are all important factors of creating resilience in the supply chain (Christopher, 2000; Ivanov et al. 2014).

In summary, the literature and interview findings support the notion that localized production through AM can decrease supply chain vulnerabilities, improve efficiency, and reduce costs. However, challenges related to machine and material costs, post-processing, and the need for satisfactory economics should be carefully considered. The ability to reduce inventory and produce on-demand provides additional benefits but should not overshadow the importance of maintaining a holistic approach to supply chain risk management.

5.1.4 Implications

The literature presented in this section highlights various implications of implementing AM in the healthcare supply chain. Interviewee 3 emphasizes the need to raise awareness and convince medical professionals about the benefits of AM, stating, *"It is immature and new; therefore we need to raise awareness, include and convince medical professionals about AM and its benefits. It is little interest for building capacity and proactive capability as long as everything runs smooth, and the doctors have everything they need. The pandemic has been an eyeopener for some, but it's still a long way to go".*

Holmström and Gutowski (2017) discuss the challenges organizations face in adapting to new technologies, and Choudhary et al. (2021) suggest that managers should focus on technological and organizational barriers during implementation. In addition, AM in healthcare is a relatively new field, and there can be lack of trained professionals with specialized knowledge and expertise in the field of AM.

Regulatory implications are identified as one of the main challenges for adopting AM in the healthcare sector. Haleem and Javaid (2020) mention the difficulty of ensuring that AM products meet quality and regulatory standards. Attaran (2020) also mentions regulatory compliance as a main implication. Interviewee 1 highlights the complexities and strict regulations in Europe, particularly in relation to medical device regulations, stating, *"Regulation is the most difficult thing to get through, and there are layers of regulation. The regulations are becoming increasingly strict in Europe through medical device regulations. However, there is a big difference between spare parts and tools, and products that are used inside patients".* As the interviewee mentions, it is important to distinguish between the different use of AM products as it provides insights into the areas where utilizing AM capacity can be most beneficial. The interviewee adds, *"Cost-benefit questions arise when setting up AM capacity because of the regulation implication, which can be resource-intensive and expensive",* which is a valid point that should be addressed when considering whether implementation of AM will be beneficial, implications taken into account. Attaran (2020) mentions cost-effectiveness as one of the main implications of AM in healthcare. These insights emphasize the need for healthcare organizations to navigate the regulatory landscape and invest in appropriate resources to ensure compliance when integrating AM into the healthcare supply chain.

Ensuring the quality of printed products is another challenge, especially in the healthcare sector where high standards are required. Interviewee 4 identifies the quality of printed products as a major challenge, stating, *"One of the biggest challenges has been ensuring the quality of the printed products".* This contradicts Attaran's (2017b) claim to some extent that AM offers the potential for quality improvement. Furthermore, Haleem and Javaid (2020) highlight the significant challenge of meeting quality standards in the healthcare sector. Additionally, Attaran (2020) mentions in another study that quality control is one of the main implications of AM in healthcare. However, Interviewee 2 said that 3D printing allows for the creation of more precise and customized devices, leading to better medical outcomes and reduced risks, stating, *"With 3D printing, we are able to create devices that are more precise and customized for individual patients, which can lead to better medical outcomes and a lower risk of complications"*. Quality is still a subjective assessment, and many factors can play a role in whether a product is perceived to be of good quality, or not. In the health sector, safety is nevertheless important, and products therefore need to be made of quality material. But there are also other factors that affect whether products manufactured with AM is perceived as good quality, as we see from the interviewee´s statement.

In summary, the literature and interview findings indicate several implications of implementing AM in the healthcare supply chain. These include the need for awareness and overcoming implementation obstacles, regulatory challenges, and ensuring the quality of printed products. The importance of addressing technological and organizational barriers, complying with regulatory standards, and balancing cost-benefit considerations are highlighted. While AM offers the potential for improved precision and customization, ensuring safety and meeting quality standards remain critical factors in the healthcare sector.

5.2 Risk and Resilience

The literature highlights the importance of supply chain design, flexibility, waste reduction, risk management, and the combination of lean strategy with agility and flexibility in achieving supply chain resilience. These concepts resonate with some of the findings from the interviews on the effects of AM on supply chain risk and resilience in the healthcare sector. Interviewee 3 highlights that AM changes the perception of supply chain risks by providing more control over the production process and the ability to quickly produce necessary parts on-site. The interviewee state: *"The use of AM has changed the way we think about supply chain risks. With traditional supply from manufacturers, there is always a risk of delays or disruptions due to issues with suppliers or shipping. However, with the use of AM, we have more control over the production process and can quickly produce necessary parts or devices on site if needed".* The interviewee follows up with a concrete example: "*We had a case where a patient needed a custom-made implant for a surgery, but the supplier was experiencing production delays. Instead of having to wait for the implant to be shipped, we were able to quickly produce the implant on site using AM. This greatly reduced the risk to the patient and proved the* *resilience that AM creates in our supply chain".* As previously discussed under the chapter of localized production, decentralized manufacturing can significantly reduce the risk of supply chain disruptions. Attaran (2017b) highlights this point in the literature by saying that the efficacy and efficiency of localized supply chains were demonstrated during the Covid-19 pandemic, which reduced the risk of supply chain disruptions. Furthermore, Haleem and Javaid (2020) argues that in the event of a global crisis or other unexpected events, localized production reduces the risk of supply chain disruption. Data from the interviews and the literature on AM's influence on risk coincide to a certain extent. The literature has somewhat more focus on the fact that AM can reduce the risk of disruptions in the event of global crises or other unexpected events.

The interviewees generally express positivity about the use of AM in the healthcare and its impact on risk and resilience. Interviewee 3 acknowledges AM as a great alternative supply chain and emphasizes the importance of proactive thinking and prioritizing measures based on a risk-benefit-supply security perspective. The interviewee stated: *"Great alternative supply chain. In the event of major supply and spare part problems, working with 3D printing as a security measure is very smart. In a critical function (operations); what can 3D printing contribute to a crisis when everything else goes wrong: have proactive thinking. Prioritize where to have capacity and think risk-benefit-supply security".* It is perhaps not so surprising that a finding from the interviews is positivity towards AM. It has brought many positive benefits to the hospitals, and the interviewees are those who work most closely with it daily, and probably those who are most enthusiastic about the use of the technology. However, from the data it seems to coincide with a lot of what the literature presented in the review also highlights.

AM can also pose potential risk to the supply chain. Interviewee 2 points out a potential risk associated with AM: *"There are also risks associated with the use of AM, such as the potential for errors or defects in the printing process".* This highlights the importance of not relying solely on AM as the sole solution but having backup plans in place, because this technology, like any other technology, can fail which will result in no supply at all if measures are not in place. Another risk is the lack of raw materials for AM, which was discussed earlier. Although AM decentralizes the production itself, it is still dependent on raw materials being delivered by suppliers. If the hospitals are to implement AM as a resilience measure, they need to ensure that they have the capacity and raw materials in inventory, in addition to alternative power solutions.

In region West, Interviewee 1 emphasizes the risk that a just-in-time (JIT) supply chain strategy can pose, which became evident during the Covid-19 pandemic. The interviewee stated: *"Before the pandemic, we were totally dependent on Just-In-Time delivery, and that the suppliers always delivered. But that did unfortunately not happen when Covid hit".* This emphasizes the vulnerability of a JIT strategy during significant disruptions and highlights the necessity of adopting a more resilient approach to the supply chain. One of the main advantages of JIT is the elimination of large warehouses and excessive inventory. However, literature emphasizes the need for redundancy measures such as security inventory and capacity buffering to enhance supply chain resilience. If a firm relies on external suppliers, maintaining sufficient inventory becomes crucial to prevent major disruptions in times of crisis. Conversely, AM enables the establishment of in-house capacity as a safety measure in a JIT strategy to address supply issues. Thus, it becomes possible to leverage a JIT strategy while simultaneously building resilience.

A JIT strategy is cost-saving and efficient, and it aligns with the Design-for-Efficiency and Responsiveness mindset. However, in a volatile market environment where disruptions have significant consequences, the Design-for-Resilience approach becomes more relevant. This approach involves designing supply chains and operations to withstand severe and unforeseen disruptions, enabling swift recovery. Key resilience assets or capabilities in the Design-for-Resilience approach include redundancies, visibility, flexibility, and contingency recovery plans (Ivanov, 2022). Additionally, awareness is considered vital for building resilience in medical supply chains, requiring the availability of necessary information for assessing, mitigating, preparing, and responding to risks by the appropriate individuals (NASEM, 2022). Achieving awareness necessitates visibility across the supply chain.

The literature and interviews confirm that AM can significantly impact risk and resilience in the healthcare supply chain. It provides greater control, reduces reliance on external suppliers, and enables rapid on-site production, which overall reduces risk in the supply chain. However, it is essential to address potential risks and implement backup strategies to ensure a robust and resilient supply chain.

Flexibility is a crucial characteristic of agile organizations and supply chains, which has its roots in flexible manufacturing systems as a business concept. These systems use cutting-edge machine technology that can provide a wide range of product variety to fulfill customer demands, e.g., additive manufacturing. Both Christopher and Peck (2004) & Mensah and Merkuryev (2014) has found that supply chain resilience is achieved by focusing on combining a lean strategy with agility and flexibility. It can be argued that an agile supply chain which utilizes AM is a flexible supply chain, which is a key part of supply chain resilience. Results from the interview also shows that one of the perceived benefits of AM is an increased flexibility in the manufacturing, e.g., they can quickly produce a customized implant if needed, and an agility to produce a product or replacement part if an essential machine fails, which prohibits further operations.

Building a holistic supply chain risk management program that encompasses supply, products, demand, and information management by integrating risk management techniques could be a good solution. However, as stated in the literature review, applying this approach to every link in a global supply chain for all potential disruptive causes would be a huge task and be expensive (Pettit et al., 2010). As previously discussed, implementing measures for risk and resilience must be prioritized based on the assessed risk, and the benefits for implementing such measures. Risk assessment can be done through an assessment matrix. As pointed out earlier, risk is the product of the likelihood of an event occurring and the potential severity of its impact. The weakness with risk quantification formulas is that firms tend to not act against events that have a low likelihood of occurring, because you have more than enough to plan for events that have a much greater probability of happening. Although it may have a much higher value for risk, which theoretically indicate that it should be prioritized. As a result, firms are not prepared for severe events such as disruptions that cause great damage.

The literature argues that expanding production capacity is a long-term solution that requires additional investment in the supply base (Johnsen et al., 2018). Decentralized capacity with low costs should be prioritized for predictable demand, while centralized capacity should be established for more unpredictable demand. However, with AM, production expansion does not require additional investment in the supply base, but in printer equipment and raw material. However, raw material still needs to be procured.

More suppliers can additionally increase the complexity and reduce the visibility of the supply chain. Localizing the manufacturing with AM in-house, decentralizes the manufacturing and expands the capacity for in-house production for the hospital. In addition, with the flexibility of AM the hospitals can manufacture whatever they need, instead of sourcing and buying different products from multiple suppliers, which reduces the transaction costs.

For many companies, focusing on risk and resilience in detail can seem like a distant goal. There are countless other priorities that demand attention before they can dedicate resources and time to this area. However, in the healthcare industry, this is particularly crucial given its critical role in society. Interviewee 1 stated that: *"Public sector should assess socially critical businesses, and especially logistics-intensive businesses, which must strengthen their capacity to deliver even in times of crisis. The health sector is a socially critical business that must be run regardless, so it is particularly important for the health sector where we depend on a lot of logistics"*. This points out the importance of reducing the risk and enhancing resilience in the healthcare supply chain. In some cases, a product shortage in the healthcare can influence the life and health of a patient. One can go so far as to say that if measures against disruptions and risks are not put in place, public health will be affected.

The literature highlights the importance of identifying critical products or parts in the healthcare supply chain and prioritizing resilience measures accordingly (NASEM, 2022). This aligns with the findings from the interviews, where Interviewee 1 emphasizes the need to identify vulnerabilities and prioritize capacity measures for critical areas: *Identify where vulnerabilities lie and prioritize capacity measures there. What is most important if things go wrong?*". By doing so, healthcare organizations can focus their resources and efforts on building capabilities that effectively address these vulnerabilities, which ultimately results in a "balanced resilience".

AM emerges as a key enabler of resilience in the healthcare supply chain. The flexibility of AM allows for the production of a wide range of products, reducing the complexity of supply chain partnerships and communication requirements. Interviewee 2 supports this by stating that AM enables hospitals to have better transparency and visibility in the supply chain, particularly in the production and distribution phases. This aligns with the literature's emphasis on the crucial role of transparency and visibility in enhancing supply chain resilience.

AM also serves as a diversification measure, as hospitals can manufacture various products in-house instead of relying on multiple suppliers. This reduces transaction costs and decreases the dependency on external sources. Furthermore, AM enables capacity buffering and readiness measures by providing localized production capacity. Interviewee 1 highlights the importance of integrating AM into planning and processes to ensure preparedness and avoid overlooking available capacity. This integration aligns with the literature's suggestion that resilience measures should be actively incorporated into operations management, following the AURA framework.

The concept of "Lean resilience" introduced by Ivanov (2022) resonates with the findings, as it emphasizes the proactive and value-generating nature of resilience measures. Interviewee 1's emphasis on building proactive capacity and flexibility through AM supports the idea of integrating resilience into supply chain operations. By investing in AM capabilities, hospitals can not only address vulnerabilities related to scarce or expensive parts but also enhance their overall supply chain performance.
The analysis of the literature and findings underscores the potential of AM to enhance supply chain resilience in the healthcare sector. However, challenges related to quality control, regulations, and cost-effectiveness must be addressed to fully leverage the benefits of AM. This aligns with Attaran's (2020) perspective, which highlights the need to overcome these obstacles for the widespread adoption of AM in healthcare supply chains.

In summary, the findings from the interviews align with the literature in highlighting the positive effects of AM on supply chain risk reduction and resilience in the healthcare sector. The literature emphasizes supply chain design, flexibility, waste reduction, risk management, and the combination of lean strategy with agility and flexibility. The interviews provide concrete examples of how AM improves risk management and enhances supply chain resilience in the healthcare setting. Overall, the findings support the importance of incorporating AM into the healthcare supply chain to mitigate risks and improve overall resilience. The integration of AM in the healthcare supply chain has the potential to minimize the risk of disruptions, reduce lead times, and improve overall efficiency and effectiveness. By identifying critical vulnerabilities and investing in AM capabilities, hospitals can build resilience and enhance their supply chain performance. However, careful consideration must be given to quality control, regulatory compliance, and cost-effectiveness to fully realize the benefits of AM in the healthcare context. The healthcare sector's critical role further underscores the importance of addressing supply chain risks and disruptions. Nevertheless, it is worth noting that AM does not provide the perfect solution to the discussed problems, and there are still obstacles to be overcome.

6.0 Conclusions

In light of the research problem regarding the effects of additive manufacturing in the healthcare sector on supply chain risk and resilience, the findings and discussions in this study shed light on important considerations. In today's dynamic business environment, it is essential to view volatility as an opportunity rather than a risk, and this requires a deep understanding of its nature and impact. By implementing approaches such as supply chain engineering, risk management, and building suitable resilience capabilities, supply chains can reduce their exposure to risk.

One of the key findings from this study is that flexible manufacturing systems like AM have the potential to enhance the resilience of the healthcare supply chain. However, it is crucial to prioritize the implementation of measures based on the vulnerabilities specific to each supply chain. Each organization must identify what is critical for them in the event of a disruption or crisis and allocate resources accordingly to achieve a good cost-benefit effect.

To create a resilient supply chain, it is important to focus on the central factors discussed in the literature. Adopting a "leagile" strategy that combines agility, flexibility, and “leanness”, along with effective risk assessment and mitigation strategies, and enhanced visibility in the supply chain, is crucial. AM, as an enabling technology, can contribute to eliminating process waste and enhancing production flexibility, thereby enabling a "leagile" approach that enhances the agility and flexibility of the supply chain.

Building a multi-layered protection system against disruptions, including mitigation, preparedness, and response measures, is an effective strategy to avoid harm to patients in the case of disruptions or product shortages. However, true resilience goes beyond protection and encompasses the ability to bounce back to a normal or improved state after a disturbance. Therefore, it is equally important to develop nimble capabilities within the supply chain alongside protection measures. The utilization of AM can lead to cost reductions, decreased lead times, improved healthcare services, and enhanced preparedness. In the uncertain and customized healthcare sector, AM provides a means to ensure continuous operation, reduce risk, and create a more resilient supply chain.

In conclusion, the integration of AM in the healthcare supply chain has the potential to enhance resilience by minimizing supply chain disruptions, reducing lead times, and improving overall efficiency and effectiveness. However, it is important to address challenges such as quality control, regulatory compliance, and cost-effectiveness to fully leverage the benefits of AM. By adopting a comprehensive approach that combines risk assessment, resilience building, and the strategic implementation of AM, healthcare organizations can achieve a more resilient and robust supply chain capable of withstanding and recovering from disruptions.

7.0 Research Summary

Qualitative research has been carried out during the course of the work with the master thesis. The aim of the research is to obtain data that can shed light on the topic chosen for the assignment. The research question that was presented at the beginning of the thesis has been a guide for the choices that have been made along the way, for the choice of literature and research method and approach. The qualitative data that has been collected derives from four semi-structured interviews that have been conducted with respondents who work with AM or close to the supply chain in one of the selected health regions. During the process, all the necessary steps have been taken to ensure that the data that comes out of the research is of good quality. There is still a big difference in the relevance of the data from the various interviewees. As the research is relatively broad, the data is also collected from people with different backgrounds and fields of expertise. This has given some variation in the relevance of the data collected from the various interviewees.

8.0 Managerial Implications

The findings of this study have several relevant managerial implications for stakeholders considering the implementation of AM in healthcare or other companies/supply chains.

The study reveals a positive correlation between AM, risk management, and resilience, highlighting the advantages of adopting this technology as it continues to evolve. The following key managerial implications should be considered:

- Reduction of Risk and Enhancement of Resilience: The study demonstrates that AM can contribute to risk reduction and enhance supply chain resilience. By leveraging AM technology, companies can minimize supply chain disruptions, improve flexibility, and mitigate the impact of uncertainties. Managers should recognize the potential of AM to address vulnerabilities and develop strategies that leverage its capabilities to enhance overall risk management and resilience.
- Utilization of Findings: The study suggests using the findings presented in this research to identify the specific opportunities that AM can provide in terms of risk and resilience. This study outlines key factors and strategies essential for enhancing supply chain resilience. Managers can use this as a guide to assess their supply chain's vulnerabilities, determine how AM can contribute to risk reduction and resilience, and develop effective strategies accordingly.

9.0 Limitations of the Study

The present study has several limitations that should be acknowledged. These limitations impact the generalizability and depth of the findings. The key limitations include:

- Scope Limited to Healthcare Sector: The study focuses specifically on the healthcare sector and its supply chain. While this provides valuable insights into the effects of AM on risk and resilience in the healthcare context, the findings may not be directly applicable to other industries or supply chains. The specific characteristics and requirements of the healthcare sector may differ from those of other sectors, limiting the generalizability of the results.
- Small Sample Size: The research faced challenges in terms of the sample size due to the limited number of individuals working on the problem in the areas under investigation. Consequently, only four interviewees were included, which is less than the initially planned number. The small sample size may limit the diversity of perspectives and experiences represented in the study, potentially impacting the comprehensiveness of the findings.

- Time Constraints: The time limitations imposed on the study affected the number of interviews conducted. Conducting interviews and processing the data require significant time and resources. As a result, the study was unable to conduct a larger number of interviews, which could have provided a broader range of insights and perspectives on the topic.
- Translation Barriers: The interviews were conducted in Norwegian and later translated into English for analysis and reporting. Although efforts were made to ensure accurate translation, there is a possibility of losing some nuances or meanings during the translation process. This may introduce a level of interpretation bias and potentially limit the precision of the responses.

These limitations should be taken into consideration when interpreting the findings of the study. Future research should aim to address these limitations by expanding the sample size, including a wider range of industries and supply chains, allowing for more comprehensive and generalizable conclusions. Additionally, conducting interviews directly in the English language or utilizing professional translation services can help minimize potential translation biases.

10.0 Suggestions for further research

The findings of this study open up avenues for further research in the field of AM and its impact on risk reduction and resilience enhancement in supply chains. Some suggestions for future research are:

- Cost-Benefit Analysis: Conduct a comprehensive cost-benefit analysis of implementing AM in healthcare and other industries to assess the economic viability and potential return on investment. This analysis should consider factors such as initial setup costs, operational costs, material costs, and potential savings from reduced supply chain disruptions and improved resilience.
- Comparative Analysis of Manufacturing Technologies: Explore the potential synergies between AM and other manufacturing technologies/methods in reducing supply chain risk and enhancing resilience. Compare the effectiveness, limitations, and cost-effectiveness of various manufacturing approaches, such as AM, traditional manufacturing, and hybrid manufacturing techniques. Investigate how

these technologies can be integrated and optimized to achieve the desired risk reduction and resilience outcomes.

- Performance Metrics and Key Performance Indicators (KPIs): Develop performance metrics and key performance indicators specific to AM implementation in supply chains. Identify and measure the impact of AM on risk reduction and resilience by considering metrics such as lead time reduction, inventory management, supply chain visibility, response time to disruptions, and customer satisfaction. This will provide a quantitative basis for evaluating the effectiveness of AM in achieving desired outcomes.
- Integration with Digital Technologies: Explore the integration of AM with emerging digital technologies, such as artificial intelligence, Internet of Things, and blockchain, to further enhance risk management and resilience capabilities. Investigate how these technologies can enable real-time monitoring, predictive analytics, traceability, and secure data exchange, thereby mitigating risks and improving supply chain agility.
- Case Studies and Longitudinal Studies: Conduct in-depth case studies and longitudinal studies to examine the long-term impact of AM implementation on risk reduction and resilience in different industries and supply chains. This research should assess the challenges, success factors, and lessons learned from actual implementations, providing valuable insights for practitioners and decision-makers.

By exploring these research directions, a deeper understanding of the benefits, limitations, and potential synergies of AM with other technologies can be gained, leading to more effective strategies for risk management and resilience enhancement in supply chains.

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12.0 Appendices

Interview Guide

1. Can you tell me a little about your role in the healthcare and your experience with additive manufacturing or the supply chain?
2. How do you perceive the potential risks and benefits of integrating AM in the hospital’s operations?
3. Can you share any specific examples or cases of how AM has been used in the hospital and its impact on supply security and operations?
4. In your opinion, how does AM impact the quality and safety of parts and products for the hospital?
5. Have you encountered any challenges or issues related to implementing or using AM in the healthcare? If so, can you describe them?
6. In your experience, how does the use of AM affect the lead-time for medical devices and parts compared to traditional manufacturing methods?
7. How do you see the use of AM affecting the overall risk and resilience of the healthcare supply chain, especially during times of crisis or disruption?
8. What is your opinion on the future role of AM in the healthcare? Do you see it becoming more widespread and integrated, or remaining niche?
9. Are there any ethical or social implications to consider when using AM in the hospitals?
10. Lastly, is there anything else you would like to add about the effects of AM on risk and resilience in the healthcare supply chain?