Master's degree thesis

LOG950 Logistics

The Effect of Additive Manufacturing on Supply Chain Resilience: A Case Study of the Norwegian Oil, Gas, and Renewables Industry

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Preface

This Master thesis is the final assessment and requirement for the two-year long master study – Master of Science in logistics at Molde University College. The research has been conducted between December 2020 and May 2021. The project has been a valuable lesson and has given us further insight in the field of logistics through interviews in addition to looking at a wide range of literature.

We would like to thank our case companies, and the people that have been available to take part in the interviews. This has been of significant value to our thesis and have provided vital information to conduct our research. The interviews were conducted through online platforms because of the problems and restrictions that are in place because of the covid-19 virus.

Further on, we would like to thank our supervisor Alok Mishra, and other faculty members for good discussions and advise during the semester.

In addition, we would like to thank family and friends for the support and good memories throughout our studies.

Molde, 25th of May 2021

Andreas Hareide Hansen *Tobias Wilhelm Wingaard*

Summary

This paper focuses on the implementation of additive manufacturing (AM) in the oil, gas, and renewables industry on the Norwegian continental shelf. Through the case study we establish if the implementation of additive manufacturing has effects on the resilience of the supply chain. The use of additive manufacturing is still in its infancy in this industry, and therefore there is still multiple opportunities of adopting the technology.

Through a literature review on additive manufacturing and supply chain, the existing literature has been evaluated to establish the knowledge of the effects that it has on the supply chain. Further we have conducted a review of the literature on supply chain resilience. In addition, we provide a theoretical framework, of additive manufacturing, supply chain, supply chain resilience and industry 4.0. The literature reviews and conceptual framework creates a foundation of knowledge to answer our research questions. Further on we have conducted three interviews with the case company and their supplier to establish what effects additive manufacturing has on their supply chain.

In the thesis we investigate (a)if additive manufacturing affects the resilience of a supply chain through a case study. (b)What challenges companies face when implementing AM technology in their supply chain, and how this implementation affects the traditional supply chain. And (c) how does the additive manufacturing model impact the supply chain resilience. Our findings are that the lead time gets significantly reduced when AM is implemented in the supply chain. Further, the effect AM has on knowledge-creation and sharing increases the collaboration in the industry. Moreover, the effects AM-hubs and home sourcing can have on the supply chain, could change the design of supply chains. When answering (c) we develop a conceptual model of the impact of additive manufacturing on supply chain resilience, based on our findings in the interviews and the literature.

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Abbreviations:

AM – Additive manufacturing

TM – Traditional manufacturing

SC – Supply Chain

AR – Augmented reality

VR – Virtual reality

SCR – Supply Chain Resilience

CAD – Computer-aided design

ETO – Engineering-to-order

MTO – Make-to-order

MTS – Make-to-stock

JIT – Just in Time

NCS – Norwegian continental Shelf

SCLT – Supply chain lead time

HSSE - Health, safety, security, and environment

3D printing – three-dimensional printing

1.0 Introduction

With the evolution of technology, there has been an increased digitalization of different industries. The emergence of additive manufacturing (AM) allows companies a new set of opportunities for more rapid production and product customizations. Throughout this thesis we will use AM, additive manufacturing, and 3D printing to describe the following defined production method. According to Ngo et al. (2018) additive manufacturing is a technique for producing parts with a wide range of structures and complex geometries from three-dimensional model data. Additive manufacturing is a part of the 4th industrial revolution and can produce positive effects on the supply chain (de Brito et al. 2020). The field of supply chain management has become increasingly more interested in the digitalization (Schniederjans, Curado, and Khalajhedayati 2020), and the implementation of industry 4.0 technologies are rapidly expanding in the industry to improve cost efficiency, production time and lead time in the oil, gas and renewables industry.

The adoption is clearly a part of the focus area of multiple corporations involved in the industry, and multiple companies are all looking at digitalization as a potential tool. To make sure of the anonymity to the companies involved we will refer to the companies as Company A, B, C. We will therefore not provide sources for the following statements. Company A has the goal of increasing efficiency and improve the health, safety, security, and environment (HSSE) in the company by an adopting digitalization tools. Some of the tools implemented are Augmented reality (AR) and Virtual reality (VR). Further on, Company B has implemented additive manufacturing and the use of drones to efficiently, and more environmentally friendly deliver spare parts to the offshore facilities. Most of the technology that is implemented are trial projects and, in its infancy, it creates new knowledge and experience in technological innovations. Company C estimates the increased investments in digitalization can reduce manhours on engineering and fabrication with 20 % the next two years.

From what we can see above there is an increased interest in the adoption of additive manufacturing and other industry 4.0 technology in the oil, gas, and renewables industry on the Norwegian continental shelf. In addition, from the literature review we have found little research conducted specifically on supply chain resilience and additive manufacturing.

Recently Naghshineh and Carvalho (2020) proposed a conceptual model for AM adoption and the effects this has on the supply chain resilience. They state that future research can look at supply chain performance through the model of AM adoptions and supply chain resilience. They further observe that the next step would be to implement the model in an industry. Further on Ivanov, Dolgui, and Sokolov (2019) and Dolgui, Ivanov, and Sokolov (2020) highlight the further research opportunity of how to make innovations work for disruption recovery (as the Covid-19 epidemic) by using additive manufacturing and data analytics. In addition to the relationship between SC disruption and additive manufacturing.

In our case study, we investigate a supply chain in the oil, gas, and renewables industry, where routine maintenance is carried out on an offshore facility. There has been taken a decision to source the product as additive manufactured part, to achieve knowledge creation and experience with the technology. We have conducted interviews with two of the companies in the supply chain to look at what effects the implementation of AM in the supply chain has led to.

Our research will provide further knowledge on the field of supply chain resilience, and additive manufacturing, to better spread the knowledge of the effects additive manufacturing has on the supply chain and its resilience. In addition to providing information to important corporations and organizations on the Norwegian continental shelf on the field of supply chain resilience and additive manufacturing's potential in the industry.

1.1 Research Problem

Throughout this master thesis we will try to answer the following research problem:

How does additive manufacturing affect supply chain resilience?

The problem statement creates the overlaying question of this thesis, where we try to provide the information on supply chain resilience and additive manufacturing through literature review and a case study on a specific industry. By using concepts as supply chain, supply chain resilience, industry 4.0 and additive manufacturing create a foundation to look at the case of the Norwegian oil, gas, and renewables industry. Further on, we have created some research questions to answer our problem statement in depth.

1.2 Research Questions

By looking at our case study we will find what effects the implementation of additive manufacturing in the supply chain of the oil, gas and renewables industry will produce. In addition to what they can expect after some time. We also view at how our case study, and the specific project compares to the existing literature

RQ1. Does additive manufacturing affect the resilience of a supply chain? (A case study of the Norwegian oil and gas industry)

Further on, we observe what the effects of implementing additive manufacturing will have on the traditional supply chain, and how this might be changed from today's situation.

RQ2. What challenges do companies face when implementing AM technology in their supply chain, and how will this implementation affect the traditional supply chain?

At last, we provide an additive manufacturing impact model on supply chain resilience, to show the effect the implementation has on the resilience of a supply chain.

RQ3. how does the additive manufacturing model impact the supply chain resilience?

1.3 Structure of the Thesis

Our thesis is structured according to the guidelines provided by the university college. The thesis is structured like this to provide a good knowledge foundation before we study our findings, and at the end discuss the findings against the available literature.

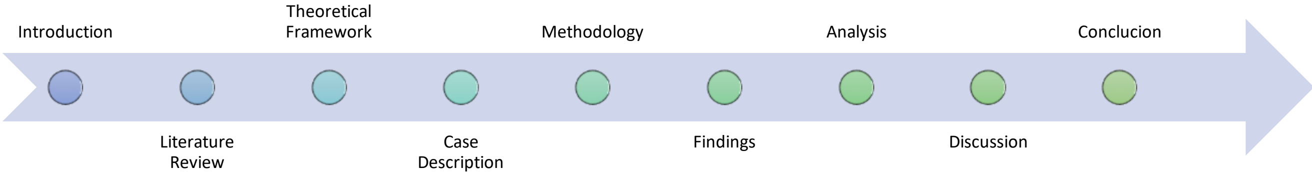

Figure 1 - Structure of the thesis

In chapter 2 and 3 we provide a literature review of additive manufacturing and supply chain resilience, to look at the available literature on the two topics, in addition to providing a theoretical framework. This is done to study the current literature and what future research and research gaps that are present.

In chapter 4 we provide a case description, and case company details to describe what problems we are looking at, and on whom we are looking at. In addition, we provide information on the data collection in the industry.

In chapter 5 we look at the chosen methodology used in our thesis. We present our research approach, design, and method before looking at the unit of analysis and case study research. At last, we look at the validity and reliability of our thesis.

In chapter 6 we provide our findings. Here the information is collected from three interviews involving two case companies. Further on in chapter 7 we analyze the findings from the interviews by looking at the difference in response.

In chapter 8 we discuss the findings from our interviews and compare to the relevant literature review before proposing a conceptual framework. By doing so we will answer our research question. Following this chapter 9 provides our conclusion, limitations, managerial impacts in addition to the further research.

Chapter 10 contains the list of references used in the thesis, followed by chapter 11 that provides three appendices, these are the interview guides from our case study.

2.0 Literature Review

In this chapter we will present literature review conducted on our main topics concerning AM, SCM and SCR, that are fundamental in our thesis.

2.1 Additive Manufacturing and Supply Chain

The literature of scientific materials on AM has increased significantly over the past couple of years, especially from 2018 until now. This is based on published scientific articles on google scholar, science direct, and various articles related to AM and supply chain topics. There are many different reasons for the increased published number of articles around this topic. Still, one of the reasons is the impact on processes and opportunities AM can bring for companies. Some common factors are reduction in lead time, inventories, safety stocks, waste, and complexity. DNV.GL (2017) and ISO/ASTM (2018) define AM 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 methodologies.

Previously AM was typically used to produce a prototype or illustrate a product better, today this technology has advanced to create products or parts. AM can be used in different locations in the traditional supply chain and reduce processes by producing more complex components and closer to the customer. Regarding the literature on both additive manufacturing and supply chain, there have been studies concerning the spare part industry, digital manufacturing, healthcare, automotive, aircraft, etc.

Holmström and Gutowski (2017) have published an article on AM in operations and supply chain management. This article's focus area is related to the four ways AM allows supply chains to improve sustainability. These four areas are: reducing transportation through localizing production, reducing material consumption through reduced overproduction, extending the life of products in use with additive repairs and on-demand spare parts, and lastly, upgrading, and refurbishing products in use with improved parts and components. They believe that some of the biggest challenges with AM implementation are slow speed, high equipment cost, and a significant need for post-processing.

Further, the article discusses the implication of new technology and what to consider if a company should adopt the technology. We found some of the gaps in this article related to further studies suggested by the authors. There is additional complexity when implementing new technology, which is creating a knock-on effect inside the company. Since this wasn't cooperation with data collection through a company, we believe some of the results may change due to more focus on the end quality and time, as Boer, Lambrechts, and Krikke (2020) mentioned in their article.

Holmström has earlier also posted an article with Partanen (2014) on the digital manufacturing-driven transformations of service supply chains for complex products. The digital manufacturing technologies allow for the automatic production of objects from computer-aided design (CAD) files without shape defining tooling. Digital manufacturing can be used in a more expansive digital infrastructure for standardized processes, and AM can be used with 3D scanning to create digital models for spare- and rare parts. This article investigates the focus on digital manufacturing, and some of the severe findings are reduction in logistics cost, inventory holding, and stock-outs. Further the implementation of digital inventory can be used to deliver faster and more efficiently towards the customer. The article further refers to the possibilities to extend the product's life cycle in use through limited product development efforts. One of the findings is that innovative combinations of digital manufacturing and supply chains will decrease supply chain complexity through more uncomplicated and more effective solutions. But there are also some limitations and challenges related to the willingness and ability to re-engineering products.

Li et al. (2017) described the topic of AM technology in the spare parts supply chain as a comparative study. This article provides the possibilities of AM technology within this industry and that it has significantly improved supply chain dynamic in this focus area. In this paper, two dynamic system models were designed for the spare part supply chain one adopting AM and the other using traditional. The models mainly imply the difference in terms of cost and emission. Further on, there are some concerns regarding service level, delivery, and customer value. However, some of the findings from this article show us that the AM supply chains have a lower total variable cost than the traditional ones. The article further considers that the fixed cost, such as the purchasing cost of equipment, also is believed to be reduced along with the development of AM technology but that the traditional manufacturing method is more fixed cost-efficient at given point in this article.

Further, de Brito et al. (2020) wrote an article on the design approach for AM in spare part supply chains. In this paper the promising capabilities is demonstrated and addressing new design challenges emerging from the widespread use of 3D printers in manufacturing supply chains. Again, AM may be considered a strategic decision and is a part of the 4th industrial revolution. The background for the study is the characteristics of AM production that allow products to be improved, more complex, and produced with a lower lead time more cost-effectively. The result of the article revealed a promising capability of a model presented with the lead-time, cost, demand, and numbers of production centers considered.

Boer, Lambrechts, and Krikke (2020) address AM in military and humanitarian missions with the advantages and challenges in the spare parts supply chain. When it comes to the area of humanitarian missions and how AM can change supply chains, there is little literature and most concerning assemblies and systems produced in low quantities. The cost of capital and tooling is a significant component of the unit. The article highlights that AM can be used to benefit both geographically and temporarily isolated places that still require the production of spare parts. Moreover, they have conducted interviews to gather data and thoughts from the industry to overview potential pitfalls and benefits along with literature. Further, a figure is illustrated to show the changes in the supply chain, responsiveness, sustainability, and boundary conditions related to AM in military and humanitarian missions to identify possible outcomes. When it comes to humanitarian- and military missions, the geographical aspects would be a critical part of the decisions making on whether to adopt AM due to the lead time for products to arrive and transportation cost.

Özceylan et al. (2018) observed in their article the impacts AM had on supply chain flow using a case study of the healthcare industry. The industry has implemented AM to investigate the potential benefits of AM. In this article, they search and assess changes associated with 3D printing to identify the potential impact of AM in the supply chain. 3D printing transforms digital 3D models into objects by building them up in layers. Further the study highlights the orthopedic steps with traditional manufacturing and 3D printing. The analysis compares an insole to a shoe where we can see a reduction in production- and delivery time, raw material used, and time spent for the customer. The reduction in overall time and increase in sustainability can further create customer value since the process is shortened. However, when investigating the unit cost comparison AM cannot compete with the traditional manufacturing, since they can produce in larger quantities. But, if you consider the overall economic effects like the cost of shipping, manufacturing, testing time, and so on, AM might be a better option compared to traditional.

In addition, various models illustrate the case aspects better, comparing traditional and additive and what benefits AM can offer to companies in terms of other elements. It is further substantiated by the solutions of distribution for AM and traditional production. This study implies that AM can decrease the number of stages in the supply chain compared to the traditional since there is a reduction in components and transportation. However, this is dependent on where the production takes place, the customer base, the complexity, and the access to raw materials.

Kubáč and Kodym (2017) address the impact of AM on the supply chain. They describe the process of AM that uses CAD to allow the production to translate the design into a three-dimensional object. Further, they also show the different generalized steps for producing with the additive technology. They further demonstrate some of the limitations and disadvantages that might appear when an organization adopt AM. The method measures low-volume and high-volume production and how this can affect a firm's cost. There is also a figure of how a traditional supply chain looks and how a potential basic AM integrated supply chain might look. The article highlights that the cost per unit might be higher. Still, with reduced storage and less outdated products, firms' costs may be lower overall than for a traditional supply chain. It can also make new market strategies and distribution channels within the firm.

In addition Rinaldi, Caterino, et al. (2021a), on the other hand, describes this technology selection in green supply chains and the effects of additive and traditional manufacturing. However, both Rinaldi, Caterino, et al. (2021a) and Kubáč and Kodym (2017) agree that production volume strongly influences the financial results, and the competitiveness of AM remains limited compared to traditional manufacturing. Further, Rinaldi, Caterino, et al. (2021a) explains that selecting a new technology is an effective decision-making process and should drive a company to evaluate different aspects. We are also presented with various topics on sustainability and its essential issues that have forced companies to adopt more environmentally friendly materials and production methods. According to this paper, the framework is so flexible and simple to implement that it allows companies in significant decision-making processes and helps companies make their decision by increasing or decreasing the number of key performance indicators. AM is further presented as a completely different manufacturing process, and that to adopt it is required to have a strategic business change.

Additionally, this article also referred to Industry 4.0 as an alternative production strategy. The technology section would become a strategic decision in the supply chain configuration and vision. If a company implements these changes in the production method, it could cause profound changes within the organizations, affecting the relationship between suppliers and stakeholder in the supply chain. When companies are implementing new technologies in the future, there should be a higher level of attention on the environmental- and economic-factors. With the increased awareness on sustainability and green supply chains, companies have had to adapt their processes as production method to respect sustainable constraints and meet the unique desires of the demand.

Rinaldi, Caterino, Manco, et al. (2021) have further published an article on the impact of AM on supply chain design as a simulation study. They describe AM as a well-known production method that differs from the traditional subtractive approach. AM focuses on adding layers by layers while traditional focuses on removing materials from a block through modeling technologies. In addition, the article presents a set of key performance indicators to identify logistics and supply chain processes. One of the significant findings from this article is that AM allows the design of a shorter supply chain and offers a substantial saving in the supply chain lead time. Still, it is worth mentioning that the investment costs for changes in supply chain design are not considered in this article.

Attaran (2017) further presents AM as the most promising technology to alter the supply chain and logistics. He describes that AM uses CAD to translate the design into a three-dimensional object. We are further presented with the fundamental issues, pitfalls, and promises related to the AM technology. Attaran also addresses different companies that have adopted AM production in their supply chain and how they have been using it for the past few years. He also implies that the research area is mainly underdeveloped compared to other domains within the market, and that he expects this technology will keep growing at a fast pace and play a significant role in the future of supply chain. Today the technology is easier to access compared to earlier. This combined with the development of technology and reduction in cost has allowed some additive manufacturers to find their way into many industries and companies.

The article further discusses the limitations of this manufacturing method and some of the significant obstacles to overcome to be more suitable. Some of the concerns are related to the government, liability, the product size, and the higher cost for larger production runs. But it is also to bear in mind that a supply chain includes various members within supply vendors, manufacturing, software, logistics, so it is also interesting to see for whom AM has the potential to make the most significant impact. Attaran states that a recent study shows that a "software-defined supply chain" can dramatically reduce lead times, costs and have the potential to overhaul the logistics industry. Moreover, Attaran (2017) present ten benefits gained with the implementation of AM alternatives into the supply chain as; 1) shorter manufacturing lead time, 2) reduced inventory, 3) reduced lot sizes, 4) shorter time-to-market, 5) reduced transportation cost, 6) reduced production waste, 7) more efficient packaging, 8) improved product range via customization, 9) hedge against disruptions and 10) improved sustainability.

DNV.GL (2017) an independent expert in assurance and risk management, has published a report on Additive manufacturing with qualification and certification process for materials and components. In order to better understand the technical requirements, principles, and acceptance criteria of this topic. In this report they present a framework for approval and certification of materials, products, and components made by AM. Further in the report companies seemed to conduct their own testing to ensure the integrity of the equipment, processes, and product. They further discussed the limitations and possibilities with the implementation of AM. These are like what Attaran (2017) posted in his article. Further, (DNV.GL 2017) provides an overview of the AM process variables, whereas the type, metallic materials, and polymers are presented. With time there have also been produced an updated version with relevant standards around AM qualifications and materials as well as risk associated with the technology for this industry.

Yılmaz (2020) uses an optimization model to examine AM in the supply chain context. Due to the increase in demand for customized product in the market, AM could be introduced to the production process to respond to this rapidly changing customer demand since it allows for more customized production. AM has emerged as a way for companies to produce new products, and along with this, new problems has occurred in different areas of the supply chain. Further in this article, we are presented that some large firms are already implementing AM technology to their production process. Several small- and medium-sized enterprises sought to benefit from AM technology day by day. Moreover, the article also explains the different production methods and materials, or methods used in prototyping and direct part production. This paper provides an insight into the AM technology in the context of a two-stage supply chain, a new optimization model, and five heuristic algorithms to better understand this technology compared in transportation and manufacturing. Overall, this article provides relevant data on how the supply chain variables and that one of the most challenging issues in a supply chain are reducing the completion time while also providing a valuable service to the customer.

Kunovjanek and Reiner (2020) write about AM and supply chains through a systematic review. This article shows an in-depth explanation of the literature collected for this article. we can see that the number of published reports has increased in recent times. Furthermore, this can also be linked to the increased focus on the supply chain due to an improved understanding of the cost related to transportation, inventory, and production. The benefits are shown and compared with the challenges through a content-based analyses, and the collected articles are measured to give us an overview of what pieces are focusing on AM in the supply chain. It provides an in-depth investigation of supply chain-specific impacts of AM in a qualitative analysis to show that there is a strong focus on the design aspect. There is an increased interest in automotive, industrial goods, consumer goods, and aerospace. Overall, this article provides a good insight into AM as a research area focusing on the supply chain.

Luomaranta and Martinsuo (2019) present supply chain innovations for AM in their article. The focus area explores the supply chain innovations dealing with AM in business-to-business supply chains. This study further draws attention to the supply chain innovations required when firms adopt AM into their processes. Moreover, it presents that AM can challenge traditional manufacturing processes or complement the conventional approach. From there on, interviews and companies are collected and analyzed before presented. This showed that the larger firms have capabilities and possibilities to invest in the whole AM supply chain process. In contrast, small and medium-sized firms are more restricted and need partnerships or cooperation to invest in AM. Moreover, it is also revealed that the different types of firms have different roles across the supply chain processes. These findings suggested that manufacturing technology innovations as AM cannot be seen as isolated innovations that are leveraged purely as technology adoption tasks. It also mentions that digitalization would affect the entire industries and not only single firms.

Verboeket and Krikke (2019b) presents AM as a game-changer within supply chain design. Some of the core values that have increased the focus and interest for AM are digitalization, customization, and sustainability. The reasons for the interest in digitalization are usually either to increase the supply chain speed and at the same time scale down the overall supply chain cost by implementing automation and robotization. Further, the decoupling point has been moved upstream with time, and the number of options has increased for the end customer. However, there is also awareness of sustainability. The supply chain design needs to balance the triple bottom line of profit, people, and planet to increase the customers' interest and companies’ reputation. Moreover, companies might replace the physical inventory with digital inventory to give the customer opportunity to impact the design and qualifications. In addition, there is interest in enabling manufacturing closer to the customer, to increase the availability and responsiveness. Another of the significant findings in this article is the awareness of design-for-AM knowledge as a critical requirement and that make-to-stock (MTS) is possible. Still, make-to-order (MTO) and engineering-to-order (ETO) products become more serious alternatives for AM. The article further contributed with knowledge on supply chain design and potential revolutionary effects of AM, and that raw materials and digital files may replace the need for a physical warehouse.

Verboeket and Krikke (2019a) further address the disruptive impact of AM on supply chains with a literature study where they propose a conceptual framework. Compared to some of the other studies done before, this study mentions that AM is considered as one of the key developments in the 4th industrial revolution and that the strength of AM would affect today's supply chains. It also highlights that AM can create traditionally impossible, complex, or just expensive products due to the change from material removal to layers-on-layers technique. However, there is also a reflection on bottlenecks and challenges. The printing materials may be scarce, and the machine and material price can be higher than for traditional manufacturing techniques. As told before, AM allows the shift from physical inventory towards digital inventory, which can influence the ability to replace a range of different stock-keeping units and change the decisions regarding warehouses.

Because of this, AM will reduce the dependency on components suppliers but increase it on the basic materials and IT suppliers because for now there is a lack of competition within this specific market. The article mentions the challenges concerning IT infrastructure might be a challenge due to a secure line if planned to enable the sharing and retention of digital files. Upgrading the IT infrastructure might require significant investments due to the complexity of the operation. In this article they also present other bottlenecks like low automation levels, slow production time, low throughput, and high equipment and manufacturing cost. The article also refers to "the unavailability costs, e.g., downtime costs and penalties due to a missing aircraft spare part, may easily outweigh the higher single-piece production costs". Which is further argued on the terms of risk related to better design quality, improved safety, reduction of stock-outs but also increased risk of knowledge leaks due to unsecured connection might constrain. Overall, this article focuses on the increased knowledge about the disruptive impact that AM has on supply chain design. Last of the findings in conclusions referring to the supply chain performance would improve with increasing AM maturity. According to the paper various bottlenecks that currently create a diffusion are likely to be eliminated.

Son, Kim, and Jeong (2021) observed the sustainable part consolidation model for customized products in closed-loop supply chains with AM hubs. The article it discusses the hesitation of smaller firms to adopt AM because of the entry barriers, such as expensive machinery, slow build speed, printing size limitations, and lack of operational knowledge. They further discuss that part consolidation can have a significant potential and create an advantage for AM potential and advantage compared with traditional manufacturing. The article also addresses those previous studies which have been restricted to a limited AM scope, such as producing components or spare parts of final products. Throughout the paper, we are presented with the sustainability aspect that AM provides, both from the point of the cost related to raw material and the lifecycle. It also states that with the increasing demand for customized products in various industries, AM technology has attracted considerable attention as a critical technical factor.

The paper by Khajavi, Holmström, and Partanen (2018b) states that a hub configuration of AM systems is better off than a fully distributed system with the technology that is available at that point in time. They further highlight that if there is a hub configuration instead of a fully distributed system where there is a machine on-site the equipment and personnel costs are lower than in a fully distributed system. Further on, in a distributed system the lead-time is dramatically reduced because of the elimination of transportation and handling time. If the demand is in a remote location and need costly transportation, this might lead to decentralization.

Boer, Lambrechts, and Krikke (2020) look at the advantages and challenges in the spare parts supply chain for military and humanitarian missions. They found that the ability to produce using AM technology on demand and on location could significantly reduce lead time and costs. Moreover, it could affect the downtime of a system because of the possibility to temporary replacement of broken spare parts. They further highlight the fact that the parts suitable for AM production is still limited.

Rinaldi, Caterino, et al. (2021a) address the effects of traditional manufacturing and additive manufacturing´s influence on green supply chains. They found that in a decentralized system with AM in a supply chain that requires high service level, and a flexible environment AM is the greenest choice. Further on, they found that AM offers potential on supply chain performance with savings in lead time and average stock. In addition, the fact that the production volume of AM is small, there is still some limitations of AM, because it is often not competitive with traditional methods.

Luomaranta and Martinsuo (2019) present a case interview where one of the participants mentioned that they needed to adjust the product every year or every two years to be competitive. This was a drastic change compared to previously where a product variant lasted for years. This creates more expensive models as the batch size reduces and the customization increases, generating a problem for the suppliers due to shorter notice of the change. Holmström and Gutowski (2017) highlight the slow production speed, high equipment cost, and the significant need for post-processing as the most challenging aspects facing AM in final part production. Kubáč and Kodym (2017) address three different areas to be aware of as technology and engineering, data management, and business impacts. The article presents categories where we can highlight the changes in material properties. Moreover, there are highlighted geographical and organizational separation of the design and production.

Griffin (2017) addressed the consistency in geometry and material properties is a big concern for AM when compared to traditional manufacturing. Holmström and Gutowski (2017) outline challenges associated with printing time and high equipment cost related to AM. At the same time, Attaran (2017) Concerns are related to the larger production runs that creates more time usage and challenges with an increased need for verifications. But Khajavi, Holmström, and Partanen (2018a) address in their the problems related to software, availability of the materials, and production finish quality. Rinaldi, Caterino, et al. (2021a) address that manufacturing technology selection is essential, affecting the whole supply chain.

Although AM has numerous advantages mentioned in the previous sections, there are still some research gaps. From the review of collected literature and our best knowledge, there has been verry little research carried out to investigate how AM technology can affect resilience in the supply chain. Research has shown us that for companies to start gaining benefits from this technology, some firms might need assistance. This is mainly related to the price and quality problems related to the implementation and production. Based on the literature reviewed in this chapter, we believe that we have highlighted the relevant literature on the field. According to Verboeket and Krikke (2019a) and Attaran (2017) the cost related to AM implementation would reduce with time and allowing further companies into the market. This implies the cost related to implementation, raw materials, warehousing, and transportation.

2.2 Supply Chain Resilience

Supply chain resilience is a field where research started picking up at the start of 2000 (Pettit, Fiksel, and Croxton 2010) and has since become a field of interest with a significant amount of literature produced. The research is often about resilient supply chain or enterprise and how aspects as collaboration affect supply chain resilience. This literature review will look at what resilience is and what constructs and activities establish and increase a company's or a supply chains resilience. The end of the literature review will look at the research gap in the literature and which fields are of interest for this thesis.

When defining supply chain resilience, there is a need to define the supply chain. To do this, we use the definition of Mensah and Merkuryev (2014b). They describe the supply chain as consisting of all the stages involved directly or indirectly at fulfilling the customer's request. The supply chain is a complex and intricate system where the supply of goods and the demand for these goods is the main focus. It is where the suppliers in the chain work towards fulfilling the customer demand most efficiently and satisfyingly. This leads to the problems that are identified as supply chain disruptions. Disruptions can be small or large, but the more significant are recognized as natural disasters, outages of IT or telecommunication systems, civil conflict, industrial dispute, or cyber-attacks (Mensah and Merkuryev 2014b). These disruptions can cause harm to the flow of goods or services throughout the chain from raw materials to the end customer and, therefore, the profits of multiple suppliers or customers.

In the introduction to the article by Pettit, Fiksel, and Croxton (2010), The following definitions of resilience is used: "the capacity for an enterprise to survive, adapt, and grow in the face of turbulent change." Mensah and Merkuryev (2014b) say that resilience is defined as the ability of a substance to get back to its original state of form after deformation. In a resilient supply chain strategy, this is the ability to bounce back after disruptions that may affect the upper and lower streams of the supply chain. In Sheffi and Rice Jr (2005), resilience is also defined as the ability to bounce back from disruption. The article provides eight phases of the disruption, and the dynamics of the company's response can be characterized. These are (1) Preparation, (2) The disruptive event, (3) First response, (4) Initial impact, (5) full impact, (6) recovery preparations, (7) Recovery, and (8) Long-term impact. In the article by Christopher and Peck (2004), resilience is defined as 'the ability of a system to return to its original state or move to a new, more desirable state after being disturbed. From the definitions mentioned above, we can understand that there are numerous ways to define supply chain resilience. Moreover, these disruptions can have multiple causes, and the effects of these disruptions can lead to minor or significant impacts on the supply chain and the profits.

Further on, Pettit, Fiksel, and Croxton (2010) states that instead of a supply chain just returning to its original state, it would be beneficial if the company or supply chain learned from the disruption and adapted to a new configuration. In the article by Gölgeci and Ponomarov (2015), they present that resilience is more meaningful if it is developed, deployed, and utilized by supply chain members jointly rather than by an individual firm. When you look at a complete supply chain, instead of focusing on a single company, the whole supply chain can excel, and the demand can be met more rapidly than just by optimizing for one company in the supply chain.

The phases of the disruptions presented in Sheffi and Rice Jr (2005) tell us the disruption profile. First, the preparation that a company can do depends on the type of disruption that is occurring. A disruption can range from no warning as in a terrorist attack or in the case of a ship stopping traffic in the Suez Canal or lengthy crisis as covid-19 that changes demand and supply. Depending on the situation and the disruption, the company can make necessary changes or adjustments to its supply chain to minimize the impact of the disruption.

The following stages are the disruption itself and the first response where the company or supply chain must act to save lives, data, or whatever is necessary for the given situation for the unique disruption. The next is the initial impact, and the initial result can vary from the type of disruption that has occurred. For cyber-attacks, the effect is complex and immediate and will make a high impact when supply, production, and communication can be affected. For others, the initial result is small, and the effect will take a long time to affect the supply chain (Sheffi and Rice Jr 2005). The impact will vary depending on the available redundancy and the organizations and supply chains inherent resilience.

Then there is the full impact, recovery preparation, and healing. In these phases, the total effect is felt, and there is an effort made to start recovery simultaneously with the first response, which can last for a long time to get back to the ordinary operation levels. The last phase is the long-term impact which can vary from small to significant. Sheffi and Rice Jr (2005) further states that if the customer relationships are damaged, the consequences can be especially long-lasting. In addition, disruptions like Covid-19 virus outbreak have caused significant and prolonged effects of supply difficulties and have further reduced the demand for a considerable amount of goods and services worldwide. Events like these will have a long-lasting and high immediate impact that can shift how products and services are being produced and consumed by the customer forever.

Mensah and Merkuryev (2014b) present the increased importance of IT systems and technology. IT systems are becoming a more significant part of every business in information, materials, and financial flow throughout the supply chain. They state that any hardware or software defect or damage to the IT system will result in a disruption that could affect the entire supply chain. Cyber-attacks are another problem to the IT systems where weaknesses in the security of the system can result in hackers getting access to the system through malware or similar approaches into the system and potentially getting control of the entire IT system of the company. This is a problem that needs focus because technology is constantly evolving and is becoming an increasingly important factor in all businesses.

The development of a resilient supply chain that can withstand disruptions or minimize the effects of the disruptions can use multiple tools or strategies to achieve resilience for the supply chain and the company. Mensah and Merkuryev (2014b) highlights four strategies to develop a resilient supply chain: lean production with just in time (JIT) delivery and low inventory, six sigma supply chain, increasing Supply chain flexibility and creating a solid corporate culture. The Lean strategy has the advantages of minimizing waste and inefficiency and the company's responsiveness, productivity, and quality. The downside of it is that it requires a rapid and frequent flow of goods, services, and information to achieve a just-in-time production and supply.

According to Mensah and Merkuryev (2014b), the introduction of the lean approach will create transparency and trust among the different supply chain partners, which is an important part of the efforts to bounce back or return to the original state before a disruption happened. Six sigma supply chain is a strategy that focuses on minimizing the defects in the supply chain and trying to have 3,4 defects per million activity or opportunities. This makes it possible for management to solve challenges effectively and pay off in the long run. The problem with six sigma is that it is highly cost and time-consuming and will not be profitable at the start. The strategy of increasing supply chain flexibility can increase resilience because it responds to a change in demand and reallocates resources when needed, which is accomplished by having a good relationship with suppliers. Developing a robust corporate culture creates an environment that makes employees well informed about the organization's activities through continuous communication. This makes it possible for the employees to make quick decisions and makes it possible for rapid recovery after disruptions.

Christopher and Peck (2004) provide tools that can help create a resilient supply chain. By designing and reengineering the supply chain, it is possible to develop resilience in the supply chain. Understanding the supply chain is highlighted to improve resilience by understanding the network to identify pinch points and critical paths. The supply base strategy is also highlighted as an important criterion because the risk awareness of the supplier and the option of using single sourcing or multiple suppliers can affect a supply chain's resilience. Further on, they provide design principles for supply chain resilience. These are the principles of supply chain strategy and to examine the trade-offs of efficiency vs. redundancy—Supply chain collaboration in the supply chain as an exchange of information to reduce uncertainty. At last, they present agility by supply chain visibility and velocity as critical criteria to achieve resilience. Agility is the ability to respond rapidly to unpredictable changes in demand or supply. Visibility is the ability to see from one end of the pipeline to another and velocity is the distance of time. We see a connection in the article by Mensah and Merkuryev (2014b) and Christopher and Peck (2004) where they suggest lean and six sigma that focuses on agility and flexibility to achieve a resilient supply chain.

In the article by Pettit, Fiksel, and Croxton (2010), they define 14 capabilities that increase the supply chain's level of resilience. The capabilities are flexibility in sourcing, flexibility in order fulfillment, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, organization, market position, security, and financial strength. By looking at these articles, we find that flexibility, agility, and visibility are essential factors in achieving supply chain resilience for a company. In the article by Scholten and Schilder (2015), There is a literature review on supply chain resilience where efficiency, redundancy, collaboration, flexibility, velocity, and visibility are terms that are frequently used.

The findings in (Scholten and Schilder 2015) indicate the relationship between collaboration activities and supply chain resilience. The more companies engage in information-sharing, collaborative communication, mutual relationship efforts, and mutual knowledge creation, the better the visibility, velocity, and flexibility, which further increases the supply chain's resilience. They also demonstrate that increased flexibility can come from interacting with competitors. In addition, the longer the collaboration between different companies, the better the resilience of the chain is because of the inherent increase in visibility and velocity. To summarize, we can see that supply chain design and reactive capabilities as flexibility and efficiency are central in making a supply chain more resilient. In addition, the possibility to produce visibility and collaboration between companies in a supply chain increases the resilience; all these effects are substantial to bring a higher level of supply chain resilience.

Christopher and Peck (2004) produced a route-map framework for supply chain resilience which connects the capabilities mentioned above to create a more resilient supply chain and which sub-factors make the capabilities possible. An example can be that by increasing visibility, velocity, and acceleration, a company or supply chain can improve its agility and, by doing so, increase the resilience of the supply chain. Based on the research from Christopher and Peck (2004), Pettit, Fiksel, and Croxton (2010) build a supply chain resilience framework where they identify the "zone of resilience". They state that there are a set of vulnerabilities and capabilities linked together to best match the vulnerabilities that a company or supply chain is facing. There is a balance between investment and risk they define as a state of "balanced resilience". To produce the framework, they make propositions that extreme vulnerabilities relative to capabilities will result in excessive risk. Those excessive capabilities relative to exposures will erode profitability, and that supply chain performance improves when capabilities and vulnerabilities are more balanced. The framework is based on seven vulnerabilities and 14 capabilities.

Further on, in the following paper by Pettit, Croxton, and Fiksel (2013), they present a new assessment tool named SCRAM. SCRAM is based on the original supply chain resilience framework from Pettit, Fiksel, and Croxton (2010) and is a survey-based assessment tool – with the name "The supply chain resilience assessment and management "(SCRAM). The assessment tool subjectively assesses the factors and subfactors based on the framework in the earlier paper. By rating the relative importance of the elements, it was possible to determine internal priorities and compare results between similar companies. The "zone of resilience" framework, and SCRAM assessment tool make it possible for managers to check the supply chain position according to supply chain resilience. In the conference paper by Naghshineh and Carvalho (2020), they propose a conceptual model to measure the impact of AM adoption on the primary dimensions of supply chain resilience, and that its sub-constructs are interconnected and interdependent. One of the dimensions is proactive capability, and some sub-constructs are flexibility, integration, redundancy, disaster readiness, and efficiency.

Another aspect reviewed is the linkage between supply chain resilience and innovativeness. It is possible to achieve flexibility and visibility using new methods, techniques, and technology by linking the two. Gölgeci and Ponomarov (2015) present firm innovativeness as a multidimensional concept that refers to openness and capacity to introduce innovation in the organization. The article highlights that innovative companies are less resistant to change and more open to creating and leveraging niches. Further on in the article, they state that companies like this have a higher ability to adopt, adapt, execute, and leverage new ideas effectively. Moreover, companies that experience disruption with high impact can lead to companies re-assessing the effects of risks of disruptions and invest more in innovative solutions to minimize similar problems and implement them and achieve long-term solutions against a threat. By doing a regression analysis, they find that firm innovativeness has a significant and positive influence on supply chain resilience.

In the article by Sabahi and Parast (2020), they look at if more innovative firms are also more resilient to supply chain disruptions. If so, what capabilities of innovative firms support the firm's resilience, as in (Gölgeci and Ponomarov 2015). The article looks at it from the resource-based theory perspective, which states that useful resources and opportunities of a firm is a primary driver of competitive advantage. The paper proposes that creativity and innovation may bolster adoption through improvisation and that innovating strategy positively impacts different types of supply chain flexibility, including new-product flexibility and delivery flexibility. They also propose a framework that demonstrates the relationship between resilience and innovation.

When we look at additive manufacturing and supply chain resilience, there is a research gap because there has not been a lot of research on the topics combined. the conference paper by Naghshineh and Carvalho (2020) present three main dimensions of supply chain resilience: proactive capability, supply chain design, and reactive capabilities. They propose that AM improves the readiness of a supply chain. Further on, they propose that it is possible to improve supply chain responsiveness by using AM either by getting the product faster to market or by manufacturing the product more quickly. By deploying AM systems to places requiring emergency supplies with shorter turn-around times. They also propose that supply chain complexity can be improved by supply chain design. Doing so can improve the company's supply chain resilience by reducing vulnerability. Using additive manufacturing can alleviate node criticality by decreasing the dependency on suppliers of complex components.

Ivanov, Dolgui, and Sokolov (2019) state that additive manufacturing can increase the flexibility of the supply chain because it can produce the exact number of products needed by the customers at a higher frequency than with TM, which in addition limits the need for inventory and safety stock. Because additive manufacturing technology makes it easier to produce at most location on-site, it can dramatically reduce the lead time for products that originally are produced in a location far away to then be shipped to the correct location. In addition, efficiency increases because of the continuous production the Additive manufacturing machines can have, with little downtime and the ability to produce without people needing to conduct the work physically. These are effects that increase the resilience because flexibility, efficiency and lead times of the supply chain is shorter and more precise than it possibly can be with traditional manufacturing. A negative aspect is highlighted in the article where there is an increase in design and control complexity.

Moreover, suppose a disruption is happening in the upstream part of the supply chain. In that case, additive manufacturing can reduce safety stock that can produce a higher level of risk. This is a result of the missing inventory can result in stock-outs, and the possibility of production or other factors in the upstream supply chain can be affected (Ivanov, Dolgui, and Sokolov 2019). They also highlight that parts consolidation or the fact that production of parts can happen from the same supplier, there will be a reduction in the supplier base, which can increase the amount of single sourcing.

The article by Remko (2020) presents connection between the available research findings and the actual practice conducted in the different industries to produce a more resilient supply chain post-Covid-19. Further it highlights three major disruptions or risks that can be a result form the covid-19 pandemic. Supply disruptions can occur because of the closure of facilities due to quarantine or other factors that result in a closure. Further the risk of hoarding of specific products can produce significant spikes in demand and change the shopping patterns of customers. The last is the necessity to involve the company's supplier in crisis response to make sure that suppliers can meet demand. To fulfill these risks, Remko (2020) presents multiple possibilities. The ability to use multiple suppliers and close collaboration with the suppliers can lead to more stability in the supply of goods and more opportunities to be delivered. He further highlights the need to have multiple suppliers or at least suppliers with various locations, so it will be possible to shift supply from one place to another to avoid lack of supply. he highlights the effect of digitization on the supply chain. The article highlights Nike's deployment of Radio Frequency Identification (RFID) in the supply chain to track demand and product availability in the chain. Maersk's usage of blockchain technology increases the visibility of the chain. Further on, there is a high degree of focus on ensuring supply continuity and ensuring a large enough supply base, as mentioned above.

Further on, Belhadi et al. (2021) observed that in the automotive industry, the best strategy to mitigate disruptions caused by the covid-19 virus was to develop and use local suppliers to reduce the supply disruptions that could be caused by sourcing from longer distances. In addition, they highlighted the use of industry 4.0 technology to mitigate the potential disruptions. Further on, the main challenge for the airline industry was to prepare for changes in business because of the pandemic. Both industries highlighted extensive data analysis to meet challenges and changes in the supply chain. The authors further highlighted collaboration and coordination in the form of technological development and implementation in the supply chain, developing a more agile, sustainable, and resilient supply chain.

We can see that based on the existing literature that we have focused on in this review, there is not a large amount of research on the field of Additive manufacturing and supply chain resilience. In the conference paper by Naghshineh and Carvalho (2020), they state that future research should use the framework and further examine the direct and indirect impacts of additive manufacturing or inclusion of SC performance via supply chain resilience. This article is the only study we have found that solely focused on supply chain resilience and additive manufacturing. Most of the literature is on supply chain resilience, where additive manufacturing is a topic within industry 4.0 or technology adoption within but not focused on. By looking at the innovative supply chain and the adoption of AM, there are significant opportunities to improve the supply chain resilience through being innovative. Innovation has multiple forms and utilities, additive manufacturing is a creative production method, and because of this, it is an innovative choice to start producing using the technique. Our thesis is vital because by looking at a specific case study, we can look at the current literature and at actual data from companies utilizing additive manufacturing in the supply chain, and what implications this can have on the resilience factors like flexibility, efficiency, and other aspects of resilience.

3.0 Theoretical Framework

In this chapter we will present the basic concepts that are fundamental to answer our research problem.

3.1 Additive Manufacturing

Additive manufacturing is a production method that adds layers-by-layers rather than subtracting material objects during the manufacturing process (Campbell et al. 2011); (Rinaldi, Caterino, Manco, et al. 2021). To create a product, prototype, or part with AM, there is a requirement for digital file that is either a CAD drawing of the new product design, or scanning the existing product design (Verboeket and Krikke 2019a). AM is a method that can be used with several materials and production methods (Yılmaz 2020). To create a product, prototype, or part with AM, there is a requirement for digital file that is either a computer-aided design (CAD) drawing of the new product design, or scanning the existing product design (Verboeket and Krikke 2019a). This production method was initially used to make physical prototypes and was introduced in the late 1980s (Vaneker et al. 2020). Since the introduction, there has been a widespread use not just for prototyping but also as toolmaking, low-volume manufacturing and to produce spare parts and end-products (Holmström and Gutowski 2017); (Verboeket and Krikke 2019a); (Yılmaz 2020). One of the reasons for the emergence of AM can be related to the green potential AM has compared to the subtractive methods, A reason for the wider adoption of AM could be the sustainable aspect that AM provides compared to subtractive methods (Rinaldi, Caterino, Manco, et al. 2021). The quick response can revolutionize manufacturing processes or complement traditional manufacturing processes with AM (Luomaranta and Martinsuo 2019).

AM is an emerging technology that further inspires manufacturers to utilize the risk reducing potential for new product design, cost, product design, customizing, products and services (Ansari, Jabari, and Toyserkani 2021). In principle, there are no limitations to geometry's complexity when producing with AM and without the need to create any tools, e.g., forming tools (DNV.GL 2017). Along with developing technology and the emergence of new materials and quality standards, AM has simply grown to allow companies to make solid three-dimensional objects just from digital models (DNV.GL 2017); (Chen et al. 2019). The new freedom from design further allows AM to combine an assembly of parts into one part as part consolidation, and therefore it can reduce the required assembly work, cost, and time

(DNV.GL 2017). Parts consolidation is an advantage and can potentially create flexibility within the supply chains as products now can be produced with greater complexity than before (Eyers et al. 2018). By positioning the AM system closer to the end customer, lead time and logistic costs can be reduced (Boer, Lambrechts, and Krikke 2020). Further, it can be used to limit the number of components, positive effect on inventory management with a reduction in the stock level and raw materials, and drastically reduce the number of suppliers

3.1.1 Build Processes and Materials

AM is also known under synonyms like 3D printing, additive layer manufacturing, and rapid prototyping. Further, it can transform the manufacturing and logistical processes with its different production methods. AM has evolved into covering new demands and printing complex structures to be more beneficial for the company (Ngo et al. 2018). The increased complexity is a result of the evolution of various new production methods, materials, and equipment. Some of the manufacturing processes further need to consolidate material after finishing building to improve the material. A reason for the expansion of AM in industries is the versatility of the production market, which is suitable for multiple markets. Usually, fused deposition modeling, laminated object manufacturing, stereolithography, and selective laser sintering, are being used for prototyping, while laser engineered net shaping, electron beam melting, and selective laser melting/direct metal laser sintering techniques are used for the direct part production (Yılmaz 2020).

3.1.1.1 Material Extrusion

Material extrusion is also known as fused deposition modeling (Serdeczny et al. 2020); (Coogan and Kazmer 2020) and is an AM process where the material is selectively dispensed through a nozzle or orifice (ISO/ASTM 2018). It involves melting a polymer filament in a heated nozzle and depositing the printed part onto the heated print bed (Coogan and Kazmer 2020) also shown in figure 2. This manufacturing technique uses a continuous filament of thermoplastic or composite material to construct the 3D part by adding layer by layer on the build platform. Through the technological development this manufacturing method has had an increase in reliability method has increased reliability and lowered the cost of the machines and materials (Serdeczny et al. 2020).

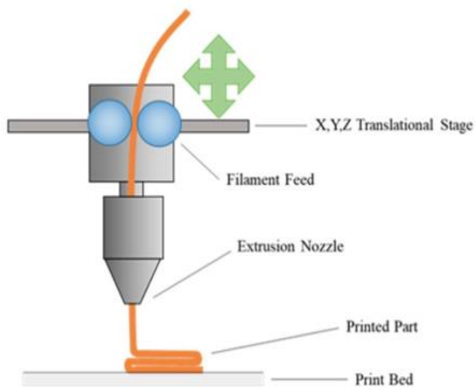

Figure 2: Material extrusion (Kjar and Huang 2019).

3.1.1.2 Material Jetting

Material jetting is also known as PolyJet and allows a precise deposition of the photopolymer onto the printer bed (Agrawaal and Thompson 2021). The inkjet nozzle places droplets of material selectively deposited on a print bed and with the use of ultraviolet lamps. (Salmi 2021); (ISO/ASTM 2018), this is illustrated in figure 3. Moreover, material jetting can construct parts in multiple colors with multiple materials to allow depositions of multifunctional products (Salmi 2021); (Agrawaal and Thompson 2021). According to Salmi (2021) this process is an excellent technique due to the accuracy of production. The fact that support structures are unscary allows a higher degree of customization for the customer at a lower cost and well suitable for the medical models.

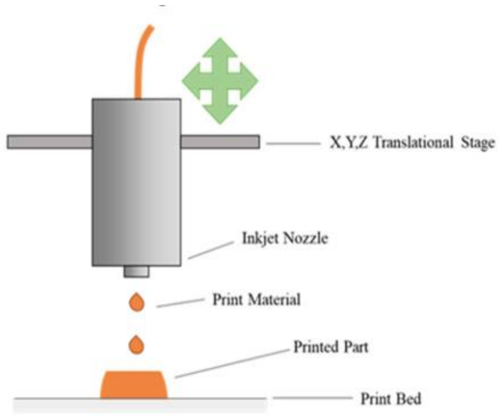

Figure 3: Material jetting (Kjar and Huang 2019).

3.1.1.3 Binder Jetting

According to Mariani et al. (2021), binder jetting has increased interest due to its simplicity compared to other direct printing processes. In this production method, it is a photopolymer disposed on the top of a moving platform with the aid of a jetting head, as illustrated in figure 4. If there are multiple jets, the user can print various materials within the same process as a part of the multifunctional material (Agrawaal and Thompson 2021). Furthermore, the process and technique make it possible to do the heat treatment while keeping the printing process simple, low energy demanding, and cheap (Mariani et al. 2021). The production method is when a liquid bonding agent is selectively deposited to join powder materials (ISO/ASTM 2018). In addition, this production method allows products to be produced with a broader range of different colors, materials, and has a faster process compared to other (Salmi 2021).

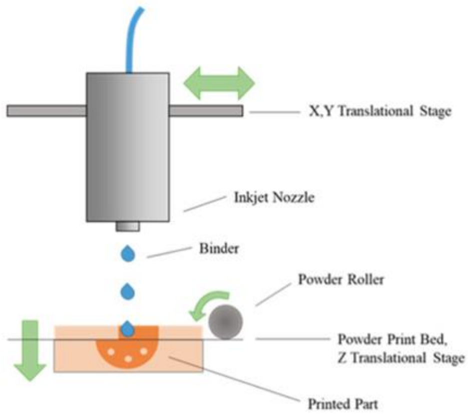

Figure 4: Binder jetting (Kjar and Huang 2019).

3.1.1.4 Sheet Lamination

According to Gibson et al. (2021), this technique was one of the earliest methods. However, due to the lack of automatization on the extensive postprocessing to remove support materials. This technique is the most similar to the traditional method since it can be used in colossal bulk objects as materials that have been used cannot be easily reused and are typically discarded after the cut, stacked, and bonded. This AM build process uses sheets of materials to bond products to a part, and it is the process of building a 3D object by stacking and laminating thin sheets of materials, as shown in figure 5 (ISO/ASTM 2018). However, Salmi (2021) presents that sheet lamination can provide an attractive market with multi-metals in the build process. Due to the technology and usage, lamination processes are often only used for the aesthetic and visual models and are not suitable for structural products (Loughborough-University 2020).

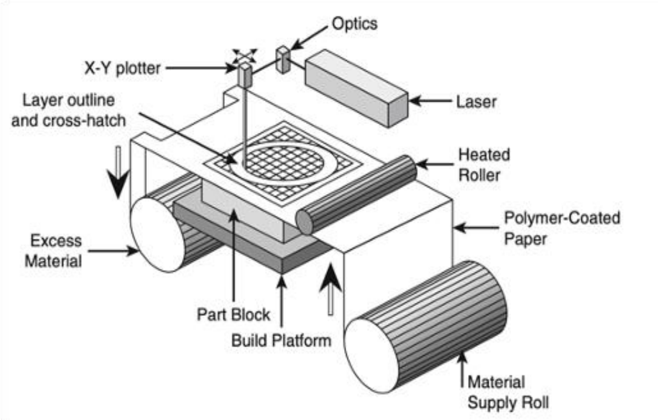

Figure 5: Sheet lamination (Engineeringproductdesign).

3.1.1.5 Vat Photopolymerization

Lovo et al. (2020) explain that using the liquid raw material as vat photopolymerization it will allow micrometric layer manufacturing or even layer less continuous manufacturing. Further, the light creates a base on the three-dimensional end part similar to the drawing. This AM process uses liquid photopolymer in a vat is selectively cured by light-activated polymerization as seen in figure 6 (ISO/ASTM 2018). This allows for constructing an object layer by layer to produce a precise product. Vat photopolymerization uses ultraviolet (UV) light to cure or harden the resin, and the object that is being made is moving downwards after each layer (Loughborough-University 2020). Lovo et al. (2020) further state that this AM process is characterized to have the best combination of resolution and surface quality among additive manufacturing processes.

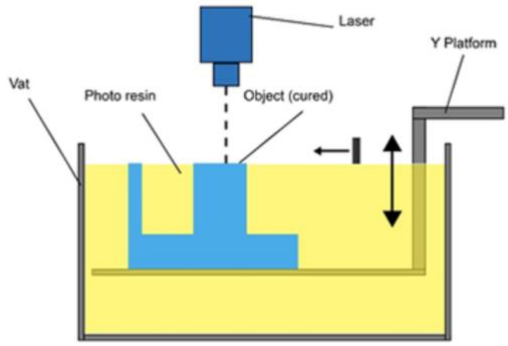

Figure 6: Vat photopolymerization (Loughborough-University 2020).

3.1.1.6 Powder Bed Fusion

Singh et al. (2020) stated in their paper that powder bed fusion is an essential AM technique. As illustrated in figure 7, it uses a heat source over the powder base material to create a product layer by layer, and this can either be a laser-, electron- or infrared beam to melt and fuse the material powder together. This process is further widely used in many industrial sectors, this is because the compatibility of every engineering material. Popov et al. (2021) highlight powder bed fusion as one of two AM technologies that are the most promising from the perspective of critical raw materials. They also imply this as the most widely used technique in the industry. DNV.GL (2017) provides information on how the building process occurs, and the processes illustrated in figure 7 to completely form the product.

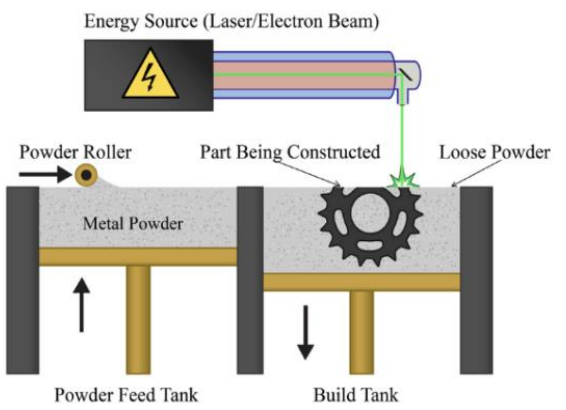

Figure 7: Powder bed fusion (3DEO 2018).

3.1.1.7 Directed Energy Deposition

According to DNV.GL (2017) directed energy deposition is the second AM technology that can produce metal products. The technique focuses on the use of thermal energy to fuse materials by melting as they are deposited (ISO/ASTM 2018). This is illustrated in figure 8, where you can see the object is produced with the help of an electron beam. The process is in principle, similar to material extrusion, but now the nozzle can move in multiple directions and is not fixed to a specific axis (Loughborough-University 2020). This further builds on Gibson et al. (2021) findings about the unique advantages and disadvantages that make direct energy deposition particularly suited for repair to an existing part. This generates industrial interest since it allows for further customization in addition to the products being reduces more rapidly and cost-effectively.

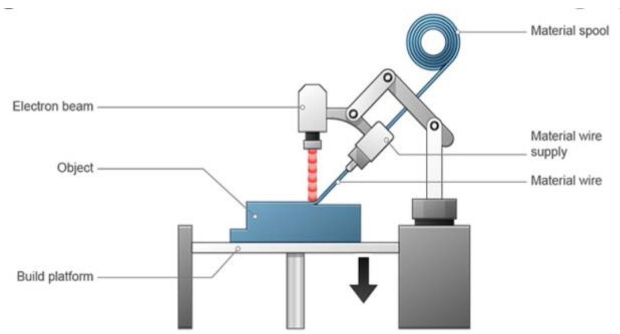

Figure 8: Directed energy deposition (Carlota-V. 2019).

3.2 Supply Chain

There is a significant amount of research conducted on the field of the supply chain, and companies have been focusing on different production methods to meet new demands in more efficient and cost- effective manner. A well-documented definition is that the supply chain as the flow of goods from raw materials to the end product is delivered to the customer. Chopra, Meindl, and Kalra (2013) define the supply chain as all the stages involved directly or indirectly towards fulfilling the customer's request. Moreover, the supply chain doesn't only include the manufacturer and suppliers but also related to transporters, warehouses, retailers, and customers. Furthermore, Weele (2014) described the supply chain as a series of companies whose consecutive stages of production of a financial product occur, from primary producer to final consumer.

Supply chain management was a set of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole (Handfield and Nichols 2002); (Jespersen and Skjott-Larsen 2005); (Mangan and Lalwani 2016); and (Christopher 2017). There is a significant amount of research conducted on the field of the supply chain, and companies have been focusing on different production methods along the way to meet new demands in more efficient and cost-affecting factors.

A central topic and trend in the field of supply chain is the rapid digitization of the different industries, or as it often is called industry 4.0 (Schniederjans, Curado, and Khalajhedayati 2020). The digitization of the supply chain has been pointed to as a valuable asset to increase flexibility and the scalability of the supply chain and productivity (Hahn 2020). The focus on future digitization or adoption of technology is also highlighted by Nagariya, Kumar, and Kumar (2021) as an existing research diversification in the service supply chain. Further on, Additive manufacturing technology is an integral part of increasing or improving the supply chain performance in the automotive industry (Yılmaz 2020).

Further on Dolgui, Ivanov, and Sokolov (2020) presents that digitalization, sustainability, leagility, and resilience have made significant progress in the research literature. They further demonstrate the need to look at all the before mentioned aspects as a whole and take advantage of the benefits of using all of them. By looking at these sources, we can see a growing interest in technology development and the impacts these possibly can have on the supply chain and the evolution of the future supply chain. By looking at these sources, we can see a growing interest in technology development and the impacts these possibly can have on the supply chain and the evolution of the future supply chain.

Further on the topic of resilience which we have studied in the literature review above, has been highlighted and especially with the eruption of the covid-19 pandemic. The pandemic has produced significant disruption and propagation in the upward supply chain and downstream supply chain. This has produced shortages in the supply of goods and raw materials, and the disappearance of demand of multiple types of products and materials (Li et al. 2021). Moreover, we have cases as the container ship Ever Given that got wedged in the Suez Canal on March 23rd, 2021. It caused a full stop of traffic through one of the most trafficked shipping lanes in the world, making international trade between Asia and Europe grind to a halt and building up a total queue of 422 ships waiting to pass through the canal before it opened on March 29th (Asmaa Khalil 2021). Disruptions like these have the potential of propagating through the supply chain, causing a ripple effect. This will be further conceptualized below.

3.3 Supply Chain Resilience

Mensah and Merkuryev (2014b) say that resilience could be defined as the ability of a substance to get back to its original state of form after deformation. In a resilient supply chain strategy, this is the ability to bounce back after disruptions that may affect the upper and lower streams of the supply chain. This is further substantiated by Sheffi and Rice Jr (2005) where they present that decreasing vulnerability means reducing the likelihood of disruption and increasing resilience. Additionally, in the article, they say that a company's resilience is a function of the company's competitive position and the responsiveness of its supply chain. Further on, to achieve strategic resilience, supply chains need to be less brittle and more adaptive through supply chain design, focus on business process management to enhance capabilities across the supply chain, visibility to demand and supply, supplier and customer relationship management, and infusing a culture of resilience (Pettit, Croxton, and Fiksel 2013).

According to Ponomarov and Holcomb (2009), resilience has three primary properties. (1) the amount of change that a system can undergo while retaining the same controls on structure and function. (2) The degree to which the system can organize itself without disorganization or force from external factors. (3) The degree to which a system develops the capacity to learn and adapt in response to disturbances. In the article, they further create a definition of Supply chain resilience based on multidisciplinary perspectives, which is: "*The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function*" (Ponomarov and Holcomb 2009).

Melnyk et al. (2014) present that supply chain resilience is the ability of a supply chain to resist disruptions and recover operational capability after disruptions occur. The article further says that to reduce the risk of supply chain disruption by focusing on either resistance or recovery, companies may not afford both. It ensures that the company sources from multiple suppliers would gain some resistance against disruption. The article presents that supply chain resilience is not something that exists, it is something that needs to be invested in. It further offers eight strategies that can increase resilience and its impact on avoidance, containment, stabilization, and return. The strategies are indirect investment, discovery, information, supply chain design, buffers, operating flexibility, security, and preparedness.

In the paper by Brandon-Jones et al. (2014), they use the resource-based view to understand how and when organizations can create supply chain resilience and robustness. The resource-based view says that the organizations may achieve a competitive advantage by bundling resources to develop capabilities. Further they argue that supply chain visibility is a crucial success factor to achieve supply chain resilience because it allows the organization to mitigate threats in their supply chain and that the effects of visibility will be maximized in a complex supply chain. The three main contributions of the article are that they further investigate the benefits visibility has on reducing risk by demonstrating the impact visibility has on disruption recovery. They extend the resource-based view analysis on supply chain visibility. Finally, they address the need for more theory application in supply chain risk management.

When cupelling supply chain resilience with additive manufacturing Naghshineh and Carvalho (2020) states that additive manufacturing can increase the supply chain's responsiveness by increasing the rate of products being produced. Further, AM technology and machines can be deployed on-site to decrease turn-around times notably. The paper further implies that the complexity of a supply chain is determined by the number of nodes in the supply chain. The AM technology can be achieved by removing parts of the supply chain with a more rapid production. In this research paper a conceptual model is presented to measure the impact AM adoption have on the primary dimensions of supply chain resilience without producing any results. The paper concludes that the article has created a framework to measure the main three dimensions of Supply chain resilience: proactive capability, reactive capability, and supply chain design. Additive manufacturing is also pointed out to be an essential contribution to the ability to rebound from a disruption (Ali and Gölgeci 2019).

3.4 Industry 4.0

Industry 4.0 also referred to as the 4th industrial revolutions is where it a focus on the digitalization, optimizations, and customizations of products (Butt 2020); (Ashima et al. 2021); (Fatorachian and Kazemi 2021); (Dilberoglu et al. 2017). Industry 4.0 can create new innovative process management, contributing to the supply chain performance regarding its flexibility and resilience through the supply chain (Fatorachian and Kazemi 2021). This can be done through techniques as automation, human-machine interaction, and value-added processes for the companies (Butt 2020). Industry 4.0 and AM can enable a higher level of flexibility and rapid production of customized products to meet customer demand. Further, it allows a digital-to-physical transfer because it is possible to visualize the product before it´s produced and thereby reduce the time to market (Fatorachian and Kazemi 2021). This brings us to the constantly changing business environment and customer demand. Companies today need to have a more flexible and responsive supply chain to handle new customized requests (Fatorachian and Kazemi 2021); (Ashima et al. 2021). This makes AM technology one of the vital components of Industry 4.0 due to the ability to create customized objects with new design and production methods (Dilberoglu et al. 2017). Further, we can see by implementing these concepts, companies can handle uncertain events better, there have also been shown vulnerabilities from some of the suppliers led by the impact of covid-19. These events might also because something called ripple effect that can increase the severity of the events impact further in the supply chain (Ivanov and Dolgui 2020).

The reasons behind the 4th industrial revolution are many. This revolution has resulted in vertical- and horizontal integration and reduction or increase in the number of suppliers to gain more real-time control of the supply chain (Butt 2020). Further, the technology-driven industry 4.0 have produced growth for cloud manufacturing production model where the goods can be made per customer prepossession. Multiple technologies are combined and implemented into traditional manufacturing processes to generate smart manufacturing (Ashima et al. 2021).

The digital-to-physical transfer capabilities in Industry 4.0, such as AM, enable rapid prototyping and reduce the time to market (Burnes and Towers 2016). Implementing these new digital technologies can advance data analytics applications to make better decision-making support when managing severe disruptions (Ivanov and Dolgui 2020). Besides improving responsiveness, AM can further eliminate the inefficiency associated with individual item production and physical transportation since products can quickly and efficiently be designed and produced (Fatorachian and Kazemi 2021).

There are also several managerial challenges for companies related to business model designs and the query about how to create, deliver and capture value in the implementation of industry 4.0 (Hahn 2020). There is also a concern about the company's organization, culture, and supply chain configurations (Patrucco, Ciccullo, and Pero 2020). This can be linked to more complexity than a simple integration in manufacturing as it must include transformation within the organization. To gain these technological advances, some might already use the technology in traditional manufacturing to produce a more fully integrated, automated, and optimized production flow with these new tools (Patrucco, Ciccullo, and Pero 2020). However, perhaps the most significant challenges companies face is reducing latencies and ensuring accuracy independent from industry 4.0 (Butt 2020).

4.0 Case Description

In this chapter the case of the thesis will be discussed, along with the focal firm and the supplier that is part of the case study. To ensure the anonymity of the case companies they will be referred to as focal firm, customer, supplier, tier 2 supplier. The information does not include references to keep the anonymity.

4.1 Case Company Description

The case company is a service provider to the oil, gas, and renewables industry. The focal firm provides a full range of engineering, procurement, and construction services. Some of the services the company provides are concepts, front-end engineering designs, detailed engineering, fabrication services, procurement, system completion, maintenance, operational and supports, and decommissioning. An impotent focus area of the company is on the evolution and development of new technology to optimize and improve established processes. The company do also take part in the industry on the NCS, in addition to other areas. With a wide range of products and solutions the focal firm is also located on multiple locations with a long history.

In addition to the focal firm, we have conducted interviews with the supplier of the focal firm. The company is a provider of pumping systems and have a wide range of product suitable for multiple industries. The company is the owner of the product that has been produced using AM and have used a tier 2 supplier to produce it.

4.2 Case Description

In this case, we look at the focal firm and the suppliers. The case is based on an offshore facility on the Norwegian continental shelf, which is owned and operated by the customer. In this project there is a pump going through routine maintenance that is getting a new impeller and our focal firm has acquired the impeller produced using AM through a request from the customer. In a joint venture, the supplier of the pumping system, the focal firm, and the customer found a solution where an impeller is produced additively. Both in AM and TM the tier 2 supplier produce the impeller in Europe. Therefore, when it was sourced produced in AM by all the involved companies in a joint venture, it is to achieve implementation of new technology and growth in the Norwegian oil and gas industry.

When the customer made a choice to source products as additively manufactured parts, the supplier got a request for quotation on claims made additively. The timeframe of delivery was more flexible for this project than for many others because the customer wanted the focus to be on knowledge sharing and knowledge building in the industry rather than focusing on the project's timeframe. The project is a trial project because the quality requirements are more challenging to achieve with additive manufacturing. The project timeline starts with planning, then there is an estimation and then studies where they find suppliers, look at technical requirements and the cost. Then there is the sourcing of products, production of the product by the tier 2 supplier, follow-up before the product is delivered, and then installed at the location.

When the decision was made, the production of the impellers was going to be done by an AM manufacturer in Europe. The focal firm, supplier, and the customer had close follow-up and more frequent meetings regarding quality, delivery, and production. The production is done by selective laser melting in a powder bed fusion machine, where the powder is added and melted in layers to produce a finished product. In addition to the part, a shaft is created simultaneously in connection with the product to do destructive tests on the produced subject, this is done to ensure that the finished products can withstand the given pressure and stress that the operation makes for a given time.

In this case, there were multiple productions of the impeller, and this is because the first print had malfunctioned on the machine that made the finished product too porous to be used. When this was discovered, the production was moved to another device because the machine malfunction could not be fixed promptly. When they started production in the other machine, there was first a problem with a section of the impeller, which led to the manufacturer making a test print to look at the support structure that led to the malfunction. When this was done, they started producing a complete impeller again. When they got a bit further on the impeller, they discovered a new malfunction that probably would be fine. Still, the manufacturer decided to produce another impeller free of malfunctions. When the production of the impeller was finished and the required tests were completed, it was then shipped to Norway. On arrival in Norway and to the appropriate site, it is sent by boat to the installation site before being installed by the company.

5.0 Methodology

This chapter will present the methodological approach for the master thesis and what framework and concepts have been used to solve our research problem. We will provide information on our data collection and the qualitative approach to our research problem. To answer our research questions in the best possible way, we will look at our research philosophy, the approach, methodological choice, the strategic choice to best answer our questions, the time horizon, and the techniques and procedures used to collect data. We provide solutions to relevant questions on data collection and our observations throughout the thesis by answering these questions.

5.1 Research Philosophy

Research philosophy is an overarching term that relates to the development of knowledge and the nature of that knowledge (Saunders, Lewis, and Thornhill 2012). Research philosophy is divided into four categories. The categories are positivism, realism, interpretivism, postmodernism, and pragmatism. Further on, if a research question does not note that a specific research question should be used, it will be pragmatic because it makes it possible to use multiple philosophies and that the importance of the meaning of an idea is its practical consequences.

Pragmatism states that concepts are only relevant if they support action. Positivism is that the collected data should be about an observable reality and look for regularities and casual relationships in the data. Realism is based on the idea that objects have an existence independent of the human mind. Realism uses a scientific approach to the development of knowledge. Then there are two types of realism, direct realism, and critical realism. Direct is that what the senses portray the world accurately, and critical realism is that what we sense is a picture of the world, not the world directly. Interpretivism, states that researchers must understand the differences between humans in our role as social actors. Postmodernism is the philosophy that focuses on the role of power relations and language (Saunders, Lewis, and Thornhill 2016).

In our case, it is a pragmatic research philosophy because it is external and starts with a problem and aims to contribute practical solutions that inform future practice in addition to making a difference for the organizational practice. The view is chosen to enable answering of our research questions best. We focus on practical applied research and look at different perspectives to help interpret the data. Further on, we adopt both subjective and objective views, and that this is qualitative research.

5.2 Research Approach

Saunders, Lewis, and Thornhill (2016) present three kinds of research approaches: deductive, inductive, and abductive. Deductive research approaches focus on a set of premises. The conclusion of these premises is derived through logic, leading to the decision being true if the premises are true. The inductive approach, on the other side, states that there is a gap in the logic between the conclusion and the premises and that the conclusion is judged to be supported by the observations made. In addition to the two, there is abductive reasoning. Abductive reasoning focuses on the conclusion instead of the premises. By looking at the conclusion, it can produce possible premises likely to be true (Saunders, Lewis, and Thornhill 2016). Our research is inductive because it generates theory and uses data to create a conceptual model.

5.3 Research Design

Research design is the general plan that shows how a person will answer the research questions (Saunders, Lewis, and Thornhill 2016). It contains the objectives derived from the research question, the sources of data for the paper, how to collect and analyze the data, and the ethical problems and constraints. The research design consists of purpose conception, literature review, approach to research, design frame and methods, and the decision about the kind and process of a case study. This is a linear approach. Thomas (2011) says that research is almost always different in social science because it needs to be recursive. By this, he means that the researcher must go back and forward as the researcher finds new things and refines the questions and decisions about the approach.

Yin (2018) states that a research design links the data to be collected to the initial questions of the study. Saunders, Lewis, and Thornhill (2012) present that there are three types of tasks in a research design. Research can either be an exploratory study, descriptive study, or an explanatory study. An exploratory study aims to clarify or help to understand a problem. A descriptive study can get a detailed profile of events, persons, or situations, and a descriptive study is often a part of an explanatory study. The last kind of study is an explanatory study which is a study that aims at identifying and explaining the relationship between variables.

The most straightforward definition between qualitative and quantitative research is that qualitative research categorizes data using words and quantitative research uses numbers (Reybold and Maxwell 2015). A qualitative approach brings into question the goal of "objectivity" in the sense of detachment from, and lack of influence on, the things studied (Reybold and Maxwell 2015).

This is like what we have done in our master thesis. The research has been conducted through the search engine Oria, Molde University College library search engine, and Google Scholar. But to provide the best solution, we are also using data from interviews to look closer at the resilience, and the differences between traditional and additive supply chains. To determine what kind of study our thesis required, we had to look at the research questions and our problem statement. We have described the problem statement as "How does additive manufacturing affect the resilience in a supply chain?" This leads to a case study approach. Yin (2018) presents that the basic categorization scheme for the types of questions is the series: "who", "what", "where", "how", and "why", and that for each formulation, there is a preferred research design. Further, it states that when the problem statement is framed as a "how" question, the research is more explanatory and likely to lead to a case study as the preferred research model (Yin 2018).

We have chosen an explanatory case study approach since collecting qualitative data was necessary to provide the best solution and explain or look at the relationship between additive manufacturing and supply chain resilience. The design can be a single-case study or a multiple-case study, and it can be an embedded or holistic case study. Further on Yin (2018) states that five components of a research design are vital in case research. These are: A case study's questions, its propositions, its case(s), the logic linking the data to the propositions, and the criteria for interpreting the findings. In our case, we started with a research questions, approved by the committee. We then started looking at relevant literature and then discussing it with faculty members. From this, we concluded with our research questions on additive manufacturing and supply chain resilience. Following this, we conducted a literature review on the two topics to collect relevant information.

When we decided to do a case study, we looked at a service provider in the oil and gas industry, and their delivery of an additive manufactured part to their customer. After conducting interviews with the company and collecting primary data, we analyze the collected literature and the primary data from the case.

5.4 Unit of Analysis

For our master thesis, we have chosen to be in contact with two companies to evaluate and analyze the impact AM has on its supply chain. In addition to conducting interviews with the focal firm, we interviewed their supplier to view other parts of the supply chain. Further, we will compare the traditional and additive supply chain to look at the resilience. This makes our case an embedded single-case study design because we will look at one supply chain with multiple units within this supply chain. Yin (2018) tells us that subunits of analyses may be incorporated within the single-case study, thereby creating a more complex or embedded design. This subunit often adds significant opportunities for extensive research, enhancing the insights into the single case.

5.5 Research Method

This part will present our research method and what we do to answer our research questions.

Yin (2018) presents that to select research questions, it is helpful to look at relevant literature for the topic that you have chosen, and by doing so, define relevant questions. Further on, a literature review is an appropriate way to collect data on a given topic. We have collected literature and done a literature review on additive manufacturing and supply chain to look at the current body of research and the research gap in the area. Further on, we have conducted a literature review on supply chain resilience to substantiate the connection between additive manufacturing and supply chain resilience.

By doing these literature reviews, we have collected data to substantiate our problem statement, "How does additive manufacturing affect supply chain resilience" and to get a better knowledge of the given topics. We further on use the literature reviews to answer and substantiate our research questions: RQ1. Does additive manufacturing affect the resilience of a supply chain? (A case study of the Norwegian oil and gas industry), RQ2. What challenges do companies face when implementing AM technology in their supply chain, and how will this implementation affect the traditional supply chain? and RQ3. How does the additive manufacturing model impact the supply chain resilience.

Moreover, we have collected primary data from the case company by conducting semi-structured interviews where the person we have interviewed has been provided with an interview guide with a selected number of questions that are possible to answer freely. When the interview has been transcribed, we analyze the answers to help solve our research questions.

In the end, we will analyze the collected data, both primary and secondary data, to try to make an impact model for additive manufacturing in the supply chain. In addition, we will look at the other research questions and try to answer them based on our interviews and the data collected from the literature. Using these methods, we will have produced new knowledge to the literature on supply chain resilience and Additive manufacturing.

5.6 Case Study Design

Thomas (2011) states that the case study method is research that concentrates on one thing, looking at it in detail, not seeking to generalize. Further, a case study is about the particular, not the general. According to Yin (2018) a case study is an empirical method that investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be evident. Saunders, Lewis, and Thornhill (2012) present that a case study explores a research topic or phenomenon within its context or several real-life contexts.

There are four case study designs: single-case holistic design, single-case embedded design, multiple-case holistic design, and multiple case embedded design (Yin 2018). A single case study looks at a specific case, while a multiple case study looks at multiple cases. The difference between an embedded and a holistic case design is that a holistic case design looks at a single unit of analysis. The other kind of case study is an embedded case study that looks at multiple units of analysis (Yin 2018).

When doing a single case study, there are five single-case rationales. These are critical, unusual, common, revelatory, or longitudinal case. A critical case is if a case is critical to the theory or theoretical propositions. An extreme or unusual case deviates from theoretical norms or everyday occurrences. Then there is the common case that tries to capture everyday situations and the circumstances and conditions of the problem. A revelatory case is when a researcher can observe and analyze a previously inaccessible to social science inquiry. The last one is a longitudinal case that studies a single case at two or more different points in time, trying to look at how circumstances or conditions change over time (Yin 2018).The time horizon can be two different kinds. This is a cross-sectional study and a longitudinal study. A cross-sectional time horizon is the most used research horizon and is when the research looks at a particular point in time or over a short time horizon. A longitudinal study looks at a longer time horizon and is often used to look at change over time (Yin 2018).

In this thesis case, we have a single-case embedded case design with a critical rationale. We are looking at one supply chain, at different departments within one company and with their supplier. It has a critical rationale because we try to underpin the effect of additive manufacturing on the supply chain. The case company is a service provider for the oil, has and renewables industry, and the supplier is a pumping system provider. The time horizon of the case study is cross-sectional because we look at a given project and the immediate effects as a "snapshot" in time and not over a given longer timeframe.

5.7 Data Collection

The data collected was done through interviews to collect primary data for our case study presented in the next chapter and some minor information sent from the company. We have collected literature from articles and books collected through online databases and the library at Molde University College.

In addition to the primary data collected from the company, we will use literature sources to help substantiate our findings. When looking for literature, we used search words as "3D printing", "Additive manufacturing", "Additive manufacturing in supply chains", "effect of additive manufacturing on supply chains", "additive manufacturing and resilience" "Additive manufacturing and supply chain resilience", “Supply chain resilience”, and similar, to look at existing articles and research to understand the field of our problem better.

5.8 Semi-structured Interviews

In our semi-structured interviews, we have conducted three interviews connected with our case company and their supply chain. In this case study, we have prepared an interview guide consisting of 12 questions for one of the interviews, one with nine questions and another with 16 questions. The interview guide is made to make it easier for the interview object to answer the question and in advance find the appropriate information to answer our questions. When we conducted the interviews, we asked follow-up questions regarding their answers. The interviews were conducted as online interviews because of today's situation with Covid-19 and are following the current GDPR rules in addition to being approved by NSD. After we finished the interviews, we have transcribed the interview. The finished material is sent to the interview object for control and to make sure that the person is satisfied with the interview result.

The first interview object is the responsible purchaser on the project. The person is responsible for purchasing the product, follows up with the supplier, the tier 2 supplier, other departments, and the customer. The purchaser is responsible for the follow-up of the delivery and coordinates with the different stakeholders in the process and the financial and contractual aspects of the purchase.

The other interview object is one of the responsible engineers on the project. He is responsible for the technical assessment and the technical qualifications of the product, production, and the supplier. Together with the purchaser, he will follow up the production process and is responsible for ensuring that the product meets the required qualifications specified by the customer.

The third interview was with two objects: a project engineer and an employee working for the supplier. The company produces and sells pumping systems to multiple industries, including the oil, gas, and renewables industry worldwide. The person is responsible for the given project and collaborates with the customer and is the link between their supplier (tier 2 supplier to the focal firm) and the focal firm. He is responsible for the quality aspect of the finished product. The other employee is the one that is mainly in charge of additive manufacturing in the company.

5.9 Validity and Reliability

Validity or validation is the process of verifying and checking that research data, analysis, and interpretation to make sure that the information is correct (Saunders, Lewis, and Thornhill 2016). Four tests are commonly used to test the validity of a research design. The test can also be used on case study design because it is a part of the larger body of research

(Yin 2018). The four tests are construct validity, internal validity, external validity, and reliability.

5.9.1 Construct Validity

Construct validity identifies the exact operational measures for the concepts being studied. To make sure that the research meets the construct validity, the concept has to be defined and that the concept and study can be checked by using the existing literature (Yin 2018).

5.9.2 Internal Validity

Internal validity is only used for explanatory and causal studies that try to establish a causal relationship between some conditions and that these are believed to lead to other conditions (Yin 2018). There are no past or recent events for the internal validity that could affect the way they answered. As far as we know, the participants have responded to the questions correctly and have no consequences of answering freely and accurately. One participant changed projects during the study, but this did not affect the result of the study.

5.9.3 External Validity

External validity tries to show if and how the findings of a case study can be generalized (Saunders, Lewis, and Thornhill 2016); (Yin 2018). This is not the case in our research, which is a specific study on the oil and gas industry on the Norwegian continental shelf. But some of the data and results would be the same. Still, the complexity of the product and the lack of knowledge and experience with additive manufacturing on the Norwegian continental shelf would probably be different from other areas of interest.

5.9.4 Reliability

Reliability demonstrates that the data collected in a study can be replicated with the same results (Yin 2018). When looking at the reliability in our case study, there should not be participant error because the interview objects were able to pick the time of the interview in advance, and they were presented with the questions at least three days in advance to have the possibility to think about and check the information before the interview. There should be no bias for the participants because they can have a confidential paper. In addition to that, they have enclosed locations either at work or at home. Further on, the researchers are objective and have no interest in pointing the view in one direction or another. There should not be a researcher error because if there are things, we are uncertain about, it will be checked, and the supervisor will look through the study. In addition, we have participation validation, where we have sent the transcribed materials from interviews to the interview-objects for validation, which then will be used as the primary data.

6.0 Findings

In our case study of the Norwegian oil, gas, and renewables industry on the Norwegian continental shelf we look at the implementation of additive manufacturing in the existing supply chain of the focal firm. In this chapter we will present the finding from the semi-structured interviews and data collection. From our interviews with the focal firm and their supplier we have found that the supply of finished products when produced with additive manufacturing machines have led to some difficulties on multiple levels.

6.1 First Interview

The first interview object was the purchaser at the focal firm. There was a wish from the end customer to source some of the parts involved in the project with additively manufactured parts. We further want to look closer into the time aspect and relevant cost for this type of adoption.

6.1.1 Delivery Time

From this interview we found that the delivery time with AM compared to TM production is much shorter. However, what takes time in this industry is the higher degree of testing and qualifications on the product to make sure it meets the required specifications. The degree of approving these tests and industry standard is similar for both TM and AM, however since this industry standard is quite new for AM and they have a higher competence with TM it would take longer time.

Another aspect is the production queue and machine failure that can impact the lead time. Within an industry that require high level of precisions this is something that might happen from time to time. During the production process an error could occur, creating longer lead time than estimated. The production time is shorter with AM compared with TM due to the production method. From the interview we found that there is a risk of error from both AM and TM, and that in this case there were some problems with the production. Therefore, the object highlights that this test-project is a necessary part of the technology implementation because it might produce benefits in reduced complexity and time savings for future projects.

6.1.2 Cost

When it comes to the cost of the production, it is more expensive to produce with AM than it is with TM as of now. The object presents that it is more costly the first time of production due to all the extra time and learning involved. Further the object addressed that what they learned from this project will result with a cost and time reduction for future projects. Another reason to the higher cost is linked to the available raw materials and production facilities at this point. To create knowledge sharing, and an increased knowledge on AM on the NCS, object 1 highlight that they have contributed to the development cost to benefit from the project themselves. In this project there has been a need to conduct meetings frequently and to do a closer follow up because of the lack of knowledge.

Moreover, we are informed that that there is not a significant change in the procurement process. We know that the purchase process of procuring the part is more or less the same for both production methods. This might have something to do with the fact that they are operating with the same supplier as before and that some of the processes are well established already, but in our case, it is the same. When there is an agreement on the contractual questions the order is placed, and it shifts to a follow-up phase to control the delivery of the product. However, there are specific processes established to conduct a purchase within this company and it would just affect the tier 2 supplier. This is again illustrates that there are some definite challenges when it comes to the technical competence with AM in the company.

6.1.3 Suppliers and Project Time

The object highlights that there aren't many suppliers that can produce this type of part. Further to produce this part there is a need for a high competence on AM in order to deliver a good end product for the customer. Similar traditional projects have led to a strong supplier connection between the focal firm and the supplier. It is highlighted that the close collaboration has been a key in this project. Further there is a strong indication that the availability of AM would increase with time. We are also presented that both the focal firm and the chosen supplier are new in this field of AM and that there is a motive for the whole supply chain to produce with AM to learn from it.

Whereas it is the focal firms' job to look over the end part and make sure it reaches the needed standard, it is their supplier job to produce according to the requirements given. Then again, it is the tire 2 supplier job to match their standard and so on. The standard is given by DNV which have presented an industrial standard for companies who wants to produce with AM in the oil and gas sector. The object highlight that delivery time, quality, and knowledge within this field is the most challenging.

There is a common interest for all the parties involved to gain as much knowledge as possible from this project. Therefore, there is no specific deadline or milestones on this project. We are informed that all parties in the process are working together to solve the challenges, and that they have frequent meetings with suppliers and customer. Further, it would be an external contract with suppliers, and there is no plan so far to implement AM in the focal firm. The object highlight that this is something that the focal firm could implement in the future. After the interview, we were informed that the lead-time of the product accumulated to 16 weeks in this project.

6.2 Second Interview

The second interview was with an engineer that worked on the project. From the interview we tried to acquire more knowledge on the quality of the end product, what types of material that is available in the market. In addition, we got information on the project and lastly on their knowledge of AM.

6.2.1 Quality and Material

The object focusses on the quality and that it might be an issue in the production process when using AM. It could need multiple attempts to produce a finished product with the right quality. Since there is a high need for quality it would be necessary to produce without or with a little degree of production error so the product can handle the pressure. Moreover, since this project was the first time any contract was given to AM for this firm, they did not calculate the material usage compared to TM. Instead, they focused on delivering a product produced with AM that is similar to TM part. However, when they order a forged object or something similar to the part that is additively produced, they would receive a lot of documentation from the whole process. This is called a manufactory record book and contains aspects that must be documented in the whole production process.

When looking at the advantages that AM brings, one of the positives was the reduction in production time and delivery time. We found that if additive manufacturing or casting have approximately the same risk and quality, the decision regarding which method to use would depend on how the delivery time is and how fast you would need the product. We also found that there is an increase in the time use for material engineering. The increased time use is a result of new technology adoption and new suppliers, that demands more time than for the already established TM.

Further, they highlight that there are different aspects that must be documented in order to be approved and are therefore overseen before choosing a supplier. There is a high level of control and documentation on processes and materials to make sure that the quality from raw materials meets the requirements. If a malfunction was to happen it is therefore possible to track the malfunction back to the production and interfere before it happens in other projects. When they have produced with AM a couple of times, they will have gained some experience and could therefore use AM as a production strategy. For future project between AM and TM it would depend on lead time and the complexity needed in addition to cost of the product.

6.2.2 Knowledge

Further with time and knowledge they highlight the possibility to home source the production. When it comes to the complexity and limitations of this production method, they believe that it would only be a matter of time before the adoption will increase, and that more products can be produced using it. The possibility to produce more extensive end parts would increase. This further leads us to the fact that they rely on the manufacturers' design program when it comes to performing simulations of the printing process to achieve the correct qualifications. This is again substantiated as they set the requirements and specifications when the product is ordered, and the supplier must provide documentation that the specifications are met. Lastly since this was the first project, the goal is to gather knowledge on AM as a production method and how it can be used to create benefits for future projects.

6.3 Third Interview

In our interview with the supplier, two persons were present, who worked at different locations and in different departments. From the interview we wanted to acquire knowledge on the production process and material usage, the lead time, adoption of AM, the collaboration, and the knowledge building and sharing.

6.3.1 Material Usage, Production, and General Lead-time

The first finding is that there is less material usage when using AM compared to TM as the production. In this exact case, the production is based on a model that is optimized for forging, which means that the print produces excess material, and therefore the product uses more raw material than if the product had been optimized for additive manufacturing. Further on, when the product design is optimized to additive manufacturing, the production time (printing time) will be shorter. When the product and method are approved, and it is ready for printing, there is a significant amount of time to save when using additive manufacturing compared to forging. The time it takes to make a sand mold and a core for the part, is the same as the complete printing of a product in a powder bed fusion machine.

In this case, the product has been produced using a powder bed fusion machine that melts powder with a laser. Moreover, they inform us when they produce a part using additive manufacturing, the supplier simulates every layer of the print to make sure that everything is built correctly in every layer. They further highlight that when a product is forged, there are usually problems with forging errors that result in a product that's not 100 % correct. When there is a need for machining to make sure that the product meets the right pumping curve that is sold to the customer, this usually needs multiple attempts for forged products. When they produced an impeller using AM for a different project, they had to machine the product on the measurements that were given, and the product met the pumping curve without further machining, this was quite impressive, according to the objects.

When the product has been printed, it is printed in the material Inconel 625. The outcome would be in the material quality super duplex when using traditional manufacturing techniques on a regular project. At the moment, there is a problem with corrosion, but this is not a problem for the product or where the product is going to be used, but it does not match the standard that usually is required for forged products. There are no immediate weaknesses in the product compared to a product in the quality super duplex. Still, the two employees believe that this product will last as long or even longer than a forged product because it is flawless. Further on, they highlight the need to optimize products for additive manufacturing and identify which products benefit from being produced using this technology, and what is better of being made using traditional methods.

When traditional production techniques produce this product (impeller), the lead time regularly is between 4-6 months, this depends on how much the supplier has to do. Compared to additive manufacturing, the lead time from traditional manufacturing techniques typically reduces by 50-60 %. An additive manufactured part regularly has a lead time of 8-10 weeks.

6.3.2 Adoption of AM

They further highlight that if the company had owned and operated additive machines, the lead-time would be significantly lower. According to the interview objects, the service leader in the company wants to have an additive machine at every location to provide service for the customers faster at the given location. The parent company has invested in a technology center investigating AM to build the knowledge and experience needed to implement the technology further in the company's system. They have started testing on materials, finishes, and prototyping.

There are multiple providers of the technology in the market, and the number is continuously growing. They highlight that to make sure the drawing/models of the product can't be duplicated or sold by the supplier they sign a nondisclosure agreement. Further the parent company has started looking at parts consolidation, but this is not something that the company has started looking at because the main objective as of now is to increase the knowledge and experience on additive manufacturing, and to please the customers.

6.3.3 Flexibility and Collaboration in the Supply Chain

Because the company is relatively new at using additive manufacturing in their production, there is not the same level of knowledge and experience in the different departments which makes it harder for the employees in the company compared to a traditional process. This is because for a forged product, they know the specifications better and the processes involved. When they use additive manufacturing, they don't have the same experience and therefore use longer time / the processes are not as flexible. They highlight that the standards for additive manufactured parts on the Norwegian continental shelf are fairly new, and the employees are not as familiar with it.

In addition, the AM suppliers are often located in Europe or other Nordic countries where there is not the same level of knowledge on material and process requirements, and standards of the oil and gas industry. This has made the process a bit harder because they don't have the same level of knowledge as the suppliers that use traditional manufacturing techniques, because they have been suppliers for a more extended period. They also highlight that the specifications and criticality of the product define the difficulty of testing and production. For our case, the product is highly complex and has many requirements. There is a Charpy test that requires that the product be cooled down to -101 degrees Celsius before they check the energy absorption during a fracture. This an example of a test that the supplier is not familiar with that creates some difficulties in the process. The objects inform us that the classes are defined as AMC-1, -2, -3, and the complexity and difficulty increase the higher the class is.

When asked about the collaboration between suppliers and customers in the supply chain, they inform us that the cooperation was good with both the customer and their supplier. In the case of the supplier, as we mentioned above, there has been a need for knowledge sharing, and the collaboration has been very good. They highlight that the need for follow-up will be decrease when they have sourced products multiple times and that it will be the same as sourcing a traditional produced part at some point in time. They further informed that the collaboration with the customer has been good.

6.3.4 Production and Lead-time for this Specific Project

When looking at the production of the impeller for this specific project, it started with a 100 % production using a powder bed fusion machine by the supplier. When the product arrived at their facilities, it was clear that the product had a texture like a sponge in some segments, which indicated that something was wrong with the machine. Then they switched to another device and started printing a new product. After they had printed approximately 50 % of the product, they noticed a printing error. They decided to produce a test print of half the product to check the support structure within the printed product. When this was done and the product was good, they started printing again. When the print was nearly complete, they discovered a new error. According to the interview object, this was not a significant problem for them, but their supplier did not want to deliver a product with faults. This resulted in a new print with no errors.

The failed prints led to a total of two complete prints and three test prints (one test print and two prints that were stopped because of errors). They further highlight that the development of products and processes usually takes longer than if it is a known product or process. Moreover, they emphasize that this kind of impeller is high-tech and high-end in the world of additive manufacturing.

7.0 Comprehensive Analysis of Interviews

In this chapter we will compare the results from the different interviews where this is possible.

There is a general agreement between interview two and three that the process of sourcing a product as an additive manufactured part is as flexible compared to a traditional manufacturing process. However, object 1 state that the procurement process when sourcing additive manufactured parts is less flexible than sourcing traditional manufactured parts mainly because of the knowledge- and experience-gap regarding AM. It is further highlighted that the focal firms' expertise is in fields like automation, electrical engineering, and structural engineering, and is harder to take advantage of because they do not have the experience with AM. This has resulted in the focal firm having to rely on the supplier. Further object 1 highlight that because of the knowledge regarding the process and the quality is a challenge since they are new to AM, and that this is somewhat time-consuming. Moreover, objects 3 also observed some difficulties. They expressed that there are challenges in the production itself, but according to them, there is not much difference for them in the processes.

Further, the knowledge of AM would be provided mainly by the supplier and the tier 2 supplier. One of the reasons for this is their experience with AM and the knowledge of material and quality that is needed to produce with AM. Object 2 addresses that something which was designed 10-15 years ago is not created to be produced with AM in the future and that it therefore could take time before products produced with AM reach a high availability.

The lack of knowledge and experience is constantly being mentioned in the interviews associated with this case. This is one of the earlier projects where the supplier has used additive manufacturing, and this is the case for the focal firm and their customer. As mentioned, this has created problems for the focal firm because they cannot make use of the vast knowledge in their company. According to interview object 3, there is also a knowledge gap or lack of experience at the tier 2 supplier that conducts the printing of the product. At this supplier, the problem is that the company is not experienced in delivering products to the Norwegian oil, gas, and renewables industries that have specific requirements on material testing. They further give an example of a Charpy test where the material strength is tested. In the test the product is cooled down to -100 degrees Celsius before testing to ensure the material quality. They later presented that the knowledge gap will be filled because of the knowledge sharing between the industries. The knowledge sharing would make the process as easy as a traditional process where the supplier and the customer know what to expect and understand what is required to meet the specifications. In addition, when we asked if they were looking at parts consolidation in their supply chain, that was not something that they had not investigated, but it could be an opportunity for the future. The parent company of the supplier had done a test on part consolidation.

Moreover, object 1 in the focal firm highlights the excellent collaboration between the supplier and the customer in this project. Further on, the collaboration between the supplier and the tier 2 supplier was excellent, and the process was very communicative. We did not get to do interviews with the tier 2 supplier because they did not answer our requests. By the interview with the supplier, we get an image of their collaboration. Overall, in the supply chain, we got the impression that the collaboration is better in this project than in a traditional manufacturing project. As we mentioned in the findings, it is a new field for most of the people involved and where therefore some insecurity on how to move forward. Early in the project it was decided to have a close follow-up to ensure that all the participants in the project were well informed and understood the challenges occurring. Further, object 1 highlighted that the project did not have the same type of time horizon that a standard project would have.

Moreover, when looking at the adoption of additive manufacturing within the companies, the supplier presents that they are looking at it, and both highlight that it is a wish from the companies to adopt in the future. The supplier wants to have a machine at their service locations globally to efficiently deliver spare parts for customers at the site it is needed. They highlight that this is not going to happen very soon. Still, the suppliers parent company has started investigating AM, and has established an additive manufacturing technology center to create knowledge and experience on the processes, in addition to look at what products are possible and efficient to produce using AM. The supplier highlights the need to optimize products for additive manufacturing and that not all products will benefit from additive manufacturing. Therefore, establishing knowledge of AM is essential for the supplier.

When we look at the production in this project, we have observed from the interview that the product itself is optimized for traditional manufacturing. Since it is not optimized, and thereby the material used when printing the product, and the printing time itself is not optimized. This results in more raw material usage during production, that later must be machined off. When we look at the specific product, interview object 3 estimates that the physical building of a sand mold and a core to forge the product takes approximately the same amount of time as it takes to print the product using AM. Based on the company's experience in additive manufacturing and traditional manufacturing, they generally experience a 50-60 % reduction in lead time. Where an additively produced part has a general lead time of 8-10 weeks, a forged product has 4-6 months. The interview objects also informed us that there is availability of producers in the market and that the number of suppliers was continuously increasing. Further on, to make sure that the product is not copied because the tier 2 supplier already have access to the model of the product, they use nondisclosure agreements with the suppliers.

When we look at this case study, the printing process did not go to plan and led to delays. This was first because of a machine malfunction, as mentioned in findings. Then, various printing errors led to a quality of the product that did not meet the customer's requirements. This led to the printing of 2 complete prints and 3 test prints. This might have something to do with the fact that there is a lack of knowledge from the tier 2 supplier to build something with this complexity and geometry. The supplier further highlights that the product that has been produced is very high tech and high end compared to other products produced using additive manufacturing techniques. The supplier believe that the product will be as strong and last as long as a product in the quality of super duplex, which is the requirement for forged products. As we can see from the general lead time of a forged impeller usually accumulates to 4 months, even though it can take longer up towards six months. The finished printed product in this project had a lead time of 16 weeks because of the printing malfunctions during the process.

As of now, the price of an additive manufactured part is significantly higher. According to object 1 there are not a lot of producers available. However, Object 3 highlight that there is availability in the market, and it is a field that is expanding. Further on, for this specific project we are looking at in the case study, the price was reduced because both got the ability to learn and gain experience in using additive manufacturing in their supply chain.

8.0 Discussion

In the discussion chapter we will compare the findings from the comprehensive interview analysis with the literature that we have collected throughout the literature review in addition to the conceptual framework. By doing this we will answer our three research questions, which are presented in the following sub-chapters.

8.1 RQ1: Does Additive Manufacturing Affect the Resilience of a Supply Chain: (A Case Study of the Norwegian Oil and Gas Industry)

In RQ1 we analyze the data from the findings and connect it with literature and concepts from theory to see if the implementation of AM in supply chain would affect the resilience of a supply chain. Our case study investigates a project in the oil and gas industry where there will be routine maintenance on an offshore facility on the Norwegian continental shelf.

According to Mensah and Merkuryev (2014a), supply chain flexibility is an important part of increasing the resilience of a supply chain because it can reallocate resources to meet changes in demand. According to our findings, using additive manufacturing in the supply chain generally shortens the product's lead time by 50-60%, which results in the possibility of meeting the changes in demand at a more rapid pace. According to Rinaldi, Caterino, et al. (2021a), the reduction of transportation requirements due to adoption of AM could bring both economic and environmental benefits. There is also evidence that the faster production process combined with the simpler supply network reduces the supply chain lead time (SCLT). It has been estimated a SCLT reduction up to 60% switching from conventional to additive manufacturing. This is further substantiated by our findings from the interview, where they observe a lead time of 8-10 weeks for parts produced by AM compared to 4-6 months when using traditional manufacturing as forging.

Further on, Christopher and Peck (2004) highlight the importance of having a large supply base to have the possibility to change between suppliers. This is not only because of the opportunity to source the shortest lead time but also because a focal firm can look at the supplier's risk strategy. This is further substantiated by Belhadi et al. (2021) that highlights the need to have suppliers at multiple locations or at least suppliers that have facilities at various locations. In our case, the possibility of printing, in addition to the traditional manufacturing, makes the supplier base larger because they can source from both supplier bases. Further, by increasing the flexibility by reducing the lead time and the increased visibility because of the increased collaboration and follow-up that the introduction of AM has had in our case, the resilience has grown as a result. It can also be argued that the agility has increased because of the new production method and the ability to produce faster. These three are highlighted by Pettit, Fiksel, and Croxton (2010) to be essential factors in achieving resilience.

Belhadi et al. (2021) further presented that collaboration and coordination on technological development and implementation are essential to developing an agile, sustainable, and resilient supply chain. By looking at our case, and as found in interview one, the decision to source product as additive manufactured parts was a decision to increase the industry's technological development. The collaboration was good, and there was a higher degree of focus on finishing the product together instead of having strict time horizons and milestones. This has led to knowledge building on additive manufacturing for all levels of the supply chain. In addition, the decision to source products produced with AM has led to establishing a broader supply base, as mentioned above, and the ability for the tier 2 supplier to learn the quality and specifications requirements that exist on the Norwegian continental shelf. We further found that the material usage can be decreased significantly, but the product must be optimized for production using AM for this to be true.

The interview subjects have, as mentioned, highlighted that after more products have been sourced using AM, the suppliers will have more knowledge on which requirements exists. This will eventually create the ability to deliver products without a high level of follow up, as the situation is today for traditional sourced products where the suppliers already have this knowledge. According to Scholten and Schilder (2015), the ability to do information-sharing, joint relationship efforts, mutual knowledge creation, and collaborative communication creates more visibility, velocity, and flexibility, which further improves a supply chain's resilience.

As we found in the interview with the supplier, there is an interest in implementing additive manufacturing on site at their service locations. The reason behind this is the fact that they then would have the ability to produce spare parts on site and on demand just-in-time. This process has not been started, but it is reasonable to believe that after the experience and knowledge is increased, this would be a possibility. We can further see that this is also an ambition of Company B as mentioned in the introduction. they have started testing this at their facilities. They have the goal of creating a digital inventory to meet the demand of spare parts in their supply chain with just in time production. Holmström and Partanen (2014) highlight that this can significantly reduce the logistics costs, inventory holding costs, and the risk of stockouts. The project is a collaboration between multiple companies. With this project they hope to be able to provide spare parts that otherwise are not available, because of the age of the product or similar. We can see from the article by Khajavi, Holmström, and Partanen (2018b) that a hub system is preferable instead of a fully distributed system. This will according to our interviews be the kind of configuration they would use, but that the production is done closer to their customers. The oil and gas industry is an industry that requires a high service level, because downtime on the production facilities are extremely costly. Rinaldi, Caterino, et al. (2021a) suggest that a decentralized AM system with a high service level and a flexible environment AM is the greenest choice compared to traditional production methods.

As a result of the implementation of additive manufacturing in the oil and gas industry, we can say that the supply chain has gotten more resilient. There is an increase in flexibility because of the decrease in lead time for an additive manufactured part is lower than for traditionally manufactured parts. Further on, the technology development and the increased collaboration and communication between the actors in the supply chain increase visibility, velocity, and flexibility. Even though the lead time for this specific case is the same as the lead time for a traditional part, this will generally not be the same. After the industry has used additive manufacturing in their supply chain more, it is reasonable to believe that the entire process will become more flexible and that there will not be the same need for follow-up.

8.2 RQ2: What Challenges do Companies Face when Implementing AM Technology, and How will this Implementation Affect the Traditional Supply Chain

When we look at the challenges affecting the supply chain when they implement additive manufacturing and how it will affect the traditional supply chain, we must first look at the difference in the supply chains. In our case study, when looking at the supply chain of the Norwegian oil and gas industry. We observed that a traditional supply chain has a customer with a frame agreement with a supplier that provides engineering, purchasing, and installation for the customer, which is the focal firm. This supplier then sources the product from a supplier that owns the product that is being sourced, in our case, this is the supplier of the pumping systems. This supplier then uses a producer that forged the product that is being supplied. The product gets forged by the producer, machined, and controlled by the pumping system supplier, then it is delivered and installed by the service provider (the focal firm), and then it is used by the customer. When we look at the same supply chain that uses additive manufacturing instead of forging, the only difference is that the product is sourced from a supplier that prints the product. The product is still owned, tested, and machined by the product owner (the pumping supplier).

Rinaldi, Caterino, et al. (2021a) and Kubáč and Kodym (2017) agree that the production volume affects the influence the economic impact additive manufacturing has on the supply chain because it cannot compete with the economies of scale that big quantities that traditional manufacturing techniques can. Luomaranta and Martinsuo (2019) present that AM can challenge traditional manufacturing processes or complement the conventional process. It's not so that companies need to choose between these two in the future but simply implement where it's needed. This is also highlighted in our findings from the interviews, where they highlight the importance of finding out which products benefit from being produced by using additive manufacturing techniques.

Machine and material prices can be higher for additive manufacturing than traditional processes (Verboeket and Krikke 2019a). This is supported by our findings where the cost of an additively manufactured part is higher than a traditionally produced part. They further state that IT infrastructure might be a challenge due to the need for a secure line if there is planned to enable the sharing and retention of digital files for production. Rinaldi, Caterino, et al. (2021a) and Kubáč and Kodym (2017) agree that the production volume affects the influence of the economic impact additive manufacturing has on the supply chain. The reason is that it cannot compete with the economies of scale with big quantities like traditional techniques can.

Moreover, the fact that there is a possibility to move the production to establish on-site production or a hub-configuration as described by Khajavi, Holmström, and Partanen (2018b). The hub configuration is also highlighted as a wish for the supplier in the interviews. The hub-configuration for the supplier is to meet demand of spare parts in a closer proximity, and to make the possibility to meet the demand just-in-time. Rinaldi, Caterino, et al. (2021a) in addition found that for supply chains which needs a high service level and flexibility a decentralized AM hub system is the greenest choice.

Company B has also started investigating the ability to establish AM hubs to meet demand for spare parts on the Norwegian continental shelf. This strategy is a move to create a digital inventory, which also is pointed out by Verboeket and Krikke (2019b) to be a potential to eliminate a physical inventory. If the digital inventory and high degree of AM hubs, gets fully implemented, it could affect the supplier market using traditional methods significantly. It could remove much of their demand and shift their production to sales of 3D-models that the customer prints on their own facilities.

When looking at our findings from the interviews, we found that the main challenge when adopting additive manufacturing in the supply chain is the knowledge of the process. This includes the quality that a finished product has, the knowledge of the printing, and what materials are required and approved for given products. This creates the need to do knowledge sharing throughout the supply chain. The purchaser at the focal firm informs us that sourcing the product is not as flexible because the lack of knowledge and experience regarding the production method and quality creates the need to have more follow-up and more meetings, knowledge-sharing and commutative collaboration during the process.

Additive manufacturing is an essential part of the fourth industrial revolution (de Brito et al. 2020) & (Verboeket and Krikke 2019a). It can be an important part of the technological implementation efforts in industries. Further on, AM allows to design a shorter SC and offers a substantial saving in the supply chain lead time (Rinaldi, Caterino, et al. 2021b, de Brito et al. 2020) & (Verboeket and Krikke 2019a). Another advantage that Additive manufacturing can create is its parts consolidation, which can improve the supply chain by eliminating suppliers or installing and delivering of multiple parts (Son, Kim, and Jeong 2021).

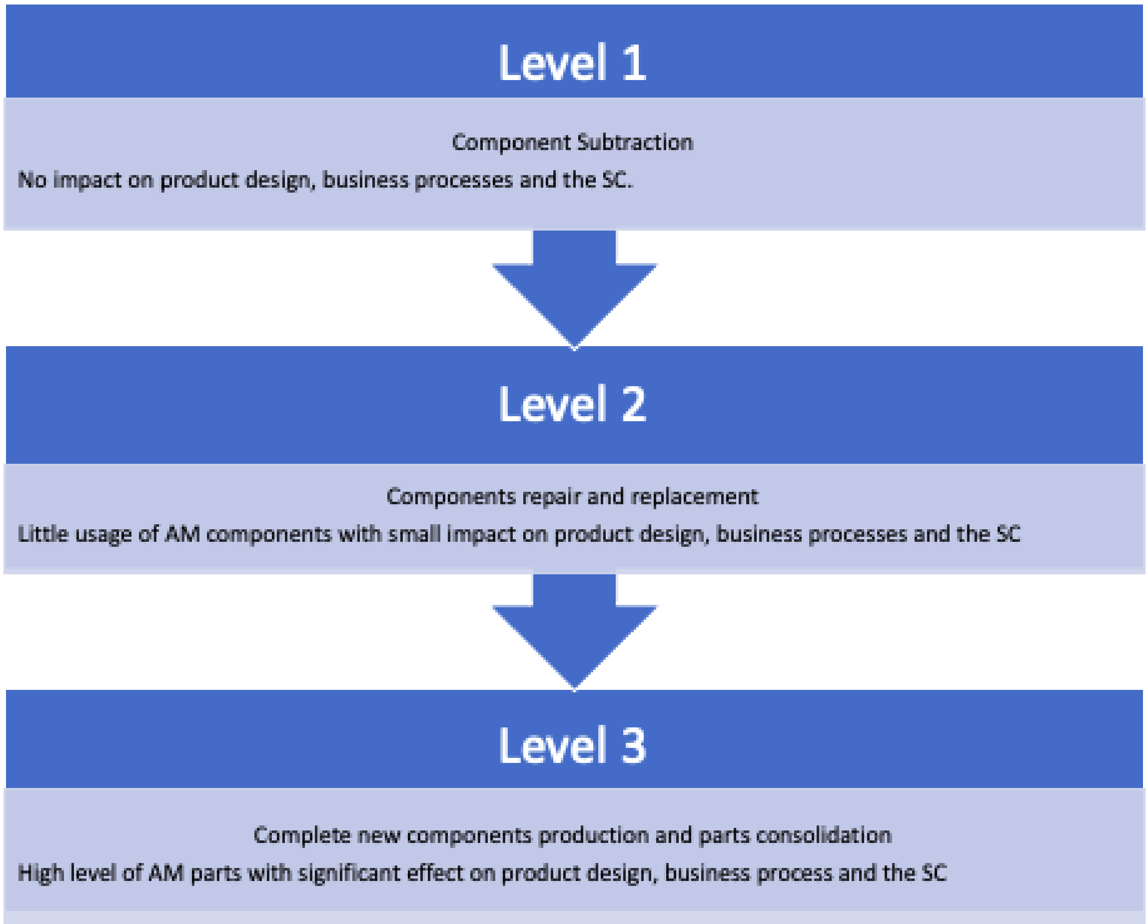

Figure 9 - AM logistical Impact Model for Manufacturers

When we look at the model for logistical impact model for manufacturers (Figure 9) adopted from Nyangari (2020), we can see that the first level is to adopt additive manufacturing on a small scale on non-critical products. The next level is to use additive manufacturing on complete component replacement. At this level, additive manufacturing influences the supply chain actors with complex structured products or products that need customization. The final step is parts consolidation, which can eliminate the number of participants in the supply chain and supply chain cost.

For the product in our case, we can see that it is situated in level 2 of AM adoption, and they are taking advantage of the printer's ability to produce complex products. Holmström and Gutowski (2017) state that the most significant challenges with implementing additive manufacturing are the slow speed, high equipment cost, and the fact that it often needs a considerable amount of post processing. For the part produced in this project, the equipment cost is high, the production speed for ETO products is shorter, and the product will always need post-production processing. In the paper by Verboeket and Krikke (2019a), AM can create traditionally impossible, complex, or just expensive products due to the change from material removal to layers-on-layers strategy.

The main difficulty with implementing additive manufacturing is the fact that there is not enough knowledge on AM. This leads to closer collaboration and follow-up with the supplier. When the implementation is finished, and the process has been conducted numerous times, we think this element will be eliminated. Further on, the fact that the cost is higher for additive manufacturing leads to a more significant barrier to entry. Still, implementing it will most likely have advantages for the organizations that do it.

We can see that the significant challenges companies face when implementing AM in their supply chain is the technical aspects of the process and product. Moreover, the need to establish a new supplier base (additive manufacturers) creates the need to teach and inform them about the requirements and specifications that are challenging on the NCS. Further on, the adoption of AM in the industry can potentially have a disruptive effect on the traditional supply chain that risks losing customers. In addition, the establishment of hub configurations and digital inventory can remove the need for production on their facility, removing some of their income.

8.3 RQ3: How Does the Additive Manufacturing Model Impact the Supply Chain Resilience

Earlier, we have discussed how AM affect the resilience of a supply chain, now we will present how a potential AM impact model would look like based on literature and data collection. From the literature, we know that supply chain resilience is the capacity of a supply chain to persist, adapt or transform in the face of change (Melnyk et al. 2014). We also know that there are various ways companies can handle new trends and demand in the marked, which we will investigate further in this chapter.

Melnyk et al. (2014) presented eight strategies that can increase resilience and its impact on avoidance, containment, stabilization, and return. These strategies are described as indirect investment, discovery, information, supply chain design, buffers, operating flexibility, security, and preparedness. Pettit, Fiksel, and Croxton (2010) also brought a foundation with the description of vulnerabilities and a set of capabilities that can be linked together to best match the vulnerabilities that a company or supply chain is facing. The capabilities are flexibility in sourcing, flexibility in order fulfillment, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, organization, market position, security, and financial strength. This is further supported by Naghshineh and Carvalho (2020) that adds three dimensions of supply chain resilience to: proactive capability, reactive capabilities, and supply chain design. Verboeket and Krikke (2019a) also address the significance of supply chain design as a strategic issue for any company. Therefore, we have adopted the conceptual model from Naghshineh and Carvalho (2020) and implemented further factors that produce capabilities that affect supply chain resilience in figure 10.

In our findings, we collected some significant factors on AM adoptions within this industry. These findings are on the knowledge within the field both in creations and sheering, lead-time in manufacturing, collaboration, home sourcing, hubs, and supplier base. Moreover, the aspect of digitization of the supply chain, which has been pointed out as a valuable asset to increase the flexibility, scalability and productivity of the supply chain (Hahn 2020). By adopting AM in the production process there might be possibilities to reduce the time it takes to recover after a severe event. In the past years we have seen some devastating impact disruptions as the Covid-19 virus, and the blockage of the Suez-canal which can disrupt the demand and supply in multiple points in a supply chain when sourcing from other continents. The conceptual model from Naghshineh and Carvalho (2020) divides the adoption into proactive capability, reactive capability and supply chain design. Further they describe that it is possible to improve the supply chain responsiveness by using AM either by getting the product faster to market or by manufacturing the product more quickly.

8.3.1 Proactive Capabilities

Proactive capabilities, considers the factors and capabilities that makes it possible for a company to be prepared for disruption. We know from Mensah and Merkuryev (2014a) that by increasing the supply chain flexibility, a company can better respond to a change in demand and have capabilities of reallocating resources when it is needed. Which again is accomplished by having good relationships and communication with the suppliers. This is substantiated by the interviews that inform us the collaboration in the project where they have adopted AM is improved compared to a traditional project. Object 1 and 3 also highlight that by creating a platform where it is possible to store knowledge about the processes, reduces the room for error next time and makes it easier to make quick decisions if something occurs. Scholten and Schilder (2015) highlights the longer the collaboration between different companies, the better the chain's resilience is because of the inherent increase in visibility and velocity.

Another benefit of adopting AM is that it can produce the exact measurement that the product needs to be operating in the optimal way (Ivanov and Dolgui 2020). Due to the technology behind AM and TM, there is a reduction in excess and overproduction. From object 3 we know that in TM there is a higher need of excess material due to the long production time and higher risk of produce something too small to fix, whereas AM on the other hand is a more precise production method. However, we also know that the design is not optimized to AM yet, and do therefore have excess material since the product is optimized for traditional production. Object 2 also implies that since the production methods are mainly focused on TM, there would be some delays until AM can be integrated further as product designs need to be adopted for AM. From the literature, we know that this can be established by either a CAD drawing of the product or by scanning the existing product design (Verboeket and Krikke 2019a). With time, we have also observed that the increased focus on AM has grown, and that new suppliers are establishing rapidly. Further by learning more within the process of AM the number of potential attempts would go down as the knowledge within the field would increase. A reason for this is the complexity of this part and that the need of qualification related to the product.

The possibilities of reductions in lead time and production time are significant, and as we have found from interviews, the lead time have the potential to decrease with 50-60%. This can again limit the need for a significant inventory and safety stock as the production time is reduced (Ivanov, Dolgui, and Sokolov 2019). Object 1, on the other hand, highlights that due to all the new processes, it would take longer in the beginning as all the standards need to be learned. Eyers et al. (2018) also highlight the possibilities AM can bring as products can be produced with higher complexity than before and the allowance of part consolidations. Further, by positioning the production closer to the service centers or end customers, the lead time and logistics cost can be reduced (Boer, Lambrechts, and Krikke 2020). From the findings, we know that the production is something the companies consider moving with time and cost as it is a part of their strategy. Further on, we know that industry

4.0 and AM can enable a shorter time to the market as it removes and integrate earlier processes (Fatorachian and Kazemi 2021).

Scholten and Schilder (2015) conducted a literature review on supply chain resilience and found out that the most frequent constructs are efficiency, redundancy, collaboration, flexibility, velocity, and visibility. In figure 10 we have therefore included these as well as findings from the interviews.

8.3.2 Reactive Capabilities

When it comes to adopting AM in reactive capabilities this is the effects that lead to increased response and recovery for a company. A finding from the interview are the thoughts around the project when it comes to learning and that the evaluations happens simultaneously with the ongoing project. The evaluation is to see if the dynamic has created a quicker response or recovery in the market and learn from the production (Sheffi and Rice Jr 2005) and (Mensah and Merkuryev 2014a).

By adopting AM companies can move towards digital inventories and create a base for digital products instead of physical products. The implementation of digital inventory would reduce the inventory and holding cost, and affect the ability to recover because of the lead-time reduction as a result of production and transportation (Boer, Lambrechts, and Krikke 2020) and (Holmström and Partanen 2014). Another reason to introduce digital inventory is to give the customer more opportunity to impact the design and qualifications (Verboeket and Krikke 2019b). Due to the growth in technology and the awareness of AM, the supplier base would increase to meet new demand. In our case, we have observed the growth of producers within this field, and according to the three objects, there is continuous development within both raw materials as well as AM suppliers.

Other factors that might change the capabilities is the supply design where we have introduced part consolidation before. However, we know from figure 9 that this is more of the final step of implementing AM as it allows for new complex part to be produced. This final step creates a new freedom in design that also allows AM to combine an assembly of parts into one part and therefore reduces the required assembly work, cost, and time (DNV.GL, 2017). When it comes to our project it would require more knowledge within the field before assessment of this is done. Another vital aspect of this project is being highlighted by object 1 and 3 regarding the importance of good communication. This is further supported by literature where Remko (2020) address the importance of the focal firms involvement in the companies supplier to make sure that they can meet the demand.

8.3.3 Supply Chain Design

Lastly, the final aspect is supply chain design. Christopher and Peck (2004) describe the supply chain can provide tools that can help companies create a resilient supply chain. It is shown by understanding the network to identify processes and critical paths. One of the most significant findings is related to what object 3 said about the thoughts of home sourcing. As this manufacturing process allows for closer production to the end customer, they highlighted the possibility to move the production to their own facilities. In a normal setting there will always be a lead-time because of the need to transport products from supplier to customer. With the establishment of AM-hubs or home sourcing this lead-time could get significantly decreased. Naghshineh and Carvalho (2020) implies that we can alleviate node criticality by decreasing the dependency on tier 2 suppliers by using AM. However, all the interview objects highlight that their biggest concerns are on the lack of knowledge within this field, and the insecurity in the usage of the industry standards providing concerns on the level of adoption.

Since the first industrial revolution, there have been implemented new production methods and machines to meet new demands. This has also forced companies to redesign the supply chains and business models to adopt the market and focus on the environmental impact. Recently we have seen cases of disruption as Covid-19 pandemic, and the blockade of Suez-canal created enormous difficulties within today's SC. Due to these events, some companies might reconsider the production locations due to the increased risk associated with transportation. This might process significant disruptions and disruption propagation in the upstream and downstream supply chain. With shortages in the supply of goods and raw materials and the disappearance of demand of multiple types of products and materials (Li et al. 2017).

8.3.4 Conceptual Model

Figure 10 demonstrates our conceptual model of the effects additive manufacturing has on the resilience of a supply chain. The model is adopted from Naghshineh and Carvalho (2020) conceptual model and extended to improve the model. We have included seven effects and strategies that we have found improves the resilience of a supply chain.

Lead-time reduction, increased collaboration, and knowledge creation and sharing are capabilities that improve the proactive capabilities of the supply chain. The introduction of AM in the supply chain can produce a just-in-time production of parts, where they can be printed. According to Mensah and Merkuryev (2014b) this can increase the transparency and trust among supply chain partners. Further Christopher and Peck (2004) state that through collaboration it is possible to improve the flexibility of the supply chain as a result of increased visibility and velocity. Scholten and Schilder (2015) further highlight that through collaborative communication, information-sharing, mutual relationship efforts, and mutual knowledge creation a supply chain can improve their visibility, velocity, and flexibility. This further improves the supply chains resilience. Sabahi and Parast (2020) and Gölgeci and Ponomarov (2015) propose that innovation improves supply chain resilience because of the ability to find new solutions and adopt new technology. Which in our case is the adoption of a new technology to improve the knowledge creation and sharing between the actors in the supply chain. The findings from the literature are also supported by our findings, where there has been an excellent collaboration between the companies involved in the project. By conducting a closer follow up between the companies, the visibility and velocity has increased. Moreover, the reduction of lead-time makes it possible to react quicker to a disruption, which again improves the resilience. With the potential to move production to AM hubs, or implement AM on their own service facilities Interview object 3 will dramatically improve the lead time to supply their customers with spare parts. Therefore, we have included these three as important parts to increase the proactive capabilities of supply chain resilience in our conceptual model.

Supplier-base increase refers to the increased number of suppliers because of the introduction of an additional production method. When looking at the oil, gas, and renewables industry they now have the potential to source products from both traditional manufacturers and AM producers. The result of this is that they can customize their products for the different manufacturing processes. The need to optimize products to fit a production method is highlighted in our findings as an important part. The optimization is important to improve production time and material usage, in addition to the decreased need for machining after printing or forging. Moreover, Object 2 highlights the effect lead-time reduction has on the choice of sourcing. If the company needs a product as fast as possible, they now can source additive manufactured parts and can choose to do so when there is a need for it regardless of the price. If there are not the same time constraints, there is a possibility to source traditionally produced parts which are significantly cheaper as of now. The ability to introduce a digital inventory can result in major changes in the supply chain, as we know it today. We have seen that this is a wish from company B, where they have started looking at the possibility to have digital spare parts, that they can produce just-in-time and on site. This would make it possible to make products available rapidly, without the same need for physical warehouses (Verboeket and Krikke 2019b). The ability to print products and spare parts on demand and on site, is also a possibility highlighted by the pumping system supplier as mentioned above. Boer, Lambrechts, and Krikke (2020) highlight that the ability to produce on site and on demand, will decrease lead-time and the costs which is further substantiated by Holmström and Partanen (2014). Digital inventory effects the ability to recover because of the reduction of lead-time and the ability to respond to disruption in the supply chain by having the ability to pull a digital file and start production on site.

When considering the supply chain design aspect, we have included home sourcing and hub configuration as an important aspect towards improving the supply chain resilience through supply chain design factor as node density, complexity, and node criticality. In our findings from the interview with the supplier we found, as mentioned, the possibility to produce spare parts through implementing additive manufacturing at their facilities. This would result in both home sourcing, and a hub configuration. As of now, the products are forged by suppliers, and then sent to the supplier for machining and testing. If they implement AM, they will have the possibility to print inhouse, and therefore, home source production. This would decrease the complexity of the supply chain. In addition, the node criticality would be reduced because they would have the option of producing inhouse, or to source as forged products.

A hub configuration would also be the case for the supplier where they can establish machines at their service locations and produce just-in-time as mentioned above. The hub configuration is further substantiated by Khajavi, Holmström, and Partanen (2018b) that states that with today's technology a hub configuration is the best option compared to a fully distributed system, but the lead time is drastically reduced because of the elimination of much of the transportation and handling. This is further substantiated by our findings, where the product would be produced than to be shipped to the required location. A hub configuration or a distributed system with on-site production can additionally decrease the down-time of a system by producing more efficiently than an alternative of getting a product shipped from a location far away (Boer, Lambrechts, and Krikke 2020).

As a result of these findings from the literature and from interviews conducted, we propose the following conceptual model:

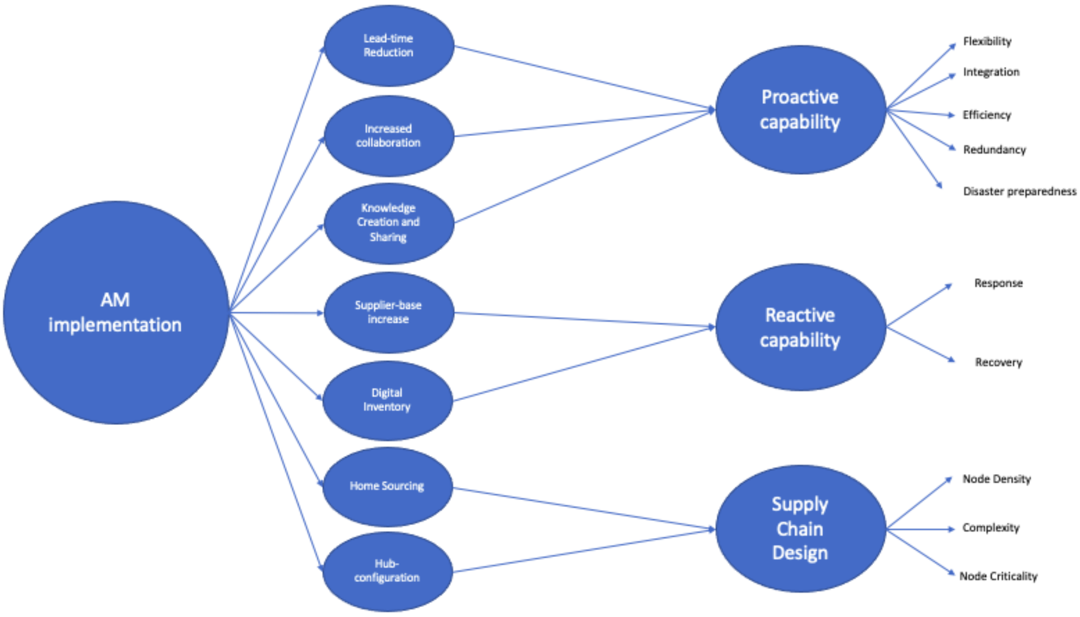

Figure 10 Conceptual model of AM adoption on supply chain resilience

We have added the seven strategies and effects from our findings that produce the most significant impact on supply chain resilience. These are then linked to the three aspects, proactive capabilities, reactive capabilities, and supply chain design that we conclude are affected the most. Further studies could implement the model to validate it further. Moreover, as the adoption of AM continues to grow in various industries the model can be further expanded or adopted to new changes and discoveries in the field of additive manufacturing and supply chain resilience. Especially the effects of a distributed system as hub-configuration and the ability to home-source should be further investigated. The model shows industries the result AM adoption can have on the supply chain resilience, and by doing so can contribute to the decision of adopt the technology.

9.0 Conclusion

Through this study we have conducted extensive literature review on supply chain and AM, and SCR, in addition to interviews with case companies to increase the knowledge of how AM affects SCR. This study has contributed to the knowledge of the implication AM has on the supply chain resilience, and what challenges this has produced. Further, we contribute with a conceptual model that can help companies make the decision to implement AM in their supply chains and what effects has the highest impact on supply chain resilience's three main aspects. This thesis contributes to the body of knowledge with a study focusing on AM and SCR, instead of having AM as a part of a larger study.

Through our thesis we have found that AM has a positive impact on supply chain resilience, but that there are barriers to implement AM include the lack of knowledge, experience, and the cost of implementation. Further the implementation of AM can have major impacts on the traditional supply chain and suppliers. The possibility to establish hubs, decrease lead-time and produce on-site and on demand can potentially have a destructive effect on the traditional supply chain. For companies who move towards AM, it is essential to increase the competence within the field of purchasing, quality and control, and manufacturing related to AM. Through collection of data from the interviews, and the literature reviews we have made a conceptual model that shows the seven strategies and effects AM has on three main dimensions of SCR and that these can positively affect the SCR.

Further we highlight that optimization of products to additive production will be beneficial to get all the benefits of AM and decrease adoption complexity. By shifting from TM to AM, there was an expected 50-60 % reduction in lead-time. Some of the impact factors are linked to the location of production, and the time it would take to produce the part. Moreover, when it comes to the procurement and engineering processes, we have concluded that there is not much difference in the process for TM and AM. The knowledge creation and sharing the adoption of AM has produced in this project, will further improve the collaboration between the companies. There are still many potentials not harvested from AM, and the possibilities of on-site production or hub configurations will have immense implications on how the TM-supply chain is operated in the future.

9.1 Managerial implications

The findings generated from this study hold important managerial implications for stakeholders considering adopting AM in their company or supply chain. We have found a positive effect of AM adoption on SCR, and that the benefits of adoption will become substantial as the technology evolves. We highlight the following managerial implications:

- Present the positive impact between AM adoption and SCR aspects
- Possibility to use the conceptual model to check what opportunities AM can create and what effects and strategies will have a positive impact on SCR
- Links AM and SCR

9.2 Limitations of the Study

Since this is an ongoing project, the data were collected coherent though our period. Furthermore, since this project faced some challenges along the way and is intended as a project to learn, the data became a little more uncertain than first thought. This study has the following limitations:

- The research was limited to coverage over emails and teams and no physically access was granted due to the Covid situation.
- We were not able to get in touch with the tire 3 supplier which were the once who produced with powder-bed fusion.
- The study only investigates one supply chain, and the results can vary from other industries or supply chains.
- All the data from the interviews cannot be generalized because the people involved have different positions and expertise, resulting in different questions in the interview.
- This was an ongoing project, and therefore the time was a limiting factor making it impossible to look at the complete case with its implications.
- There has been a limitation of time, due to this being a master thesis with a limited timeframe.

9.3 Suggestions for Further Research

Earlier we have mentioned that there are multiple providers of the technology in the market, and that the number is continuously growing. Further we know that products within this marked that once were forged or casted would be challenged by AM due to the benefits it can bring. Therefore, it would be interesting to look further into raw materials and investigate if warehousing would change due to new suppliers. Further we know that companies would start investigating part consolidation and it would be interesting to compare the logistics between TM and AM within a part consolidation project. From our point of view there have been interesting to follow the learning process and collaboration between companies, and this could be further measured when the project is finished.

Propositions for future research:

- Investigate AM adoption in other industries where there is a make to stock.
- Further AM adoption in engineering to order products and how the knowledge is collected and captured
- Further studies could implement our conceptual model to prove it.
- What benefits can a hybrid manufacturing process bring to existing companies.
- Investigate part consolidation in companies like General Electric and Siemens.
- Investigate the hub configuration and home sourcing capabilities that AM produce in ETO businesses.

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11.0 Appendices

The appendices are three interview guides distributed to the people who have participated in the interviews. The guides make it possible for the person to prepare for the interview and know what to expect. There are three different guides customized to the field of knowledge of the interviewed persons.

11.1 Appendix A – Interview Guide One

1. What is the lead time when a product is sourced using Additive manufacturing compared to traditional methods for this project?
2. Is there a difference in the production time for additive manufactured parts compared to traditional production?
3. Will it be an alternative for the company to using additive manufacturing within the company, or will it be sourced?
4. Is there a price difference when sourcing using additive manufacturing compared to traditional manufacturing in this project?
5. Is there a difference in time used on the project using additive manufacturing compared to traditional manufacturing?
6. How is the availability of the material used, both raw material and for finished products?
7. Is the procurement process different when using additive manufacturing compared to traditional manufacturing?
8. Are there challenges associated with the sourcing of additive manufactured parts compared to traditional products, if so, which?
9. Where are the products produced when using additive manufacturing and traditional production?
10. Which challenges are there when the products are sourced using additive manufacturing? (In this project)
11. How is the collaboration within the company and with suppliers and customer in a project using additive manufacturing compared to a project when using traditional manufacturing?
12. Would you say that by using additive manufacturing, the procurement process more flexible?

11.2 Appendix B – Interview Guide Two

1. Have there been calculations on material usage in this project, comparing additive manufacturing and traditional manufacturing?
2. Is there a difference in time used on the project using additive manufacturing compared to traditional manufacturing?
3. How is the estimated lifetime of a product using additive manufacturing compared to a traditional project?
4. Which challenges are there when the product is produced using additive manufacturing?
5. Which material is being used on this project, and are/have there been challenges with quality?
6. Are there production limitations when using additive manufacturing?
7. Does the use of additive manufacturing make your job easier when considering testing and calculations?
8. Do you use digital twin to do testing or similar things?
9. How is the collaboration within the company and with suppliers and customer in a project using additive manufacturing compared to a project when using traditional manufacturing?
10. Would you say that by using additive manufacturing the processes are more flexible?

11.3 Appendix C – Interview guide Three

1. How is the material usage when the product is produced using additive manufacturing compared to traditional manufacturing?
2. How long is the production time on a part produced using additive manufacturing, and how long is it when it is produced using traditional manufacturing (forged)?
3. What is the lead time when the product is sourced using additive manufacturing compared to traditional manufacturing (forged)?
4. Would you say that the processes are more flexible when using additive manufacturing compared to traditional manufacturing processes?
5. Which type of machine / method is used in the production of the part using additive manufacturing?
6. How is the collaboration with the customers and supplier when products are sourced using additive manufacturing compared to traditional manufacturing?
7. Do you use digital twin to perform tests etc.?
8. Which material is used, and are there problems / challenges with the quality?
9. How many attempts did it take to print the finished product in this project?
10. Which challenges are there when a product is produced using additive manufacturing?
11. Is there a difference in time used on the project using additive manufacturing compared to traditional manufacturing?
12. Are there differences in estimated lead time when the product is produced using additive manufacturing compared to traditional manufacturing (forging)?
13. How does the company make sure that drawings / models of the product are not produced / copied?
14. What opportunities does the company see with additive manufacturing creates, and what is the company's goal with additive manufacturing?
15. Has the company investigated the opportunities for parts consolidation?
16. Does the company use multiple additive manufacturing suppliers, and how is the availability in the market?