Master's degree thesis

LOG950 Logistics

Assessing the Impact of Additive Manufacturing in Spare Parts Logistics: A Case Study of Norsk Hydro

Fredrik Wiklund

Number of pages including this page: 86

Molde, 22.05.2023

Mandatory statement

Each student is responsible for complying with rules and regulations that relate to examinations and to academic work in general. The purpose of the mandatory statement is to make students aware of their responsibility and the consequences of cheating. Failure to complete the statement does not excuse students from their responsibility.

*Please complete the mandatory statement by placing a mark **in each box** for statements 1-6 below.*		
1.	**I/we herby declare that my/our paper/assignment is my/our own work, and that I/we have not used other sources or received other help than is mentioned in the paper/assignment.**	☒
2.	**I/we herby declare that this paper** • Has not been used in any other exam at another department/university/university college • Is not referring to the work of others without acknowledgement • Is not referring to my/our previous work without acknowledgement • Has acknowledged all sources of literature in the text and in the list of references • Is not a copy, duplicate or transcript of other work	☒
3.	**I am/we are aware that any breach of the above will be considered as cheating, and may result in annulment of the examinaion and exclusion from all universities and university colleges in Norway for up to one year, according to the Act relating to Norwegian Universities and University Colleges, section 4-7 and 4-8 and Examination regulations section 14 and 15.**	☒
4.	**I am/we are aware that all papers/assignments may be checked for plagiarism by a software assisted plagiarism check**	☒
5.	**I am/we are aware that Molde University college will handle all cases of suspected cheating according to prevailing guidelines.**	☒
6.	**I/we are aware of the University College`s rules and regulation for using sources**	☒

Personal protection

Personal Data Act

Research projects that processes personal data according to Personal Data Act, should be notified to Data Protection Services (NSD) for consideration.

Have the research project been considered by NSD? ☒**yes** ☐**no**

- If yes:

Reference number: 530853

- If no:

I/we hereby declare that the thesis does not contain personal data according to Personal Data Act.: ☐

Act on Medical and Health Research

If the research project is effected by the regulations decided in Act on Medical and Health Research (the Health Research Act), it must be approved in advance by the Regional Committee for Medical and Health Research Ethic (REK) in your region.

Has the research project been considered by REK? ☐**yes** ☒**no**

- If yes:

Reference number:

Publication agreement

ECTS credits: 30

Supervisor: Bjørn Jæger

Agreement on electronic publication of master thesis

Author(s) have copyright to the thesis, including the exclusive right to publish the document (The Copyright Act §2).

All theses fulfilling the requirements will be registered and published in Brage HiM, with the approval of the author(s).

Theses with a confidentiality agreement will not be published.

I/we hereby give Molde University College the right to, free of charge, make the thesis available for electronic publication: ☒yes ☐no

Is there an agreement of confidentiality? ☐yes ☒no

(A supplementary confidentiality agreement must be filled in)

- If yes:

Can the thesis be online published when the period of confidentiality is expired? ☐yes ☐no

Date: 22.05.2023

Preface

This thesis marks the end of the two-year Master of Science programme in logistics at Molde University College. Two years have gone by quickly, but they have given me considerable insight into logistics and a great professional challenge.

I wish to thank the case company representatives for their participation in the case study and discussions regarding the formulation of the research problem. The information they have provided has enabled me to conduct this study, which I am thankful for.

Productive discussions with my supervisor Bjørn Jæger have also proved helpful for the development of the thesis. Your expertise and advice has been valuable, for which I am grateful.

My gratitude also extends to my classmates for all the memories made in the past two years. During the writing of this thesis, memorable lunch breaks and countless great conversations have provided me with relief and kept me motivated.

Molde, 22.05.2023.
Fredrik Wiklund

Abstract

The emergence of additive manufacturing (AM) as an alternative to traditional manufacturing methods presents firms with the option of including it in their supply strategy. AM can enable on-demand production, potentially reducing inventories and supply chain emissions. The past years have seen considerable growth in the use of AM for manufacturing of spare parts.

This study explores the application of AM in the spare parts context through a case study in the heavy metal industry. The advantages and limitations of implementing AM at aluminium producer Norsk Hydro´s Sunndal plant are considered. As part of the study, current spare part management processes are outlined, as well as the challenges experienced in spare parts supply. The plant´s experience with in-house production of non-critical spare parts helps highlight the advantages of using AM for spare parts. In addition, motivations for further development of AM are outlined, with respect to how they relate to different strategic considerations, such as the supply chain configuration (centralized vs. decentralized) and the decision to outsource or develop AM in-house.

Findings indicate that the use of AM for spare parts may improve maintenance and support in asset management by potentially alleviating certain challenges faced in spare parts supply, such as high costs or lead time for certain parts and some parts no longer being available on the market. Another aspect is AM´s ability to facilitate design improvements for spare parts.

Contents

1.0 Introduction 1

1.1 Research Gaps 3

1.2 Background 4

1.3 Research Problem 5

1.4 Research Questions 5

2.0 Research Methodology 7

2.1 Research Philosophy 8

2.2 Research Approach 8

2.3 Research Design 9

2.4 Case Study Approach 10

2.5 Data Collection 11

2.6 Primary Data 11

2.6.1 Semi-Structured Interviews 12

2.7 Secondary Data 14

2.8 Data Analysis 14

2.9 Validity and Reliability 14

3.0 Literature Review 16

3.1 Supply Chain Management 16

3.2 Asset Management 17

3.3 Spare Parts Logistics 18

3.4 Additive Manufacturing 20

3.5 Sustainability Impacts of Additive Manufacturing 25

3.5.1 Servicification Through Cloud-Based Design and Manufacturing 27

3.6 Supply Chain Configuration with AM 28

3.7 Sourcing Strategy for AM 31

3.8 Outsourcing vs. In-House AM 32

3.9 Additive Manufacturing´s Impact on the Supply Chain 34

3.10 Digital Inventory 35

3.11 Classification of Spare Parts 36

4.0 Case Description 38

4.1 Case Company Description 38

4.2 Case Description: Spare Parts at Hydro Sunndal 39

5.0 Findings 41
5.1 Current Handling of Spare Parts Logistics 41
5.1.1 Non-Critical Parts 41
5.1.2 Critical Parts... 42
5.1.3 Process Overview.. 43
5.1.4 Classification of Spare Parts 43
5.1.5 Challenges in Spare Parts Logistics 44
5.2 Suitability of Additive Manufacturing.. 44
5.2.1 Motivation for Implementing Additive Manufacturing............................. 45
5.2.2 Effects of AM Implementation 47
5.2.3 Requirements for AM Service Providers... 49
5.3 Summary of Findings.. 50
6.0 Discussion...52
6.1 RQ1: What is the current handling of spare parts logistics in Norsk Hydro Sunndal´s supply chain?.. 52
6.2 RQ2: How does the current use of additive manufacturing affect spare parts logistics?... 53
6.3 RQ3: What are the implications of future strategies for further development of additive manufacturing for management of spare parts logistics?................................ 54
6.3.1 Motivation for Future Developments.. 54
6.3.2 Outsourcing vs. In-House 56
6.3.3 Supply Chain Configuration 57
6.3.4 Sustainability... 58
6.3.5 Location of AM... 59
6.3.6 Sourcing Approach 59
6.3.7 Potential Future Spare Part Logistics with AM 60
7.0 Conclusion...61
7.1 Research Summary 61
7.2 Managerial Implications 63
7.3 Limitations 63
7.4 Suggestions For Further Research 64
8.0 References 65
9.0 Appendices..73
9.1 Appendix 1: Interview Guide 1.. 73

9.2 Appendix 2: Interview Guide 2 75

List of Figures

Figure 1: The research onion (Saunders, Lewis, and Thornhill 2012)................................. 7
Figure 2: Decision-making phases in spare parts logistics (Cavalieri et al. 2008). 19
Figure 3: The AM process (ISO/ASTM 2021) 21
Figure 4: Unit costs of AM vs. TM (Handal 2017) 22
Figure 5: Comparison of AM cost models (Baumers and Holweg 2019)........................... 23
Figure 6: Unit costs of AM (Ituarte, Khajavi, and Partanen 2016).................................... 23
Figure 7: Spare part classification for AM parts. Adapted from Lastra et al. (2022) 36
Figure 8: Hydro´s supply chain (Hydro 2022a) 38
Figure 9: Spare parts logistics process 43
Figure 10: Spare part classification in relation to case study. Adapted from Lastra et al. (2022)... 53
Figure 11: Spare parts logistics process with AM 60

List of Tables

Table 1: Summary of research gaps 3
Table 2: Summary of contact with the case company.. 11
Table 3: Supply chain management definitions 16
Table 4: Sustainability impacts of AM 27
Table 5: Summary of findings 50

Abbreviations

SCM – Supply Chain Management
AM – Additive Manufacturing
TM – Traditional Manufacturing
CAD – Computer-Aided Design
CBDM – Cloud-Based Design and Manufacturing
OEM – Original Equipment Manufacturer
PLA – Poly-Lactic Acid
MRP – Material Requirements Planning
FDM – Fused Deposition Modelling

1.0 Introduction

Additive manufacturing (referred to in this thesis by the abbreviation "AM") has developed into a technology that now competes with conventional manufacturing methods (Achillas et al. 2015). The AM sector has developed into a 13,4-dollar industry, with an estimated growth of 22 % annually (Bromberger, Ilg, and Maria 2022). Several industries are already gaining significant benefits from applying AM, particularly due to its suitability for customization. For instance, the medical and dental industries use it to manufacture personalized equipment of implants tailored to fit patients (Khorasani et al. 2022; Petrovic et al. 2011). During the Covid-19 pandemic, AM was applied for producing personal protective equipment and related products to help combat the pandemic (Colorado et al. 2022). For the automotive and aerospace industries, AM has allowed for the production of more complex and lightweight parts, contributing to reduced energy use (Praveena et al. 2022). In the oil and gas industry, AM has also seen significant use for on-demand production of parts on offshore platforms (Vafadar et al. 2021).

By building a product one layer at a time, guided by a digital 3D model, AM allows for on-demand production of items. This ability makes AM interesting from a logistics perspective, as it may be introduced in spare parts logistics as a safeguard against reduced production downtime as a result of inventory stockouts or postponed deliveries from spare part suppliers (Khajavi, Partanen, and Holmström 2014). The potential of AM is not limited to reducing downtime, but also potential reductions in supply chain emissions (Li et al. 2017) and keeping lower inventories (Holmström et al. 2010).

AM is growing as an alternative to traditional manufacturing, providing manufacturers with the opportunity to switch parts from traditional manufacturing to AM. While simply changing manufacturing methods may not be advantageous in itself, the benefits of AM´s unique technological characteristics are more obvious. For instance, AM may facilitate redesign, such as reducing the number of components in a larger assembly by combining features (Bromberger, Ilg, and Maria 2022).

As an emerging technology, additive manufacturing does however face some challenges, such as high costs, size limitations and the fact that not all spare parts may be suitable for AM (Chekurov et al. 2018). Though interest in AM for spare parts is increasing, its use is still limited in industries. A literature review on the use of AM for spare parts was conducted by Peron and Sgarbossa (2021). They concluded that though researchers are attempting to address the challenges of AM, a significant amount of work is still needed to fully understand the profitability of AM in relation to traditional manufacturing. In particular, the authors highlight four research areas requiring more knowledge:

- Mechanical characterization of parts produced with AM.
- Guidelines for choosing which parts to produce with AM and which parts to redesign to suit AM.
- Life cycle cost analysis comparing traditional manufacturing and AM.
- How AM impacts the structure of the supply chain, considering both a centralized and decentralized configuration.

A more comprehensive literature review, performed by Mecheter, Pokharel, and Tarlochan (2022), covers 60 articles concerning the application of AM for spare parts. The review shows an increasing trend in researchers considering the application of AM for spare parts. Overall, the consensus is that AM is considered complementary to traditional spare part management, as opposed to a replacement. Especially for smaller parts with variable demand, AM has the potential to induce greater supply chain efficiency. The review highlights challenges relating to making a specific investment in a new technology and new materials, as well as the difficulty of converting existing manufacturing processes to digital ones.

When researching the applicability of additive manufacturing in spare parts logistics, several issues are typically discussed in the literature, such as the configuration of the supply chain; should manufacturing be centralized or decentralized? In addition: whether a single or dual sourcing approach is most suitable. Another key aspect to be discussed is whether AM capability should be implemented in-house or outsourced to an AM service provider.

1.1 Research Gaps

A research gap highlighted by Oettmeier and Hofmann (2016) relates to the procurement of customized parts produced through AM; the nature of the interaction between the buying company and the AM service provider may differ from procurement of traditionally manufactured parts with respect to information flows and processes. Another gap in the literature is highlighted by Belhadi et al. (2022); The authors emphasize that there is a limited understanding of how AM can change the supply chain´s structure to combine efficiency and resilience.

Tziantopoulos et al. (2019) developed a decision-making framework for planning AM supply chains. As part of this, they examined existing literature. The authors highlight a research gap in terms of literature assessing the trade-off between SC strategies for additive manufacturing and their sustainability effect and commercial feasibility in relation to traditional manufacturing.

Table 1 displays a summary of research gaps found in the literature relating to AM.

Table 1: Summary of research gaps

Author(s)	**Research gap**
Oettmeier and Hofmann (2016)	How does procurement of parts produced with AM differ from traditionally manufactured parts? Are processes and information flows different?
Belhadi et al. (2022)	How can AM change the supply chain to achieve both efficiency and resilience?
Mecheter, Pokharel, and Tarlochan (2022)	Lack of studies on AM specifically from a spare parts logistics perspective.
Tziantopoulos et al. (2019)	Understanding the effect of the trade-off between sustainability and commercial feasibility on the viability of AM supply chains versus traditional supply chains.
H. Rogers, Baricz, and Pawar (2016)	Where should AM service providers locate themselves?

To summarize, several supply chain related research gaps have been identified in the literature (Shown in Table 1). Though recent years have seen a significant increase in AM literature (Costabile et al. 2017), several research gaps exist. For one, AM spare parts literature is dominated by a few industries, particularly the aerospace sector (Mecheter, Pokharel, and Tarlochan 2022). More research is also needed on the procurement processes and information flows connected to AM parts (Oettmeier and Hofmann 2016), as well as the location of AM service providers (H. Rogers, Baricz, and Pawar 2016). Belhadi et al. (2022) highlight a need to examine how AM may affect supply chains with respect to efficiency and resilience. Similarly, Tziantopoulos et al. (2019) propose more research on the trade-off between sustainability and economic aspects of AM.

1.2 Background

The term “Industry 4.0” defines several changes to manufacturing systems driven mainly by IT. These changes do not only have technological implications, but also implications for how firms organize themselves (Lasi et al. 2014). The digital transformation presented by industry 4.0 may include benefits such as a more transparent and efficient supply chain, as well as a closer focus on customer needs, which may facilitate an improved quality of decision-making (Barreto, Amaral, and Pereira 2017).

According to Rüßmann et al. (2015), the industry 4.0 revolution is comprised of several main technological developments, some of which are: cloud computing, big data analytics, simulation, autonomous robots and additive manufacturing. As one of the pillars of industry 4.0, AM has developed into a technology that seeing increasing usage, particularly in industries such as the aerospace and medical sectors (Butt 2020).

Butt (2020) explains that AM plays an important role in how industry 4.0 facilitates improved customization and faster manufacturing, particularly in the way that it enables the ability to print on-demand, reducing transport costs and the time it takes to reach the market. These advantages may help manufacturing firms react promptly when they face challenges. Overall, AM is becoming an increasingly more competitive alternative to traditional manufacturing.

The wider context of industry 4.0 provides the background for this thesis, which aims to better understand one of the key technologies presented by the industry 4.0 revolution. Especially in light of how the industry 4.0 revolution changes the competitive landscape as firms are no longer competing with just each other; competition is now also between supply chains (Kehoe and Boughton 2001).

1.3 Research Problem

This thesis will seek to answer the following research problem:

“How may implementation of additive manufacturing of spare parts improve maintenance and support in asset management?”

This thesis will study this topic through a case study of Norwegian aluminium producer Norsk Hydro. Through a case study of their production plant in Sunndal, this thesis will examine the use of additive manufacturing of spare parts and how this may improve the maintenance and support of assets. This includes current effects of the technology thus far, as well as future perspectives related to more widespread use, outlining the implications of the various strategic considerations of further implementation of the technology. This may provide insight into how the company may reorganize the supply chain in order to benefit fully from implementing additive manufacturing.

1.4 Research Questions

Based on the research problem, three research questions have been formulated. The research questions will be examined through a case study of the aluminium producer Norsk Hydro, specifically their primary production plant in Sunndal.

The first research question (RQ1) relates to detailing the current nature of spare parts logistics at Hydro Sunndal. The aim is to get a better understanding of current spare parts operations, stocking policy and decision-making processes. Added to that; the flow of information and materials between departments and suppliers. Answering this research question will seek to uncover challenges in the supply of spare parts. This will provide a baseline for understanding how AM can fit into the plant´s supply chain if the AM capacity is expanded.

RQ1: “What is the current handling of spare parts logistics in Norsk Hydro Sunndal´s supply chain?”

The next research question (RQ2) will seek to understand how the implementation of additive manufacturing in the spare parts context affects spare parts logistics operations. This entails uncovering the benefits and challenges AM has presented thus far, and how the technology has changed the management of the plant´s assets.

RQ2: “How does the current use of additive manufacturing affect spare parts logistics?”

Finally, RQ3 relates to the further development of the application of AM for spare parts. This research question intends to examine the implications of the different strategic considerations regarding the organization of AM capabilities and their effect on spare part logistics. Wider use of additive manufacturing may have implications for the structure and configuration of the supply chain, which will be discussed as part of answering this research question.

RQ3: “What are the implications of future strategies for further development of additive manufacturing for management of spare parts logistics?”

2.0 Research Methodology

This chapter will outline concepts related to research methodology applied in the study. Kothari (2004) defines research methodology as “a way to systematically solve the research problem.” The author further elaborates that researchers need to be aware of more than just their chosen research techniques, but also understand what criteria formed the basis for their decision. In other words, the authors stress that the term “research methodology” is a wide term including many considerations beyond just describing the research technique applied to solve the problem. The term includes several dimensions such as: how the problem has been defined, why it has been defined, what data has been collected and how data has been collected.

As explained by Kothari (2004), the research methodology of the study must be understood with background in the research problem and its purpose. Based on this, there are several methodological considerations, which this chapter will outline. This includes research design, philosophy and approach, case study approach, data collection and the validity and reliability of the study.

A theoretical framework for research methodology is presented by Saunders, Lewis, and Thornhill (2012). Dubbed the “research onion” is shown in Figure 1. It describes the different layers of research methodology a researcher should consider.

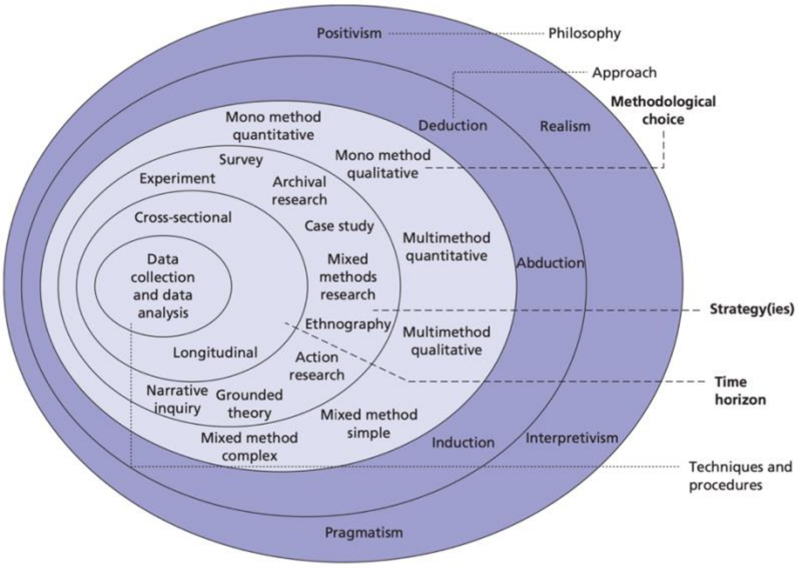

Figure 1: The research onion (Saunders, Lewis, and Thornhill 2012)

The outer layers in the research onion relate to research philosophy and research approach. The inner layers relate to research design choices, including specifying the research methods used and describing how data is collected and analyzed.

2.1 Research Philosophy

The first layer of the research onion relates to the overarching philosophical position that your research bases itself upon (Saunders, Lewis, and Thornhill 2012). Here there are several differing views. For instance, a positivist philosophy is akin to the philosophy of a natural scientist, with a preference for gathering data about observable facts and making generalizations based on regularities and relationships in the data (Johnson and Gill 2010).

Those who criticize the positivist approach often argue that it becomes hard to provide valuable insight into a complex world when the complexity is described by “law-like generalizations”. This viewpoint adheres more to the interpretivist philosophy, which emphasizes the need to understand variations between humans and their roles as “social actors” (Saunders, Lewis, and Thornhill 2012).

Pragmatism is another philosophical position that is not devoted to either positivism or interpretivism, but rather seeks to apply whichever viewpoint is appropriate for the given research. In other words, pragmatism may adopt both objective and subjective views in the research (Saunders, Lewis, and Thornhill 2012).

Pragmatism is considered the most appropriate for this case study, as it deals with an existing phenomenon (additive manufacturing), of which some observable facts may be observed, but the subjective opinions of managers also provide valuable information since we are examining managerial and organizational issues related to AM.

2.2 Research Approach

Often literature describes three kinds of research approaches; inductive, deductive and abductive. Inductive reasoning is concerned with exploring a phenomenon in order to build theory. Deductive reasoning on the other hand seeks to apply a given research strategy to verify or falsify a theory found in the literature. A third research approach, abductive reasoning, can be considered a mix between the aforementioned approaches. The abductive approach seeks to study a phenomenon in order to generate theory that is then tested by collecting additional data (Saunders, Lewis, and Thornhill 2012).

An inductive approach, as is common in qualitative research (Saunders, Lewis, and Thornhill 2012), is applied in this thesis. The rationale for this is firstly, that the thesis seeks to investigate an existing phenomenon (additive manufacturing) and generate theory and knowledge about the nature of the phenomenon, as opposed to testing whether a given conclusion can be verified or not. Secondly, an inductive approach is often linked to exploratory research (Stebbins 2001).

2.3 Research Design

Saunders, Lewis, and Thornhill (2012) define research design as the overall plan detailing how you obtain the answers to your research questions, such as specifying your sources for data collection, as well as your methods for collecting and analyzing the data.

Saunders, Lewis, and Thornhill (2012) separate between exploratory, explanatory and descriptive research design. Exploratory studies intend to gain insight into a particular topic by asking open-ended questions. Descriptive studies attempt to accurately describe situations or people, while explanatory studies attempt to explain relationships between variables.

For this study, exploratory research is considered the most suitable approach since the topic at hand (3D printing of spare parts) is an emerging technology that is still in an early stage in terms of established knowledge. Saunders, Lewis, and Thornhill (2012) explain that exploratory research is especially useful if one is “unsure about the precise nature of the problem”. RQ3 seeks to examine the effect that further AM implementation may have on the Hydro Sunndal plant´s management of spare parts, a question to which there exists no clear-cut answer in the literature. There does exist research on the topic, but naturally, findings from specific case studies on other supply chains may not be generalizable to the context of Norsk Hydro. We consider RQ3 to be of exploratory nature since it ventures into a relatively new and emerging technology with the aim of contributing knowledge about the topic.

RQ1 and RQ2, on the other hand, may be considered to be of descriptive nature, as they seek to give an accurate profile of the current handling of spare parts logistics at Norsk Hydro´s production plant in Sunndal (RQ1) and the current effects of AM implementation (RQ2). Saunders, Lewis, and Thornhill (2012) state that the goal of descriptive research is not merely to describe the events, but that you should be able to formulate conclusions based on the descriptions. That is why descriptive research is often combined with exploratory or explanatory research. In the case of this study, descriptive research (RQ1 and RQ2) is followed by exploratory research (RQ3).

2.4 Case Study Approach

A case study may be defined as “the study of the particularity and complexity of a single case” according to Stake (1995). The difference between a case study and other forms of research is essentially how much information that is gained from studying a single case (Gomm, Hammersley, and Foster 2000). They explain that other kinds of research might investigate more cases (e.g. surveys with many respondents), but give less detailed information about the individual cases. When applying a case study, as opposed to other methods of research, you are accepting a trade-off as you can gain significant detail about a single (or a few) cases, while you simultaneously sacrifice the ability to generalize your findings (Thomas 2010).

Voss (2010) describes several challenges when conducting case studies, such as their time-consuming nature and the need for a skilled interviewer. In addition, one must be careful with drawing conclusions as generalizability from a small set of cases is limited. Despite these challenges, case studies can lead to “new and creative insights” and aid theory development. Case studies may also ensure validity from the practitioner´s point of view, which is important when theory is generated based on real-world problems.

Though much of AM spare parts literature is rooted in operations research (though many qualitative case studies exist), using quantitative methods for optimization and simulations (Mecheter, Pokharel, and Tarlochan 2022), case study research is still important as explaining the results of such quantitative studies and the consequent formulation of new theory will be based on a qualitative understanding (Meredith 1998).

2.5 Data Collection

Hox and Boeije (2005) distinguish between primary and secondary data collection. They describe primary data as “original data collected for a specific research goal”. When primary data is made available to the rest of the research community, and used for another research problem, it is referred to as “secondary data”.

2.6 Primary Data

Primary data can be collected in a variety of ways, however, this thesis will concentrate on data obtained through semi-structured interviews. Preliminary discussions about the research problem with case company representatives started in September. Table 2 displays an overview of the contact with the case company throughout the thesis.

Table 2: Summary of contact with the case company

Date	Contact form	Topic	Involved
26.09.2022	Digital meeting	Preliminary discussion of research problem	Maintenance manager Supervisor competency development Others
05.10.2022	Digital meeting	Preliminary discussion of research problem	Supervisor Maintenance manager Supervisor competency development
19.01.2023	Physical meeting at Hydro´s aluminium plant in Sunndal	Plant visit and discussion of research problem	Maintenance manager Supervisor competency development Purchaser
15.03.2023	Group Teams-Interview	Current state of spare parts logistics /	Maintenance manager

		Effects of AM implementation / motivation for 3D printing	Supervisor competency development Purchaser
31.03.2023	Teams interview	Requirements for AM suppliers / service providers	Maintenance manager

2.6.1 Semi-Structured Interviews

There are several types of interviews applicable for case studies. Thomas (2010) highlights structured, unstructured and semi-structured interviews. Structured interviews are conducted with a predetermined set of questions, while unstructured interviews are more like conversions, where the interview object dictates the direction of the interview. Semi-structured interviews may provide the best of both worlds.

Formulating an interview guide that details what will be covered in the interview provides the basis for the discussion. This gives the flexibility to go through the different issues (which need not be formulated as detailed questions) in any order. The semi-structured interview allows for follow-up questions in response to the interview object´s replies (Thomas 2010).

Semi-structured interviews are therefore chosen as a data collection method in this thesis. The rationale for this is that formulating a semi-structured interview guide “contributes to the objectivity and trustworthiness of studies and makes the results more plausible” according to Kallio et al. (2016).

A mix of group interviews and individual interviews were conducted with employees at Norsk Hydro´s plant in Sunndal. The rationale for the selection of interview objects was to be able to highlight different aspects that are vital to the understanding of additive manufacturing. This relates to aspects within maintenance, spare parts logistics, procurement and competence development. Capturing these different considerations, and the interplay between them forms the background for the sampling of interviewees for the case study. The Interview guides developed for this study can be found in appendix 1 and 2.

Group interviews may encourage a productive dialogue since participants may either validate or challenge each other’s answers to the interviewer´s questions. A prerequisite for this kind of productive discussion is however an environment that does not inhibit interviewees´ ability to give their true opinions; such as situations where certain individuals dominate the interview and others shy away from publicly stating their disagreements. Therefore, it is vital to encourage participation from all participants, as well as posing open-ended questions (Saunders, Lewis, and Thornhill 2012). The interview guide has been developed with this in mind, aiming to ask questions of open-ended nature. The sampling of interviewees in group interviews is also important to create an environment where interviewees are comfortable voicing their opinions. In the case of the sampling in this case study, the participants work together on a regular basis and are roughly homogenous in terms of seniority, which led to productive discussions with the involvement of all participants.

Together these interviewees may be able to touch on different considerations of AM implementation, each providing insights into their areas of expertise, for instance, the maintenance manager may have key insights about spare parts and maintenance processes, while the purchaser may have insights about the warehouse. In a group interview setting, they can combine their expertise and verify each other’s statements, as well as engage in discussions from their differing perspectives (Saunders, Lewis, and Thornhill 2012). As part of the group interview, the current handling of spare parts logistics at the plant was detailed. This involves interactions and collaboration between the maintenance and purchasing departments. Therefore, the group interview setting can contribute to the accuracy of describing the processes.

Interview object 1 is the maintenance manager at the plant, who is responsible for organizing the maintenance processes at the plant, maintenance personnel and maintenance of vehicles used in the plant.

Interview object 2 is a purchaser who is involved in the management of the plant´s central warehouse. Interview object 3 works with the development of competency within the maintenance department.

Interview objects 1 and 3 have been the ones primarily involved in the implementation of AM. While interview object 2 (purchaser) along with other purchasers is in the process of developing knowledge on the topic of AM, e.g. through talks from external parties.

2.7 Secondary Data

Secondary data used in this thesis includes scientific articles with research directions closely related to the research problem formulated in this study. Through search engines such as Google Scholar and Oria, secondary data sources have been identified. Search terms like "additive manufacturing" and "3D printing" have been used. However, the sheer number of articles, as well as the need for more specific information gave rise to other search terms (that were often used in combination with the previously mentioned search terms) such as: "centralized supply chain", "spare parts" and "decentralized supply chain".

2.8 Data Analysis

The interviews were transcribed on the same day they were conducted, to ensure accurate transcription. The gathered data has then been coded into several different themes, as recommended by Creswell and Creswell (2018). The findings chapter is then organized according to these themes.

2.9 Validity and Reliability

The quality of research design may be judged through a series of logical tests described by Yin (2018). The author for instance presents the concept of construct validity, which deals with the degree of objectivity of the measures used to evaluate the results of the case study, describing that case studies are commonly critiqued for using "subjective judgments" for data collection. Testing for construct validity requires the researcher to make sure the set of measures for evaluating the case study are defined through the use of specific concepts, preferably ones that use published studies that use the same concepts (Yin 2018). To contribute to the construct validity of this study, an extensive literature review has been performed prior to conducting interviews with case company representatives. Interviewees were selected from different parts of the organization, as recommended by Ellram (1996). This may help ensure that the gathered information is accurate.

Another concept outlined by Yin (2018) is external validity, which relates to the degree to which a case study´s results may apply for conditions other than those described in the case study (Yin 2018). For instance; will the findings of the case study hold true for a firm in a different industry? Or even for a different firm in the same industry? For this study, RQ1 and RQ2 attempt to document the current handling of spare parts logistics and the current effect of AM implementation respectively. RQ1 and RQ2 do not intend to be generalizable to a wider context, but rather to describe the situations accurately. RQ3 on the other hand intends to be more generalizable to a wider context, seeking to understand how different strategic considerations impact the development of AM of spare parts.

Ensuring reliability of the study is also important. The reliability of a study can be judged by whether the study would yield the same results if repeated by another researcher using the same methods and procedures. A good way to achieve this is to document the research process sufficiently enough so that another researcher in theory could repeat the case study with the same result (Yin 2018). Common threats to reliability include factors related to errors or bias from either the researcher or the participants of the case study (Saunders, Lewis, and Thornhill 2012). In order to ensure the reliability of the study, interview guides were constructed and sent in advance to the interviewees. The interviews were taped and then transcribed by the researcher on the same day as the interviews took place.

3.0 Literature Review

The following chapter will present a literature review related to the research problem. Starting with background on supply chain management, asset management and spare parts logistics, before describing the literature tied to the different dimensions of AM. First, the technology of AM is presented, followed by aspects such as sustainability, supply chain configuration, sourcing strategy, outsourcing compared with in-house approaches, the supply chain impact of AM, and the digital inventory concept.

3.1 Supply Chain Management

The term "supply chain management" (SCM) has grown in popularity over time. Particularly in the 1990s, SCM practices such as the exchange of demand information across the supply chain to decrease inventory levels, were increasingly adopted by firms. A wealth of definitions of exactly what SCM is has since appeared in academic literature (Min, Zacharia, and Smith 2019). A selection of commonly used definitions is presented in Table 3.

Table 3: Supply chain management definitions

Author(s)	Definition
Beamon (1998)	*"an integrated process wherein a number of various business entities work together in an effort to:* *1: acquire raw materials* *2. convert these raw materials into specific final products, and* *3. deliver these final products to retailers."*
Christopher (2016)	*"The management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole"*
Cooper, Lambert, and Pagh (1997)	*"is the integration of business processes from end user through original suppliers that provides products, services and information that add value for customers."*
Mentzer et al. (2001)	*"…the systematic strategic coordination of the traditional business functions within a particular company and across businesses within the supply chain, for the purposes of*

> *improving the long-term performance of individual companies and the supply chain as a whole."*

A common theme among these definitions is that SCM encompasses coordination or management of several business entities and their respective processes. The definitions slightly differ in terms of what the end goal of SCM is; but in essence, the goal of SCM according to these definitions seems to revolve around providing customer value. The definitions by Cooper, Lambert, and Pagh (1997) and Beamon (1998) in particular, emphasize that SCM entails managing a process of a product or service from its inception all the way to the end user.

The emergence of AM could however have implications for the nature of supply chain management. AM may impact several aspects of the supply chain. In particular, AM has shown to reduce complexity in the upstream supply chain, for instance in the automotive industry (Zijm, Knofius, and van der Heijden 2019).

3.2 Asset Management

For management of assets, production machines in particular, there are different maintenance strategies. Broadly, we can separate between preventive and corrective maintenance strategies. Preventive maintenance intends to perform the necessary repair or replacement prior to a part failing. Preventive maintenance follows a schedule and provides background for the planning of spare parts demand. It is however unable to stop all parts from failing before planned maintenance and repairs. A Corrective maintenance strategy is applied when parts fail unexpectedly, which creates unplanned demand for spare parts (Haroun and Duffuaa 2009).

When it comes to after-sales of spare parts, Haroun and Duffuaa (2009) explain that after sales services are often regulated in one of two ways; by either warranty contract or service contracts. Warranty contracts define the conditions for which the OEM (the original equipment manager; the manufacturer of spare parts in this case) should provide maintenance or replacements for the customer. When applying service contracts on the other hand, the OEM may be compensated for the service costs. Alternatively, they can be compensated based on the level of system performance they maintain for the customer.

3.3 Spare Parts Logistics

Spare parts inventory management may be considered a separate branch of inventory management, with distinct features such as significantly smaller demand levels. However, the goal is generally still the same; securing a satisfactory service level at the smallest inventory and administrative costs possible (Huiskonen 2001). Based on Dekker, Kleijn, and De Rooij (1998) we can observe that there are three main elements to spare parts logistics; 1) costs: there are costs associated with physically storing spare parts. 2) availability: When a spare part is not yet available when it is required, there may be consequences related to the delivery of products and services. 3) time: Production of spare parts can take significant time, which in turn can cause downtime for machines that require them.

Securing a sufficient service level tends to come at a cost, as it can result in problems related to large inventory costs, obsolescence costs and capital costs related to parts considered to be “slow-moving” (Khajavi, Partanen, and Holmström 2014). Spare parts logistics can pose a big challenge as a spare parts inventory is often made up of high-priced parts with long lead times. They may also be slow-moving parts, that are rarely used (Knofius et al. 2021).

According to Roda et al. (2014), several characteristics separate spare part logistics from other types of inventory. These include the large uncertainties of both when a spare part will be required and the quantity of which it will be required. Inventory control is made complicated by the sometimes large number of different spare parts. In addition, the number of suppliers for spare parts is severely limited, leading to restrictions concerning costs and lead time.

When dealing with spare parts inventory management, the financial consequences of stock-outs can be significant. Added to that, it can be difficult to estimate demand levels due to the sporadic nature of spare parts demand (Huiskonen 2001).

Another challenge is that sourcing of spare parts tends to be limited to just one, or a small number of suppliers. This leads to challenges related to procurement lead times and costs. In the case of a multiple sourcing strategy being applied for spare parts, problems may arise related to the risk of variations in the quality of materials differing between the suppliers (Chekurov et al. 2018). Another characteristic of spare parts logistics is obsolescence. In the case of an obsolescent machine that is to be phased out, it is challenging to determine appropriate stock levels for the machine´s spare parts (Roda et al. 2014).

Cavalieri et al. (2008) present a decision-making framework for spare parts logistics. Given the complexity of spare part logistics, they consider the need for sequential ordering of five decision-making steps, as shown in Figure 2.

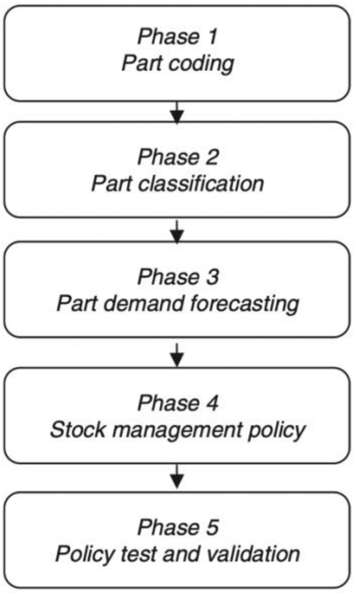

Figure 2: Decision-making phases in spare parts logistics (Cavalieri et al. 2008).

The first phase is the coding system for spare parts, where the code should provide an understanding of the technical characteristics of the part, its storage location and the supplier of the part (Cavalieri et al. 2008). The second phase involves the classification of spare parts, which is necessary to provide guidelines on the appropriate stocking strategy for the parts. Examples of classifications defined by the authors include:

- Consumables: items with consistent usage and many viable suppliers (E.g. oils, filters).
- Generic spare parts: parts that may be used on several machines or equipment, with many viable suppliers (e.g. valves, cylinders, switches)

- Specific spare parts: Parts tailored to specific equipment, typically available through a single supplier.
- Strategic spare parts: Similar to the above, but also characterized by unpredictable wear-out time, high costs and delivery lead time.

Phase 3 entails the forecasting of demand for spare parts. Forecasting for spare parts will be different from forecasting of demand for materials in production, due to the lower level of consumption and the more variable demand patterns. The fourth phase is stock management strategies; stocking policies are tailored to the classification of the part. The final phase is related to the testing and validation of policies through review of the completed steps to refine the process (Cavalieri et al. 2008).

3.4 Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing, is a technology that enables the production of entities by assembling the material one thin layer at a time. The construction of the product is based on input from a digital file detailing the design of the product, which has been created using computer-aided design (CAD) software. A consequent advantage of AM is that the inputs are limited to the digital design model and the raw materials used to print. In other words, additive manufacturing requires little in terms of setup time and tools (Achillas et al. 2015). The lack of expensive setups implies that production of smaller batches becomes economically viable (Pour et al. 2016).

Industry 4.0 is transforming supply chains, inventory management and production logistics. The manner in which companies think about all aspects of a product´s lifecycle is being changed; all the way from design to production to distribution. As part of this process, AM presents a digital transformation of inbound logistics (Araújo, Pacheco, and Costa 2021). Kehoe and Boughton (2001) describe that as a consequence of industry 4.0, competition is no longer merely between companies, but also between supply chains.

The ISO/ATSM standard for AM describes a “physical” and “digital” level for the AM process (shown in Figure 3). The first step of the process is to acquire the CAD file. Next, it is converted to a file format suitable for the slicing utility, such as a “.stl” or “.3mf” file (ISO/ASTM 2021). By “slicing” the file, instructions are generated that are then sent to the printer in the form of a set of 2D sections, which are then fabricated on top of each other to create the part (Bogue 2013). The physical level of the process includes a range of technologies able to convert the digital file into a physical object (ISO/ASTM 2021).

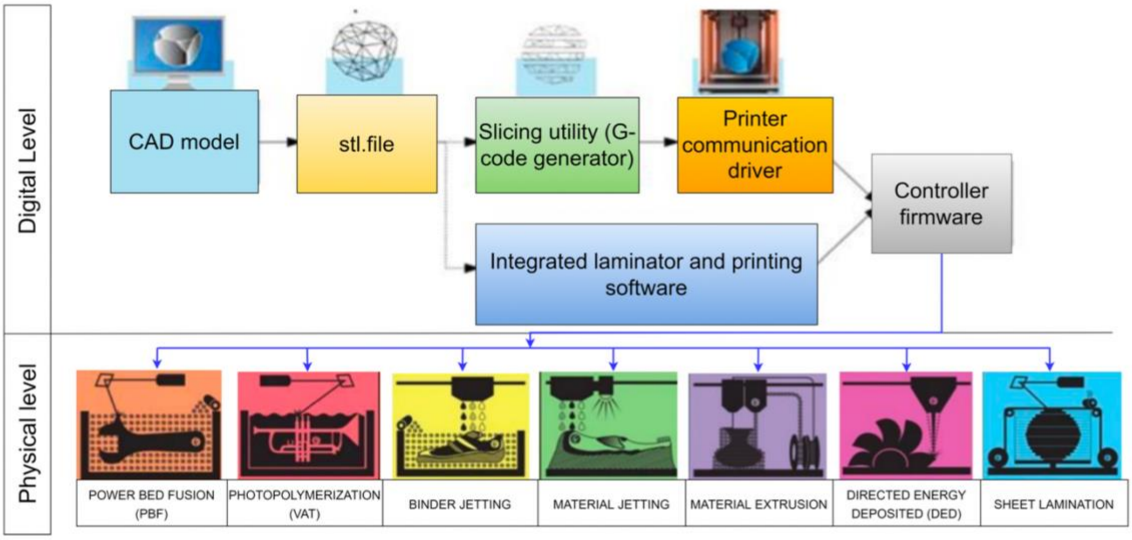

Figure 3: The AM process (ISO/ASTM 2021)

On the physical level, several technologies exist, using different materials. (Lastra et al. 2022) consider that polymers and metals are the most commonly used materials in AM. Although AM with other materials does exist, such as rubbers, concrete, glass and ceramics (Bogue 2013). AM is rapidly evolving with respect to material alternatives, meaning that the number of materials is steadily growing. AM using metals includes materials such as titanium alloys, aluminium alloys and magnesium alloys among others. For AM with polymers, there are various alternatives including poly-lactic acid (PLA), nylon, polyamide and polycarbonate (Srivastava et al. 2022).

The different 3D printing technologies all share the additive production process (the part is built one layer at a time). However, the different technologies differ in how the layers are constructed. Technologies such as Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS) construct the layers by softening and melting material. While Stereolithography (SLA) utilizes laser technologies to build layers (Lastra et al. 2022).

Initially, AM was used as a prototyping tool, but technological advancements have facilitated its transition into a manufacturing method for end-use parts. In particular, the medical and aerospace sector has found AM to be a useful tool for producing complex spare parts in small volumes (Petrovic et al. 2011). For manufacturing, AM is especially suited to manufacturing parts with complex geometry that are challenging to produce with traditional methods (Bogue 2013).

In contrast to traditional manufacturing, where unit costs decrease as production becomes larger, economies of scale function differently for AM. Handal (2017) proposes a hypothetical graph (shown in Figure 4) displaying the unit of costs of AM and TM, where unit costs for AM are constant.

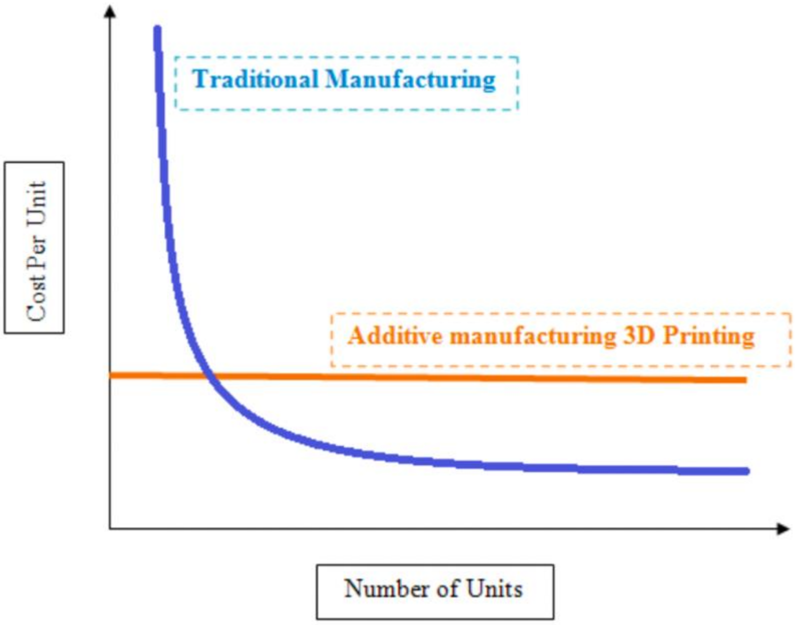

Figure 4: Unit costs of AM vs. TM (Handal 2017)

A study on the economics of laser sintering machines showed that economies of scale apply only partially to AM; it applies to the point of maximum utilization of the build space of the machine, but no further than this (Baumers and Holweg 2019). In other words, they describe a cost curve that is not exactly flat, but instead has decreasing unit costs as you better utilize the build volume of the 3D printer. The cost curve is shown in Figure 5, where the authors have adapted from cost models developed by Ruffo, Tuck, and Hague (2006).

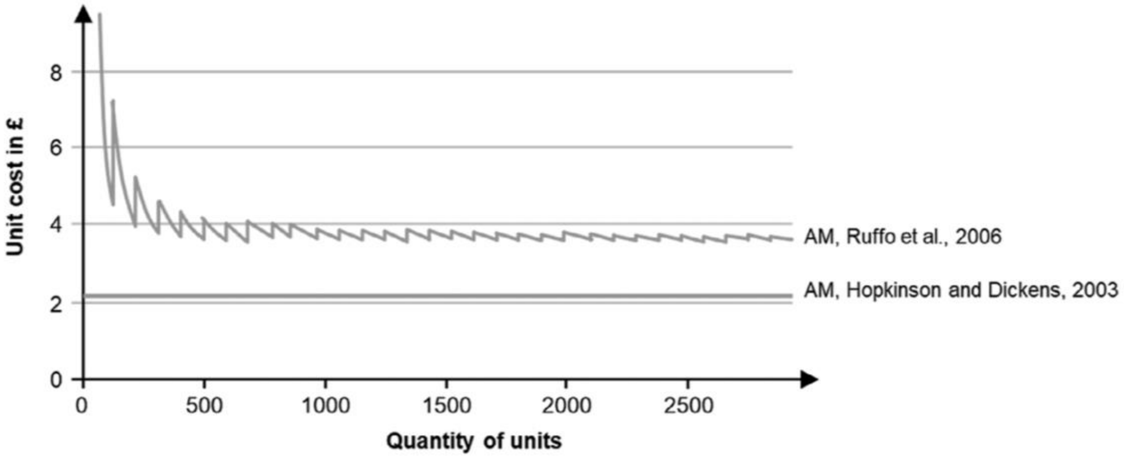

Figure 5: Comparison of AM cost models (Baumers and Holweg 2019)

Another unit cost model (Figure 6) is proposed by Ituarte, Khajavi, and Partanen (2016), displaying the break-even point for SLS and SLA techniques in relation to traditional injection molding. The graph also includes a hypothetical estimation of future costs. Their results show that AM is currently not suitable for mass production. It might be reasonable to expect a reduction in cost as AM technologies evolve. Therefore, the authors include a hypothetical scenario in the graph: Should the cost of AM become 10 times cheaper in the future, AM will become more suitable for mass production, but will still struggle to compete with traditional manufacturing for higher volumes. Still, AM is an attractive option for small volumes and situations where production needs to be quickly adjusted.

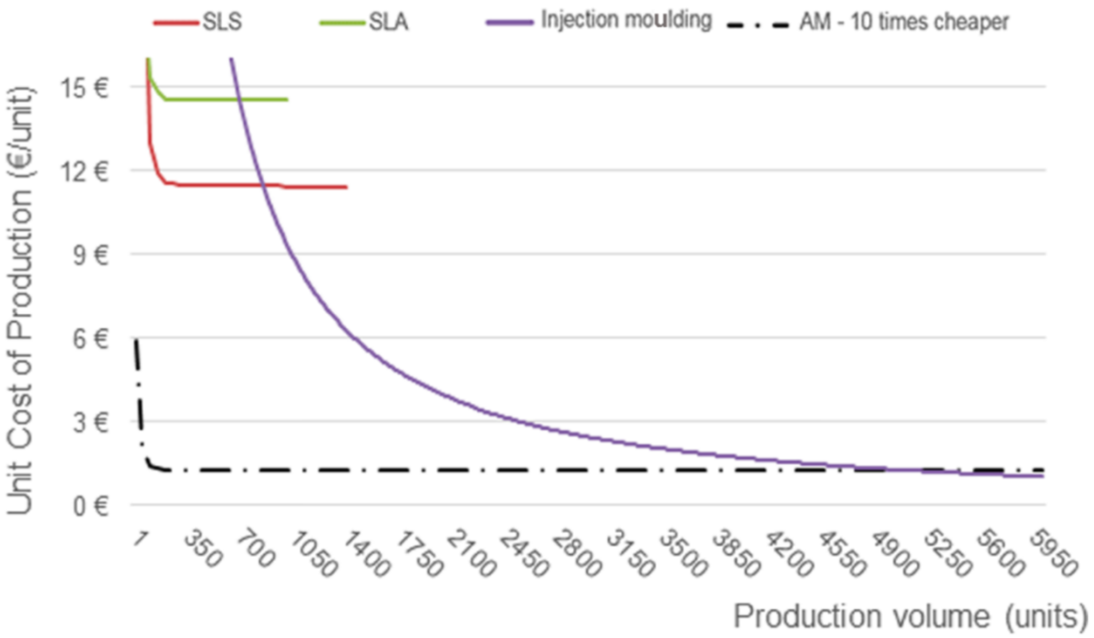

Figure 6: Unit costs of AM (Ituarte, Khajavi, and Partanen 2016)

Chekurov et al. (2018) examined the attitudes of companies to additive manufacturing of spare parts through focus group interviews. The high costs were often mentioned by the interviewed companies as a major barrier to implementation of additive manufacturing of spare parts. Many of them also considered size constraints to be problematic, as additive manufacturing is perceived as less suitable for bigger spare parts.

Attaran (2017) also mentions equipment costs as a barrier, but emphasizes that this is not permanent. Over time, the number of 3D printing firms will increase leading to reduced costs in the future. The author also cites major investments by governments (e.g. the Chinese government) in the technology as a clear sign that the cost will go down eventually.

According to Khajavi, Partanen, and Holmström (2014) having 3D printing of spare parts localized on the production site, may allow for higher uptime in production as you avoid the possibility of running out of inventory and late deliveries from the spare parts supplier. This increases flexibility and protects against unforeseen demand spikes.

While AM has existed for several decades now, its adoption in industries may not have reached the level that it was predicted to. Though difficult to quantify, an industry report on AM produced by Wohlers (2019) found that AM comprised less than 1% of total manufacturing at the time. Authors like Kunovjanek and Reiner (2020) point to E.M. Rogers, Singhal, and Quinlan (2014) for an explanation of why AM´s degree of adaptation perhaps has not lived up to the hype. Rogers proposed that the majority of innovations tend to initially grow at a slow rate despite their benefits.

On the topic of bottlenecks preventing the use of AM in spare parts logistics, Ballardini, Ituarte, and Pei (2018) identify several issues through a multiple case study. The low technological maturity of AM was found to be a common issue the companies were concerned about, as they feared that AM would result in inferior product quality. Another key issue among the companies examined in the study was the lack of digitalized information about the spare parts; often CAD files do not exist. Furthermore, original drawings could sometimes not be located. In addition, suppliers offering AM as a production method were few in comparison to traditional methods of manufacturing.

3.5 Sustainability Impacts of Additive Manufacturing

Ford and Despeisse (2016) highlight three main advantages of AM from a sustainability perspective. Firstly, AM can enable more efficient use of resources for products where AM is an alternative manufacturing method. Secondly, the longevity of products can be extended with AM. Lastly, supply chains can be reconfigured to be less complex.

The production process may also require less materials by limiting overproduction. Additive manufacturing can also enable repairs of spare parts which will increase the life cycle of products (Holmström and Gutowski 2017).

In terms of reducing carbon emissions, Li et al. (2017) found through simulation modelling comparing traditional supply chains with AM supply chains that the latter had lower carbon emissions. In these supply chains, most of the emissions were tied to the raw materials needed for the 3D printing process.

Rupp et al. (2022) evaluated the carbon emissions of 3D-printed steel spare parts using a decentralized SC configuration. They found that transportation costs made up somewhere between 5% and 11% of total supply chain emissions for the spare parts. The study also presents the importance of the energy mix of manufacturing the spare parts, which greatly impacts the total emissions. The authors explain that companies often choose manufacturers based on price and not CO_2 emissions. The result of this is often manufacturing in places with a fossil fuel dominated energy mix.

According to Rejeski, Zhao, and Huang (2018), the majority of 3D printers use more energy than the equivalent conventual manufacturing technique. In particular, AM using metal materials consume significantly more energy. That said, AM´s ability to combine production steps means that you can avoid waste associated with several production processes and assembly of parts. Although AM leads to less waste in manufacturing, waste is still existent. It should be noted that waste can sometimes be more than expected as a consequence of human or machine errors (Song and Telenko 2017).

Estimation of energy use among AM processes is difficult due to large variations in the energy efficiency between different AM machines. Variables like material type and usage rates also contribute to the difficulty in estimating the energy efficiency of AM (Rejeski, Zhao, and Huang 2018).

Although life cycle assessments (LCA) of AM have been performed, some uncertainties are tied to the results, for reasons such as limited data tied to the manufacturing of the feedstock (raw materials). Typically rough estimates are used for feedstocks in LCAs (Rejeski, Zhao, and Huang 2018).

Holmström and Gutowski (2017) highlight several ways a supply chain supported by additive manufacturing may improve sustainability. For one, transportation may be reduced by locating the production of spare parts on-site. However, this may come at a cost considering the often high cost of additive manufacturing equipment.

Table 4 presents a summary of the sustainability implications of additive manufacturing.

Table 4: Sustainability impacts of AM

Positives	**Author(s) cited**	**Negatives**	**Author(s) cited**
More efficient use of resources (less waste)	Ford and Despeisse (2016), Holmström and Gutowski (2017)	AM is more energy intensive than traditional manufacturing	Rejeski, Zhao, and Huang (2018)
Potential of AM to extend life cycle of products	Ford and Despeisse (2016)	AM may still be wasteful without skilled operators	Song and Telenko (2017)
Less complex supply chains	Ford and Despeisse (2016)	Difficult to conduct accurate LCAs on AM because of limited data on feedstock manufacturers	Rejeski, Zhao, and Huang (2018)
AM may combine production steps	Rejeski, Zhao, and Huang (2018)		
On-site AM, though expensive, may improve sustainability	Holmström and Gutowski (2017)		

3.5.1 Servicification Through Cloud-Based Design and Manufacturing

A recent trend in sustainability is servicification through the concept of distributed cloud-based design and manufacturing (CBDM). The background for this new concept is the exceedingly competitive nature of business in an international economy compelling firms to change the way they think about manufacturing, design and innovation, and seeking knowledge within these areas from sources beyond their own organization. Developments in cloud computing have facilitated easier access to collaboration between firms with respect to innovation of design and manufacturing processes (Wu, Rosen, and Schaefer 2014). This new paradigm presents some implications for sustainability, such as enabling firms to decrease their dependence on transporting materials and holding inventory which allows for a leaner, more sustainable supply chain (Nagarajan, Raman, and Haapala 2018). Additive manufacturing is a technology that becomes a key part of this concept (Wu, Rosen, and Schaefer 2014).

3.6 Supply Chain Configuration with AM

Li et al. (2017) define two different supply chain configurations for the use of additive manufacturing in spare parts logistics.

- Centralized: where 3D printers are located at a centralized location, and spare parts are produced and then transported to the service location.

- Decentralized (also referred to in the literature as “distributed”): where each service location has 3D printing capabilities and produce to cover their own demand.

On the topic of centralization, Mecheter, Pokharel, and Tarlochan (2022) found that most supply chains supported by additive manufacturing of spare parts were neither centralized nor decentralized, but rather a mix of the two.

Examining the topic of spare parts in the aircraft industry, Liu et al. (2014) illustrated that additive manufacturing may have potential to reconfigure supply chains to facilitate a decrease in safety stock levels and their consequent inventory costs. They emphasize that the appropriate supply chain configuration depends on the characteristics of the spare parts in question. For parts with long lead times in manufacturing, low average demand and significant demand variation, they deem a centralized AM configuration to be appropriate. Conversely, parts with high and stable demand favour a decentralized configuration. If demand is low and volatile, a centralized AM supply chain may be applicable if manufacturing lead time is significantly short, since the parts may be produced on-demand.

Li et al. (2017) explain that while AM has several advantages over traditional manufacturing, the decision to implement AM should be based on the individual firm´s supply chain circumstances. Based on the results of simulations, the authors describe a trade-off between the economic and environmental benefits, explaining that the economic benefits shown by the study may not necessarily be strong enough to convince managers to implement AM. Environmental benefits on the other hand were more obvious. The environmental benefits described by the authors are not necessarily because AM is an inherently more environmentally friendly technology, but rather as a result of the supply chain reconfiguration it enables. A reduction in supply chain tiers in the spare parts supply chain may enable a reduction in carbon emissions.

Further, Li et al. (2017) found that AM-supported spare part supply chains were preferable in terms of variable costs. The main cost element in centralized supply chains were transportation costs, while decentralized supply chains´ costs were mainly manufacturing costs. However, when taking into account the fixed cost of acquiring the AM equipment, AM-supported supply chains were no longer cost-effective in relation to traditional spare parts supply chains. Naturally, this calculation is based on the cost of purchasing AM equipment given the technological development at the time of the article´s writing (2017). Future advancements in AM technologies could very well lead to reductions in the purchasing cost.

Khajavi, Holmström, and Partanen (2018) conducted empirical research comparing scenarios with centralized and decentralized AM in spare part supply chains in the aerospace industry. A key finding was that the role of the annual cost of personnel and equipment tied to AM is highly consequential for the decentralized configuration. The decentralized configuration has a higher number of locations than the centralized configuration, therefore even small reductions in the equipment cost tied to AM functions favours a decentralized configuration.

Earlier analysis by Holmström et al. (2010) concluded that on-demand centralized production was the approach for spare parts most likely to succeed, given the trade-offs involved. The authors describe three important trade-offs to consider for application of AM in the spare part supply chain. The first trade-off was the choice of batch production or on-demand production. Several variables are in play here, namely inventory costs, material costs and the costs of having manufacturing capacity. Obsolescence costs also apply, and if these costs are high, this favours on-demand production since it can effectively eliminate costs of obsolescence. For AM production, the size of the part is the dominant cost driver, while the costs of traditional manufacturing are mainly influenced by the complexity of the part.

The second trade-off described by Holmström et al. (2010) was the configuration: centralized or decentralized. Several factors influence this trade-off. For one, the capacity utilization of the equipment is important. Low utilization of the AM equipment will favour a centralized approach. For spare parts that are consequential for the uptime of equipment, the decentralized approach will be attractive.

Finally, a trade-off between general purpose and specialized AM equipment is described. This is because general-purpose AM capacity can be shared between users, which gives rise to the ability of AM service providers to serve several companies and manufacture different kinds of spare parts. The authors state that further development of AM into a more available general-purpose technology will favour the decentralized approach (Holmström et al. 2010).

Selection of the optimal manufacturing technology and supply chain configuration has been discussed by Rinaldi et al. (2021). Through an AHP (analytical hierarchy process) model, they assigned weights to KPIs to compute a sustainability index. According to their calculations, they deem additive manufacturing to have potential over traditional manufacturing, considering a 50/50 split between economic and environmental criteria. Especially when a high service level is required, a decentralized AM setup is considered the best choice from an environmental standpoint. If a low service level is required and the demand is low, a centralized AM configuration is superior. That said, if assigning a very low value for environmental criteria (10%), traditional manufacturing was preferable. Looking exclusively at economic criteria, TM was preferable when demand was high. For low demand, centralized AM was economically superior because centralized AM allowed for higher capacity utilization of the AM equipment.

Though the different extremes of centralized and decentralized configurations have been presented in the literature, with some authors predicting a trend towards more decentralization and greater proximity to customers and responsiveness. Other authors have been more reserved about the prospect of decentralization of AM, with authors such as Holmström et al. (2010) and Liu et al. (2014) emphasizing that centralized AM may be more effective for higher volumes. How AM service providers will organize and locate themselves therefore becomes an intriguing question. Boon and Van Wee (2018) describe two opposing forces influencing the choice of location; AM is a driver for efficiency and customization, however, it creates the burden of complexity and quality control. This may mean that more complex parts may be more applicable for being produced by AM service providers, while simpler parts may be more applicable for in-house production by firms.

3.7 Sourcing Strategy for AM

Another key question when talking about spare parts derived from additive manufacturing is whether to have a single or dual sourcing approach. Are you better off sourcing purely 3D-printed spare parts or is it better to source a mixture of 3D-printed and traditionally manufactured spare parts? Multiple authors have examined this.

Mecheter, Pokharel, and Tarlochan (2022) performed a comprehensive review of the existing literature on additive manufacturing in the context of manufacturing of spare parts. The review found that most authors, based on the current state of additive manufacturing technologies, recommended a dual or mixed sourcing approach, as opposed to single sourcing.

Knofius et al. (2021) find through case studies in the aviation industry that dual sourcing tends to outperform single sourcing given the characteristics of spare parts logistics; low demand, high inventory costs and large backorder costs. They emphasize that dual sourcing may help avoid the drawbacks associated with additive manufacturing in spare parts logistics. Such drawbacks, as highlighted by Westerweel, Basten, and van Houtum (2018) include larger unit costs and uncertainty regarding quality. The model developed by Knofius et al. (2021) takes into account the difference in costs and failure rates between 3D-printed parts and traditionally manufactured parts. They assume a lower lead time for the 3D-printed parts. Overall their model attempts to find a trade-off between the two production methods using a dual sourcing approach.

Through their analysis, they found that dual sourcing was the cheaper option compared with single sourcing either 3D printed or traditionally manufactured parts. This applied even when assuming unflattering circumstances for the AM parts, like three times the cost or failure rate of traditionally manufactured parts. Under these conditions, they found a 30% saving compared with the single sourcing approach. They generally found that AM functions well as an emergency source of supply that compliments traditional manufacturing. A dual sourcing approach allows for utilization of the benefits of AM while keeping the impact of AM´s disadvantages low. The authors also find that single sourcing of AM parts was not suitable for parts with high impact on downtime. Having stock is necessary to mitigate the risk of downtime (Knofius et al. 2021).

If a situation where traditionally manufactured parts are single sourced results in higher backorder and holding costs compared to other costs, dual sourcing is preferred. Usually, this situation is characterized by high holding costs and backorder costs, coupled with low resupply rates of traditionally manufactured parts and low demand (Knofius et al. 2021).

3.8 Outsourcing vs. In-House AM

Another aspect of the supply chain design side of AM implementation is the make-or-buy decision; Should AM be outsourced to a provider of AM services or should companies build AM competence in-house? H. Rogers, Baricz, and Pawar (2016) state that though outsourcing AM removes risks such as expensive investments in machines, training and employees, companies will still face risks related to ordinary "manufacturer-supplier relationships".

Regarding the make-or-buy decision for AM, Friedrich, Lange, and Elbert (2022) identify several arguments with implications for this decision. For instance, investment in an emerging technology like AM implies a level of technological uncertainty that may favour outsourcing as a way to approach AM as opposed to making considerable in-house investments that come with uncertainty given the emerging state of the technology.

Friedrich, Lange, and Elbert (2022) point to references such as Khajavi, Partanen, and Holmström (2014) and Hedenstierna et al. (2019) who mention the inherently flexible nature of AM; It is not specific to any specific product. AM being a general-purpose machine seems to be an argument that AM has low asset specificity. At the same time, findings from Friedrich, Lange, and Elbert (2022) testing these arguments in a case study of AM-adopting firms suggest that the firms found certain aspects of AM to be at odds with this argument. For instance, the firms point to the fact that operating AM machines require a great deal of knowledge and experience. In addition, AM incurs costs related to training of staff, pre- and post-processing of parts and maintenance of the 3D printers. This echoes the viewpoint of Mellor, Hao, and Zhang (2014), who emphasizes that AM implementation will incur considerable costs related to the education and training of engineers with traditional manufacturing backgrounds. While AM could be described as general-purpose equipment, these additional aspects are also part of the investment in AM and have implications for the decision of whether to outsource or implement in-house.

Another key finding from the case study by Friedrich, Lange, and Elbert (2022) is related to the outsourcing of core competencies. The firms examined in their case study were hesitant to outsource AM as they considered AM design proficiency as a source of competitive advantage, particularly the ability to use AM to improve the design of structures.

Concerns related to intellectual property rights are also found among most of the firms in the study, who feared that outsourcing of AM would pose the risk of opportunism from the partners in the shape of counterfeiting and copying. The companies described uncertainty regarding the protection of intellectual property rights beyond “standard contracts and trust” (Friedrich, Lange, and Elbert 2022).

The case study also observed that the firms found a challenge in achieving high utilization of AM equipment and generating satisfactory demand for parts produced with AM. This leaves AM service providers in a better position given their ability to pool orders and specialize deeper in AM technologies (Friedrich, Lange, and Elbert 2022).

To summarize this chapter, the decision to outsource AM or keep it in-house is based on several aspects. The technological uncertainty of an emerging technology such as AM may favour outsourcing as a means to reduce related risks (Friedrich, Lange, and Elbert 2022; H. Rogers, Baricz, and Pawar 2016). However many firms consider AM as a core competency that should be kept in-house in order to mitigate risks of opportunistic behaviour from other firms. The cost of educating and training engineers´ AM capabilities may also favour the argument towards outsourcing. In addition, AM service providers are better positioned to achieve higher utilization of AM machines (Friedrich, Lange, and Elbert 2022).

3.9 Additive Manufacturing´s Impact on the Supply Chain

The emergence of AM is often referred to as a “disruptive technology”. Kothman and Faber (2016) argue that AM is a disruptive technology as it changes several different domains; it fundamentally alters the product, which consequently alters both the manufacturing process and the supply chain.

Kothman and Faber (2016) describe that by increasing manufacturing performance and integrating functions, AM shortens the supply chain, thereby reducing the number of partners involved, and requiring closer collaboration with the partners. This point is also mentioned by Gebler, Uiterkamp, and Visser (2014) who project that AM will make supply chains shorter by “inducing more direct means of production”. The authors also describe that supply chains can become more dynamic since digitalized pre-chains will replace physical ones.

The lack of a global network of AM service providers able to compete with traditional manufacturing does however limit the application of AM for spare parts (Ballardini, Ituarte, and Pei 2018). The inclusion of AM in supply chains is limited by three factors, according to Tziantopoulos et al. (2019). Firstly, achieving economies of scale with AM is costly. Secondly, there is a limited selection of materials. Finally, the legal environment and regulations remains a challenging topic since AM is still an emerging technology.

A substantial obstacle to large-scale implementation of AM is the need for qualification and control of parts produced with AM (DNV 2023). DNV is an example of a provider of certification and quality control of parts produced with AM in the maritime sector. Though certification standards for AM are growing, the lack of a well-established certification process remains a challenge (Chen et al. 2022).

Heinen and Hoberg (2019) state based on their study of a large dataset of a company’s spare parts assortment, that companies only need to acquire a “relatively low” level of AM capacity to experience the benefits of AM. The spare parts in the case company´s portfolio that were considered for a switchover to AM were characterized by low demand. Parts with high demand rates should still be traditionally manufactured according to the study.

In the case of supply-side effects of the introduction of AM, Oettmeier and Hofmann (2016) describe that implementation of AM leads to an increased need for closer collaboration between the suppliers of the raw materials and machines required for AM, as these two components need to be compatible with each other. In the case of outsourcing of AM activities, close communication between engineers who perform the 3D-modelling and the AM provider will be required to facilitate design changes swiftly.

To summarize this chapter, AM holds the potential to alter the supply chain by shortening its length (Gebler, Uiterkamp, and Visser 2014). Although its adoption among companies has been somewhat limited because of factors like costs, limited material selection and a complex legal environment (Tziantopoulos et al. 2019). That said, a low-scale implementation is enough to yield the benefits of AM according to Heinen and Hoberg (2019). Another important note is that AM will require closer collaboration with suppliers of equipment and raw materials (Oettmeier and Hofmann 2016).

3.10 Digital Inventory

The traditional manufacturing of spare parts gives rise to some challenges. For one, parts may be stored for long periods of time. The difficulty of estimating when spare parts are needed gives rise to the possibility of a spare part never being used. Some spare parts may deteriorate to a degree where they can no longer be used as they do not meet performance requirements. Spare parts inventories are often large, especially if a company is the manufacturer of products that are highly customized. These challenges, coupled with the expensive nature of holding such a spare part inventory, add to the complexity of inventory management (Salmi et al. 2018).

The aforementioned challenges provide the background for the “digital spare parts” concept. By having information about the spare part in a digital format and producing it with AM when needed, the spare part does not take up space in the warehouse. Consequently, the challenges mentioned above are eliminated. The digital spare parts concept can also facilitate a reduction in labour and costs related to customs when ordering traditionally manufactured spare parts (Salmi et al. 2018).

The digital spare parts concept does however have its challenges. A major barrier that prevents the introduction of digital spare parts and AM is a lack of digitalized design files for the parts (Khajavi, Salmi, and Holmström 2020). This point was also highlighted by Ballardini, Ituarte, and Pei (2018), as mentioned earlier in the literature review. Further, adopting AM is also heavily reliant on information flows. While AM may improve multiple supply chain capabilities, it may cause vulnerability in the shape of heavily relying on information flows. Satisfactory ICT structures are therefore needed prior to AM implementation (Naghshineh and Carvalho 2022).

3.11 Classification of Spare Parts

A flowchart for spare part categorisation was developed with AM in my mind by Lastra et al. (2022). It distinguishes between simple parts and complex assemblies, followed by the dimensions (small/medium/high volume) of the part. Next, material class is determined (metal, polymer, or both). Although the author further classifies parts into different categories, a simplified version is shown in Figure 7 to illustrate different applications of AM for spare parts.

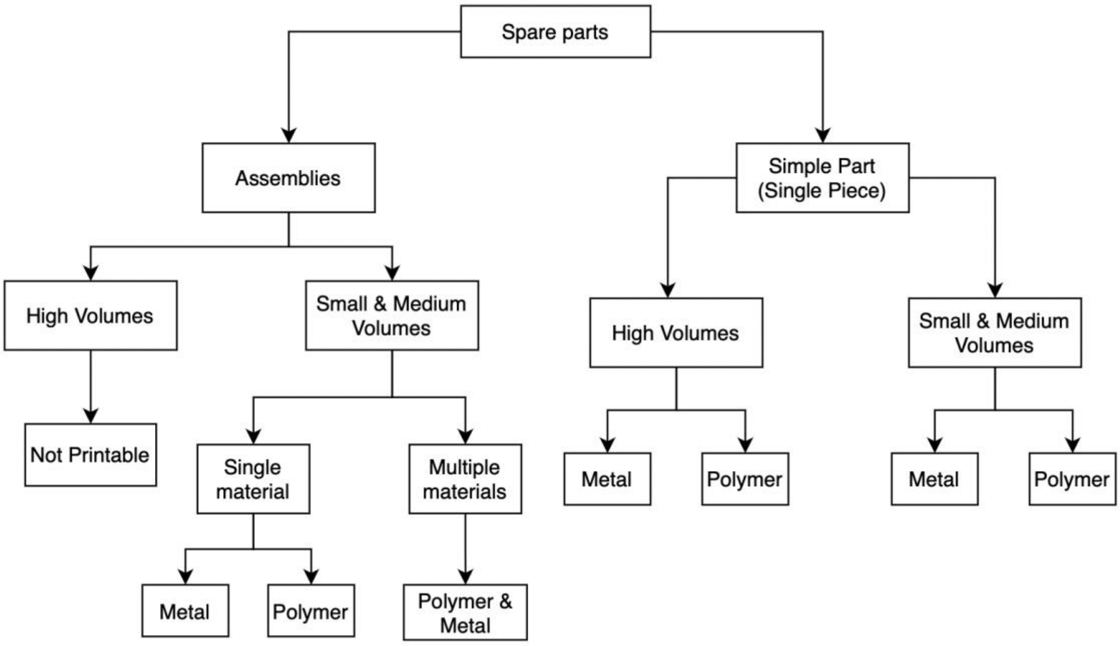

Figure 7: Spare part classification for AM parts. Adapted from Lastra et al. (2022)

The first step for introducing digital spare parts through AM according to Khajavi, Salmi, and Holmström (2020) is analysis of the suitability of the spare parts assortment for 3D printing. The authors describe that digitalized information should include not merely the geometry and dimensions of the part, but also information detailing the material, the need for post-processing and the required surface finish.

4.0 Case Description

This chapter will present the case company, along with a description of the problem that will be examined in the case study and the surrounding context of the case company.

4.1 Case Company Description

Hydro is one of the world´s leading companies in aluminium and renewable energy, with a presence of over 140 locations spread over 40 countries, totaling 32 000 employees. They are involved in several aspects of the aluminium value chain, such as energy production, mining and refining of raw materials, aluminium production and recycling of aluminium (Hydro 2022a). Figure 8 displays Hydro´s supply chain.

Figure 8: Hydro´s supply chain (Hydro 2022a)

The first two parts of the supply chain include the extraction of bauxite and the refining of alumina. What follows in the supply chain is energy production; much of this energy is then used to supply Hydro´s aluminium production. As one of Norway´s three leading producers of hydropower, Hydro has access to renewable energy to supply its production plants. Over 70% of electricity applied in the primary aluminium plants is acquired through renewable power (Hydro 2022a).

Hydro´s aluminium metal division includes primary aluminium production and casting, which is comprised of products such as standard ingots and alloys. Primary aluminium production takes place at Hydro´s fully-owned Norwegian plants in Sunndal, Karmøy, Husnes, Høyanger and Årdal, as well as co-owned plants in Australia, Brazil, Slovakia, Canada and Qatar (Hydro 2022a).

Extrusions produce tailor-made components for sectors such as the construction, heating and automotive industries. Lastly, Hydro´s aluminium can be found in end-use consumer products, vehicles, or buildings to name a few applications (Hydro 2022a).

As a means to achieve more resilient value chains, as well as decreasing waste and contributing to a lower carbon footprint, Hydro recycles both post- and pre-consumer scarp and operates 25 recycling facilities throughout Europe, Canada and the US (Hydro 2022a).

The global demand for aluminium is expected to rise considerably in the coming years. In a 2022 media statement, Hydro points to the International Aluminium Institute (IAI) who forecast a global demand increase to be as high as 70-80% by 2050. Hydro wants to take a leading position by meeting this demand increase in a sustainable way, with the intention of contributing to the Paris climate agreement´s goal of keeping the planet´s increase in temperature below the 1,5-degree threshold. While an increase in post-consumer scrap recycling is planned to cover most of the demand increase, the rest must be facilitated by aluminium production with net-zero emissions (Hydro 2022b). In the past 30 years, Hydro has reduced the carbon footprint of its aluminium products by 70%. However, the annual production output has seen a 400 000 ton increase, meaning that the emissions of total aluminium production have dropped by 55% from 1990 to 2021 (Hydro 2021).

Hydro has outlined a roadmap for achieving a net-zero aluminium product by 2050 which includes the growth of their recycling volume, as well as decarbonization of their upstream supply chain and their aluminium production through technological developments. The goals for 2025 and 2030 are 10% and 30% reduction in emissions respectively (Hydro 2021).

4.2 Case Description: Spare Parts at Hydro Sunndal

The company holds an extensive inventory of critical and non-critical parts. The plant´s warehouse is large and expensive to hold and maintain. Over time, spare parts will decay and lose their value. Digitalization of inventory management processes therefore become an interesting topic for discussion. The introduction of industry 4.0 technologies like AM is relatively recent and requires more knowledge. This case study hopes to contribute to a better understanding of AM´s impact on spare parts logistics within the organization thus far, as well as reflecting on what the technology holds for the future for Hydro; in terms of solving challenges in spare parts logistics and contributing to their overarching strategic goals related to improving the sustainability of their upstream supply chain to facilitate net-zero aluminium production.

5.0 Findings

This chapter will detail findings from the interviews conducted with the case company. The interviews were concerned with detailing the current processes for managing spare parts logistics at the plant, as well as highlighting common challenges faced when dealing with the supply of spare parts to the plant. The suitability of additive manufacturing is also explored, and how it relates to these challenges. In addition, the effects of the implementation of AM so far are considered, as well as the requirements for future development of the AM capacity tied to the plant.

5.1 Current Handling of Spare Parts Logistics

The general process of acquiring spare parts is described by interview objects working in the maintenance and purchasing departments.

Several strategies related to purchasing of spare parts are outlined. Frame-agreements largely dictate the choice of supplier. If a frame-agreement is in place then Hydro will generally purchase from that supplier. Or in the event of a simple part with low cost, they would likely go to the supplier offering the best conditions in terms of price and delivery time.

When considering a part with no frame-agreement, and a considerable price that is over a given sum, the purchasing department is required to involve at least three suppliers in the tender in order to ensure competition in the market.

The demand for spare parts is triggered by the maintenance department. The process is described by the company as different for critical and non-critical parts.

5.1.1 Non-Critical Parts

For non-critical parts, they have the description of the spare part in SAP, which is their maintenance planning tool. The process starts with the maintenance department creating a purchase requisition that goes to the purchasing department. The requisition is then handled by the purchasing department and the order is placed.

5.1.2 Critical Parts

For critical spare parts, it is necessary to keep them in stock. The purchasing department has set a pre-determined ordering point. When the maintenance department takes a part out of the warehouse and this causes the stock level to drop to the ordering point, an automatic order is sent to the supplier for a set amount of parts.

MRP (Material Requirements Planning) data includes information about how much is currently in stock, what the ordering point is and how much should be ordered. The ordering point and order quantity can be adjusted if for instance:

- There are challenges in operations that may increase the consumption of a spare part.
- A supplier is experiencing challenges that cause increased lead time.

There may also be developments in prices that influence the supply situation. If Hydro has an agreement with a supplier for a critical spare part, but they experience that prices or lead time become too high, they might have to evaluate the situation and consider to include other suppliers for this spare part.

5.1.3 Process Overview

An overview of the process of acquiring a spare part is shown in Figure 9 below.

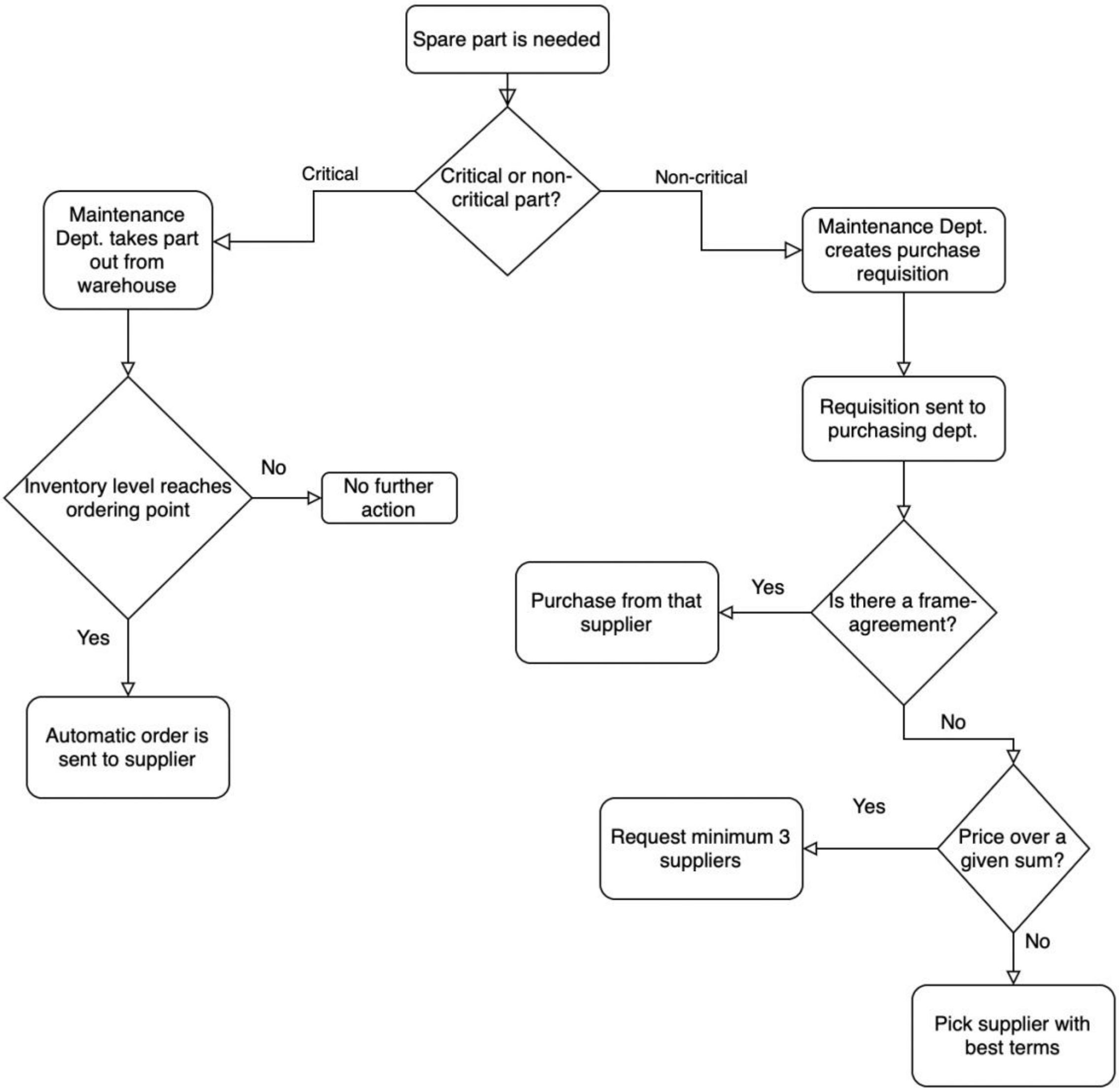

Figure 9: Spare parts logistics process

5.1.4 Classification of Spare Parts

The need to classify spare parts is born out of the need for defining critical functions. Some functions have high criticality, while some functions are less critical. For critical functions, there is a need to examine the components that contribute to the function and analyze the probability of the component´s failure and the consequences of failure. If the consequences of the part failing lead to the disruption of an entire function, then keeping the component in stock is necessary.

In some cases, there are suppliers able to deliver a part within 12 or 24 hours. In situations like this, the company does have the option to purchase storage space at the spare part supplier´s facilities. This is not something that the plant does often. They do however have some of their suppliers´ inventory stored at the plant.

The maintenance department performs the classification regarding criticality. They determine what is critical enough to keep in stock. The central warehouse is responsible for adjusting the ordering point and stock level, which they might do if they for example face a significant increase in lead time for a part. Smaller adjustments are made by the warehouse themselves, while bigger adjustments require communication with the maintenance department. Therefore, the interaction between the maintenance department and the warehouse is important.

5.1.5 Challenges in Spare Parts Logistics

As for challenges experienced in the supply of spare parts, the maintenance manager and the purchaser explain that they often relate to high costs and increased lead time. In addition, many parts may become obsolete over time. Another aspect is the preservation and maintenance of the spare parts inventory. They emphasize that there is a need to preserve the spare parts inventory as it decays over time, especially since you do not know when it is needed; it could be in 6 months' time or significantly more. Some of the plant´s spare parts are stored for up to 10 years. The capital tied up in this inventory can be a challenge. In addition, a large spare parts inventory takes up significant space and becomes harder to keep track of. These aspects present a motivation to reduce storage levels.

5.2 Suitability of Additive Manufacturing

Following the findings above related to current spare parts logistics, findings related to the suitability of additive manufacturing for the case company will be outlined. This includes the effects of the plant´s current small-scale in-house AM implementation, as well as perspectives related to the motivation for 3D-printed spare parts. Findings related to future developments of the technology and the surrounding supplier market are also presented.

5.2.1 Motivation for Implementing Additive Manufacturing

The maintenance manager explains that the plant´s 3D printing journey was born out of a wish for more competency among the maintenance operators. This wish was then followed up by introducing more training schemes for the operators, by purchasing new equipment and receiving training from suppliers. To further materialize the training of operators, a partnership with a vocational school was initiated. Among the courses in the training program was a course about 3D printing and digital drawings.

The motivation for starting with 3D printing at the plant was described as the fact that a spare part was desired, but there were uncertainties regarding the exact shape and specifications. Therefore, AM was used to develop prototypes, which were then tested and adjusted until a working design was found, and re-printed.

In addition, there has been motivation to 3D print because of difficult supply characteristics. Such situations include:

- When spare parts are entirely unavailable on the market.
- When purchasing a given spare part separately is not possible, but the part can only be bought as part of a larger assembly to which it belongs.
- When spare parts are available on the market, but the price is too high.

In the event of high prices, the company has on several occasions been able to print parts for a much more reasonable price using one of their in-house 3D printers. The maintenance manager explains: "*We have also encountered that some parts cannot be sourced, or that you cannot buy the exact part, but you can buy a bigger component which contains that part. We also see that some parts can be bought, but the price is relatively high. We come out with a fully-fledged product here at a far more reasonable price."*

The globalized nature of modern supply chains is highlighted as a complicated aspect that forms a part of the motivation for 3D printing. The maintenance manager describes that *"The motivation for 3D printing will be multiple things. Lead time is one aspect. The international environment makes it so that we observe a considerable increase in ordering time and lead time of components."*

The maintenance manager also explains that obsolescence is an important aspect behind the desire to 3D print: *"We have a plant that has been assembled over many years. We have installations of different ages, and some of the equipment is no longer available on the market."* The plant is comprised of components and machinery going back many years. Consequently, obsolescence complicates spare parts logistics. The event of failure of components in an obsolete machine gives rise to modifications. Typically, a replacement part is purchased from a supplier, and the parts of the machine are reconfigured to fit the replacement part. Such modifications are difficult to execute, not to mention expensive.

The maintenance manager also imagines that producing a spare part with AM could be cheaper if the alternative is hiring a Norwegian industry worker to traditionally manufacture the part, given the high labour costs in the Norwegian market.

Though AM has mainly been utilized for prototyping so far at the plant, the ambition is to include AM as a part of the overall supply strategy for spare parts and integrate it into the overall management system for maintenance. The maintenance manager also stresses that if one is to succeed with 3D printing, it needs to be included in the overarching supply strategy of the company: *"No matter how you attack 3D printing it is about a supply strategy that includes that possibility. it is something that follows a decision-making process; it is not just a simple activity you start. It entails a strategy for supplying spare parts and materials to an organization. it is important that the overarching strategies are there in our management system if we are to succeed with it."*

In terms of the long-term goal of AM. The interview objects together highlight that large-scale in-house implementation of AM is not likely, nor is it the goal. The company´s 3D printing journey is largely concerned with the aim of "training" the ability to see opportunities that arise from AM. In essence, they are awaiting a development in the surrounding market of suppliers to include AM as a manufacturing method. That also entails the suppliers having the competency regarding legal considerations such as intellectual property rights.

The ambition cited by the purchaser for the purchasing department is to collaborate more with external companies, the maintenance department and Hycast (a daughter company of Hydro concerned with R&D activities) to build competence and take advantage of the possibilities of AM for spare parts. This goal is one of the sustainability goals that the purchasing department has set.

The maintenance manager points to the fact that companies will over time be pushed more in terms of sustainability by governmental regulations. This provides a motivation for companies to become more circular and attempt to extend the life cycle of their equipment: *"If a component has a part that makes up 10% of the purchasing cost; if that part is worn out, we need to replace that part and continue to use the equipment. A simple way of putting this is that it costs more and more to dispose of waste."*

The plant experiences a supplier market that leverages its position by offering a discounted initial price and then gaining bigger profits on the aftermarket. This results in high price levels for spare parts, especially for individual components that are part of a bigger assembly. The prices for these individual parts are often marked up to a point that encourages buying the complete assembly.

The maintenance manager states that the emergence of 3D printing might change this landscape. The suppliers might be forced to look at "other methods" of repairing or acquiring parts for a cheaper price, such as with AM.

5.2.2 Effects of AM Implementation

Hydro has aluminium plants in Sunndal, Husnes, Høyanger, Karmøy and Årdal, but Sunndal is the only plant that has implemented AM. They currently operate two FDM (fused deposition modelling) 3D printers; Flashforge Creator Pro 2 and Prusa Raise3D Pro 2.

Hydro Sunndal has experimented with AM on a small scale, starting in 2021. So far a handful of different spare parts have been produced in-house using AM. These first few pilot projects were non-critical parts. For instance, they have 3D-printed hooks and clothes hangers for wardrobe lockers. Another project was battery covers for headsets. The battery covers would often break, and ordering this individual part from the supplier was not a possibility, you would have to order a whole new headset. Therefore it made sense to print these small parts. This resulted in estimated savings of 40 000 NOK per year. Initial pilot projects such as this example have sparked interest in more widespread use of the technology.

In terms of AM competence at the plant, they have established a small group of engineers and operators responsible for 3D printing parts. They receive suggestions for what parts to manufacture from other departments, which they then digitally draw and print. Following this, they receive feedback on whether the part fits or if it needs to be reprinted. In some cases, Hydro Sunndal has 3D-printed prototypes of parts and then adjusted the drawings before sending them to a supplier to be traditionally manufactured with metal.

Though the plant´s 3D printing journey started fairly recently (2021), they have had some pilot projects. Some were mainly prototyping projects, while some parts have been put to use at the plant. Some parts were additively manufactured because the original supplier for the part no longer exists. While other parts were made with AM in order to improve the design of an existing part.

When it comes to the purchasing process, the purchaser explains that it is hard to see any changes following AM implementation, considering that the plant has not sought out to purchase 3D-printed parts from suppliers. Eventually, as the supplier market for 3D-printed spare parts grows, one might be able to examine the effect AM has on the purchasing process.

In terms of procurement of the materials and 3D printers used at the plant. The maintenance manager states that there have been no challenges regarding the supply. The material they print with is PLA. The supervisor for competency development states that AM with metal materials becomes more challenging; they envision that in that case, you would need to involve someone in the material science field in the process, given the complicated nature of different qualities of metal.

In terms of supply chain effects, the purchaser explains that they are not able to say that they have experienced a shortening of the supply chain following the implementation of AM. Given that they have only implemented AM in a small-scale, mostly prototyping capacity, the purchaser describes that they do not know of such effects yet, but that it could be an interesting hypothesis for the future.

5.2.3 Requirements for AM Service Providers

The maintenance manager describes several capabilities that a potential AM supplier needs to have. He explains that the supplier needs to be skilled in material science, as well as the construction of machine parts. He emphasizes that AM opens up new possibilities when compared with parts traditionally manufactured by molding; such as the ability to create parts that are hollow and have air pockets.

In addition, legal expertise surrounding AM is mentioned as an important ability the supplier needs to have. Being good at sales and marketing is also mentioned as important in the initial phase. According to the maintenance manager, large parts of the industry are not “mature” in regards to AM, and do not see the possibilities. Sufficient marketing from the suppliers may therefore help convince companies to adopt AM.

In terms of the nature of the relationship with a potential supplier, the maintenance manager envisions a frame agreement they may call on when it is needed both in terms of replacing broken spare parts and printing parts to extend the life cycle of older machines. Demand will probably be variable, therefore they stress the importance of the supplier having a market beyond just Hydro´s Sunndal plant, but also other companies within the mid-Norway region. The location of the supplier being relatively close is preferable in an initial phase, as it better enables close collaboration and dialogue with the supplier.

The maintenance manager emphasizes that a potential supplier should not only look to Hydro, but also other manufacturing companies, including the spare part suppliers if AM provides an alternative solution to traditional manufacturing for certain parts.

Currently, many suppliers apply a pricing strategy that does not favour overhauling and repairs. Also, suppliers often price individual parts so high that they almost reach the price of the complete component they are part of. The maintenance manager believes that spare part suppliers need to rethink their strategy to provide more overhauling and repairs as opposed to mainly sales.

The emergence of AM could be an avenue for spare parts suppliers to earn money on digital parts according to the maintenance manager. The implications of this possible change in strategy become interesting for Hydro and the industry as a whole, especially in light of sustainability and reshoring. While many spare parts are produced in low-cost countries, AM might provide an opportunity to move production closer to home as manufacturing will to a higher extent be performed by machines rather than by traditional labour.

5.3 Summary of Findings

An overview of key findings is presented in Table 5.

Table 5: Summary of findings

#	Finding	Supported by
1	**Current handling of spare part logistics** • Different processes for critical and non-critical parts • Critical parts kept in stock, automatic orders sent out when stock level reaches ordering point • Non-critical parts not kept in stock	• Maintenance manager • Purchaser
2	**Challenges in spare parts supply** • High costs • Spare parts becoming obsolete (no longer manufactured) • Preservation and maintenance of inventory present a motivation to reduce storage levels	• Maintenance manager • Purchaser
3	**Motivation for implementing AM** • Certain spare parts unavailable on the market • Certain spare parts can not be purchased separately, resulting in purchasing of the larger assembly of which the part belongs • High price levels for certain spare parts • International supplier market makes for increased lead time • Increasing regulatory push for sustainability that can be met by repairing machines using AM parts • AM´s ability to manufacture parts with complex geometries	• Maintenance manager • Purchaser

4	**Current effects of AM implementation** • "3D printing group" of engineers/operators established • prototyping use • The plant currently produces some non-critical parts in-house with AM cheaper than the market could offer	• Maintenance manager • Purchaser • Supervisor competence development
5	**Requirements for AM providers (for future outsourcing of AM activities)** • AM provider expected to have legal expertise regarding intellectual property rights • Location being somewhat close is preferable, at least in initial phase • Variable demand probably means that AM provider should have a customer base beyond just Hydro Sunndal	• Maintenance manager
6	**Strategic direction for further AM** • Intention is to outsource AM in the future	• Maintenance manager • Purchaser • Supervisor competence development

6.0 Discussion

The following chapter will discuss the findings from the case study in light of the existing academic literature, to provide further insight into the research problem: *"How may implementation of additive manufacturing of spare parts improve maintenance and support in asset management?"* by discussing the related research questions.

6.1 RQ1: What is the current handling of spare parts logistics in Norsk Hydro Sunndal´s supply chain?

When it comes to managing spare parts, the company describes similar elements to what is found in the literature (see finding 2 in Table 5). Dekker, Kleijn, and De Rooij (1998) describe three main elements of spare parts logistics; costs, availability and time. This is consistent with the main considerations that the company describes. On the cost side, Khajavi, Partanen, and Holmström (2014) and Knofius et al. (2021) highlight slow-moving parts as particularly challenging. This challenge is also felt at the plant where some parts can be stored up to 10 years. These slow-moving parts especially incur costs related to the maintenance and preservation of the spare parts. In addition, the spare parts inventory is large, taking up significant space, adding to the complexity of spare parts logistics.

Authors like Chekurov et al. (2018) describe the limitations of the supplier market for spare parts as another challenge. The company often finds themselves in a position where they have to accept high prices from their suppliers, indicating that the limited number of spare part suppliers puts the suppliers in a strong position with regard to their pricing strategy (see finding 2 in Table 5).

With regard to the decision-making process model (Figure 2) developed by Cavalieri et al. (2008), the plant´s strategies for phase 2 (part classification) and phase 4 (stock management policy) are outlined. When it comes to the classification of spare parts, the company broadly separates between critical and non-critical parts (see finding 1 in Table 5). Critical parts are parts that are kept in stock, while non-critical parts are parts which need not be kept in stock. The stock management policy for critical parts is defined with MRP data, with orders being sent out automatically in the event of the stock level dropping to a pre-determined ordering point. However, this ordering point must be adjusted in the event of challenges in Hydro´s operations, or if the supplier faces challenges in their manufacturing.

6.2 RQ2: How does the current use of additive manufacturing affect spare parts logistics?

While AM has developed from being a prototyping tool to a fully-fledged manufacturing method (Petrovic et al. 2011), it has mostly been used in a prototyping capacity by the case company (see finding 4 in Table 5).

The literature mentions several benefits tied to AM. A fundamental advantage over traditional manufacturing is that setups are less expensive and time-intensive. There is also a reduced need for tools during the production setup (Achillas et al. 2015; Pour et al. 2016). This fact has enabled the case company to produce small batches of spare parts, something that likely would have been less economically viable than if traditional manufacturing was used (see finding 4 in Table 5). They have also utilized the ability of AM to manufacture complex geometries as mentioned by Bogue (2013) and Petrovic et al. (2011) to improve the design of the original traditionally manufactured part.

With reference to the classification tree mentioned earlier in Figure 7 (Lastra et al. 2022), the plant has mainly applied AM for simple polymer spare parts of smaller volumes, as shown highlighted in Figure 10.

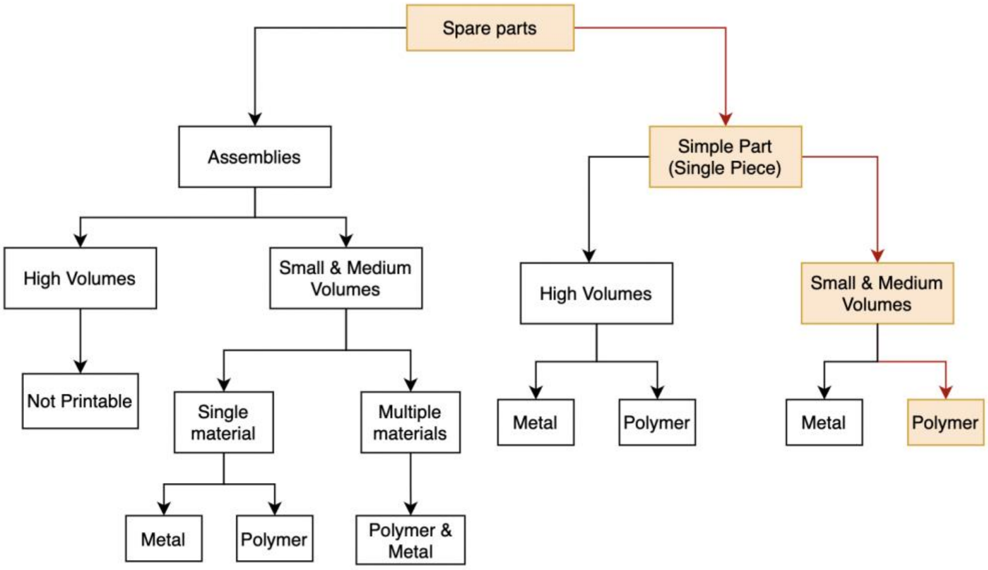

Figure 10: Spare part classification in relation to case study. Adapted from Lastra et al. (2022)

6.3 RQ3: What are the implications of future strategies for further development of additive manufacturing for management of spare parts logistics?

6.3.1 Motivation for Future Developments

A benefit outlined in the literature is the ability of AM to manufacture parts with complex geometries better than traditional manufacturing (Bogue 2013). This is highlighted as a major benefit by the case company (see finding 3 in Table 5) and provides motivation for further engagement with AM technologies. The ability to improve certain spare part designs, for instance by including air pockets or having hollowness, is something that AM opens the possibility for.

In terms of the cost-effectiveness of AM as a manufacturing method, several authors have analyzed the unit costs of AM technologies in relation to traditional manufacturing (TM) methods (Baumers and Holweg 2019; Ituarte, Khajavi, and Partanen 2016; Ruffo, Tuck, and Hague 2006). A fundamental difference between AM and TM is the lack of economies of scale. Economies of scale only partially apply to AM, where unit costs decrease as you improve the utilization of the 3D printer´s build volume. In terms of AM´s competitiveness over TM, Ituarte, Khajavi, and Partanen (2016) describes that AM will struggle to compete with TM for high-volume production, even if the AM cost curve decreases heavily in the future. The implication is that AM is more attractive as an option for manufacturing smaller volumes and for production where adjustments are made frequently. Based on findings from the interviews, it seems that high-volume production is not favoured from the case company´s perspective. They primarily look to AM for producing spare parts that have lower consumption levels. However, mass production of non-critical spare parts using AM might be a future avenue for spare part manufacturers. The case company views AM as a cost-effective method under the right conditions. They have on several occasions been able to 3D print spare parts for cheaper than what the market could provide (see finding 4 in Table 5). Situations where this has been the case have been characterized by problematic supply situations such as very high prices or the part not being available on the market. In some cases, parts are available to purchase, but suppliers mark up prices on individual parts to encourage buying the complete assembly that the part is included in (see findings 2 & 3 in Table 5).

Authors like Chekurov et al. (2018) and Attaran (2017) highlight equipment costs as one of the main barriers to implementation of AM among firms, though this is likely more of a problem for smaller companies compared with the case company. The maintenance manager viewed AM as a cost-effective method for the manufacturing of spare parts explaining that while investments in machines and digitalizing design drawings are necessary, the 3D printer can then work without requiring wages. This aspect is interesting as it makes AM an alternative in situations where the alternative is hiring an industry worker, given the wage level in Norway.

Other authors such as Ballardini, Ituarte, and Pei (2018) point to barriers such as the fear of inferior product quality. In the case of the case company, they expressed that they did not have sufficient experience with AM to truly say whether they believed AM to have inferior product quality. However, they have in some instances used AM to improve the quality of certain spare parts by redesigning them (see finding 4 in Table 5).

Another important issue highlighted by Ballardini, Ituarte, and Pei (2018) and Khajavi, Salmi, and Holmström (2020) is that many firms seem to lack digitalized information about their spare parts in the form of CAD-files. This represents a hurdle when attempting to implement AM, and could indicate that AM is immature for logistics. The case company having taken the initiative to build competency among their engineers in AM design and digital drawings is a good sign that they can avoid this barrier (see finding 4 in Table 5).

6.3.2 Outsourcing vs. In-House

The decision to implement AM in-house or outsource the activity is another important point of discussion (see finding 6 in Table 5). The interviews revealed that the plant´s ambition is not a large-scale in-house implementation of AM, but that the current small-scale implementation has been done in preparation for an outsourcing partnership. Still, the plant has some in-house AM capabilities. The decision to outsource AM in a strategic partnership is based on the idea that an AM supplier may have the right resources and the right equipment to deliver a supply of spare parts. Friedrich, Lange, and Elbert (2022) and H. Rogers, Baricz, and Pawar (2016) identify the technological uncertainty of an emerging technology like AM as an argument for outsourcing, explaining that outsourcing can remove risks related to this uncertainty. By outsourcing AM, the plant will not bear the risks of large investments in machines, equipment and training. The variable demand for spare parts might make it hard to achieve a high capacity utilization of the 3D printers if one is to implement AM in-house. Friedrich, Lange, and Elbert (2022) mention that AM service providers (suppliers) on the other hand would be better positioned to achieve economies of scale by utilizing the capacity of AM machines by pooling orders.

Some arguments in the literature against outsourcing of AM include concerns related to intellectual property rights such as copying of designs (Friedrich, Lange, and Elbert 2022). To counter this aspect, the plant would expect a supplier to have a certain level of legal expertise regarding AM (see finding 5 in Table 5).

Some firms may also consider their AM capabilities as a core competency and therefore not want to outsource in order to protect their competitive advantage (Friedrich, Lange, and Elbert 2022). The plant´s AM capabilities are however in an early stage, and they are seeking to outsource to better utilize the technology (see finding 6 in Table 5). This may be an indication that they do not consider AM competence as a core competency.

In addition, the certification of spare parts produced with AM becomes an important avenue for further implementation. Certification of spare parts could be necessary especially when considering applying non-standard parts produced with AM in machines which may imply consequences with regard to warranty contracts related to maintenance of machinery from the supplier.

6.3.3 Supply Chain Configuration

Currently, the plant has a decentralized configuration; with its 3D printers located in-house serving the demand for additively manufactured parts (see finding 4 in Table 5). The demand comes from various departments involved in plant operations. The findings from the interviewees indicated the plant´s ambition to connect themselves to an AM service provider to further build their AM capabilities (see finding 6 in Table 5). This would mean opting for a centralized supply chain configuration in the future, or at least a mixture of decentralized and centralized; since the plant could keep (and possibly expand) their current in-house AM capabilities. Still, the interviews indicate an intention to mainly use an AM service provider for the manufacturing of AM parts. With their current centralized AM set-up, they have experienced some of the benefits outlined in the literature, such as no transportation costs for the parts as they are produced at the plant on-demand. As well as the reduction in lead times.

When switching to a centralized SC configuration, transportation costs will become the dominant cost factor (Li et al. 2017). Consequently, the location of the AM service provider greatly impacts the transportation costs of the AM supply chain.

Liu et al. (2014) recommend a decentralized approach for parts with high and stable demand, and a centralized approach for parts with long lead times, and low and variable demand. In light of this, it could be appropriate for the plant to use its in-house AM capabilities to produce parts with high and steady demand while using the AM service provider to produce parts with low and variable demand. This is logical as producing high-demand parts at the plant will save on transportation costs. However, manufacturing costs may be high, and as pointed out by Friedrich, Lange, and Elbert (2022); it may be difficult for a firm to generate enough demand on its own to achieve high capacity utilization of the 3D printers. This again may be an argument for an outsourced centralized AM solution being the more cost-effective option, considering that achieving high utilization of 3D printers might be difficult.

The Sunndal plant is the only Hydro plant to have implemented AM thus far. However, if more of Hydro´s Norwegian plants implement AM this could generate more demand for additively manufactured parts within the organization. The other plants will likely have some similarities in terms of the spare parts they require. If AM is introduced to other Hydro plants, a decentralized configuration might be costly given the investment in AM machines, not to mention other costs related to training of personnel and maintenance of the 3D printers (Friedrich, Lange, and Elbert 2022; Mellor, Hao, and Zhang 2014). Therefore a centralized configuration may be more realistic for serving all the plants with 3D-printed spare parts. For a centralized approach, the location of the AM service provider will be of great importance when it comes to the more critical parts where lead time could be of the essence.

Authors such as Li et al. (2017) and Khajavi, Holmström, and Partanen (2018) hypothesize that future reductions in the cost of acquiring AM machinery will favour the decentralized configuration. Holmström et al. (2010) also point to the future technological development of AM into a more general-purpose technology as another point that will increase the attractiveness of decentralized AM in the future. In the case of the plant examined in this case study, a long-term goal of opting for the centralized configuration in the future has been defined (see finding 6 in Table 5). However, if there are considerable reductions in the cost of AM equipment in the future, this may contribute to a mixed configuration being a realistic option.

6.3.4 Sustainability

Calignano and Mercurio (2023) explain that AM is a technology that could facilitate the reshoring of manufacturing processes. The authors state that reshoring of manufacturing with AM may simplify supply chains and reduce costs related to transportation and warehousing. It may also provide proximity to customers. In the context of this study, reshoring of manufacturing by spare part suppliers could solve some problems for the customer (Hydro), since one of the findings was increasing lead time as a consequence of spare part suppliers having manufacturing in low-cost countries (see finding 3 in Table 5). It could also be reasonable to assume that the reshoring of spare part manufacturing by the spare part suppliers through AM could be a necessary method for the spare part suppliers to stay competitive.

Another key element for sustainability is extending the life cycle of products, which is cited in the literature as one of the benefits of AM (Ford and Despeisse 2016). This ability was found to be a way to meet the increased regulatory push for sustainability that is expected in the years to come (see finding 3 in Table 5).

6.3.5 Location of AM

When outsourcing AM, close collaboration is required with the supplier (Oettmeier and Hofmann 2016). Close collaboration will likely be easier if the AM supplier is located near the plant. This point is echoed by the case company; one of the findings (see finding 5 in Table 5) was a desire for proximity with regard to the location of the supplier.

One of the challenges in spare parts supply (see finding 2 in Table 5) was found to be the preservation and maintenance of the spare parts inventory. This is an interesting aspect as it presents a motivation to reduce the spare parts inventory level. By using an AM provider (or “AM hub”) the plant will not experience the benefits of the on-demand production capabilities of AM which eliminates the need for inventory and transportation. Spare parts will be produced by the AM provider, then transported, and finally stored in the warehouse. Still, the AM provider may in some instances offer better lead time than traditional manufacturers/suppliers, especially since some suppliers have manufacturing in foreign countries potentially making the lead time high.

6.3.6 Sourcing Approach

Regarding the sourcing approach, Knofius et al. (2021) emphasized that AM may function well as a complement to traditional manufacturing, providing an emergency supply source. The plant indents to collaborate with an AM service provider in the future, which could diversify their options for the supply of spare parts, possibly contributing to solving challenges in spare parts logistics such as high costs or obsolescent parts (see finding 2 in Table 5).

AM may provide the ability to have a dual sourcing approach for certain parts, with the potential to alternate between a traditional supplier and an AM service provider. As the technology matures, single sourcing with just AM may become more attractive for certain parts. However, single sourcing of AM parts may not be suitable for critical parts with a high impact on downtime (Knofius et al. 2021).

6.3.7 Potential Future Spare Part Logistics with AM

When it comes to future integration of AM into the plant´s strategy and management of spare parts supply, its applicability may first and foremost be for non-critical parts. Since current use is concentrated around non-critical parts, it would be reasonable to assume that AM for non-critical parts is more mature than AM for critical parts. Concerning the plant´s spare part logistics process outlined in Figure 9, AM most likely fits in on the non-critical side. Figure 11 displays how AM fits into the spare parts logistics process.

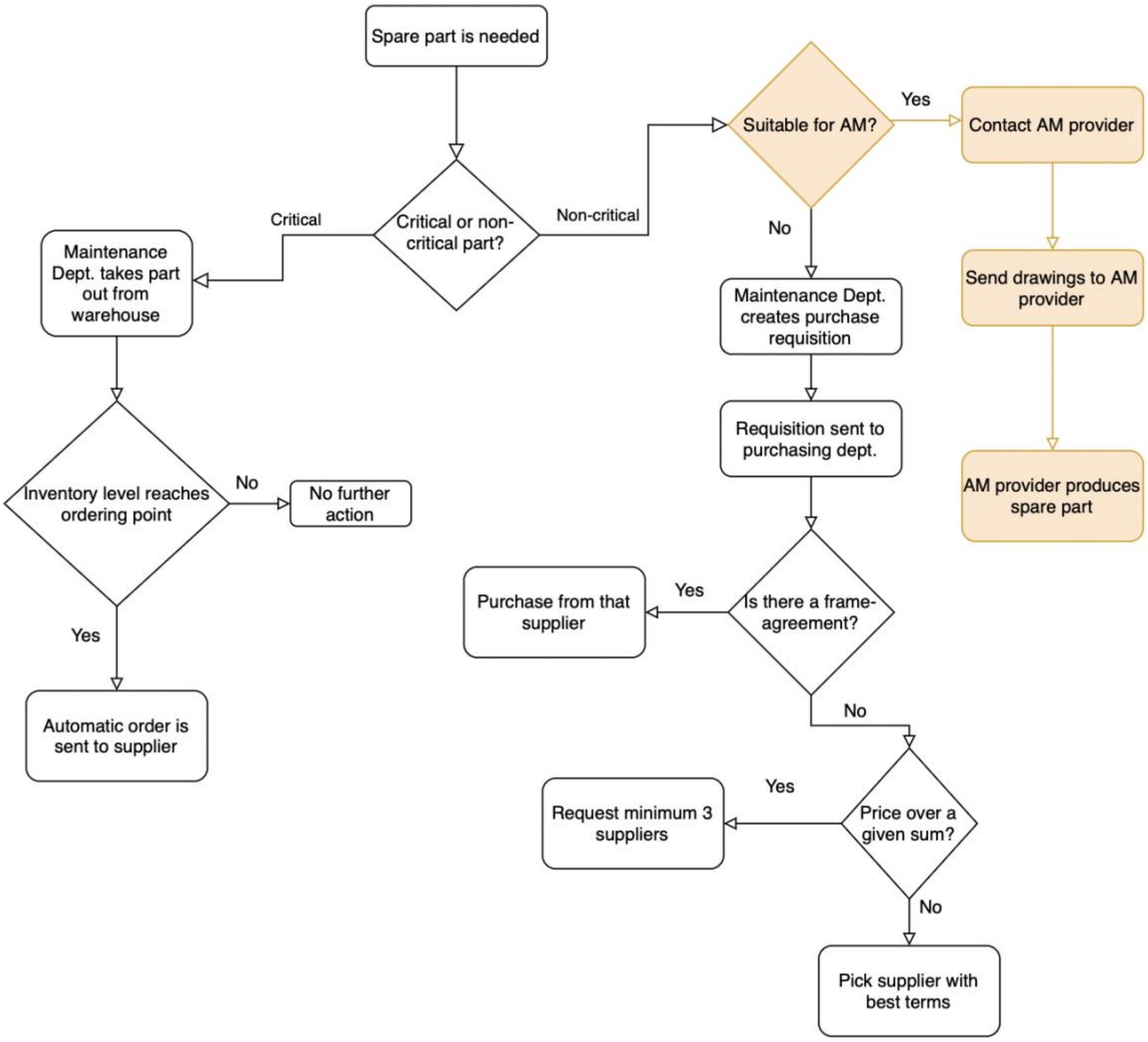

Figure 11: Spare parts logistics process with AM

7.0 Conclusion

This chapter will present a summary of the case study´s key findings, as well as the managerial implications they present. In addition, the study´s limitations are discussed. Finally, further research areas are suggested.

7.1 Research Summary

The research problem examined in this case study related to the potential of additive manufacturing (AM) to facilitate improvements in the management of assets, specifically the management of spare parts:

“How may implementation of additive manufacturing of spare parts improve maintenance and support in asset management?”

The research problem has been studied through several research questions. The first research question was concerned with detailing existing spare part processes: *“What is the current handling of spare parts logistics in Norsk Hydro Sunndal´s supply chain?”* This research question has been answered by detailing the process of acquiring spare parts, which is different for critical and non-critical parts. Spare parts are classified as either critical parts which are kept in stock, or non-critical parts which are not kept in stock. Challenges in the spare part supply are also outlined.

The second research questions intended to examine the current use of additive manufacturing at the plant: *“How does the current use of additive manufacturing affect spare parts logistics?”* The findings revealed that AM had been used primarily for prototyping and that AM had facilitated some design improvements for non-critical parts. Some non-critical parts were also manufactured in-house with AM for cheaper than what the market could offer.

The third research question was concerned with examining the future applications of AM: *“What are the implications of future strategies for further development of additive manufacturing for management of spare parts logistics?”* This research question has been answered by examining the plant´s motivation for the development of AM, as well as their requirements for AM service providers in the event of future outsourcing of AM activities.

The main motivations for using AM for spare parts relate to utilizing AM to solve certain challenges related to the supply of spare parts. Such challenges are for instance that certain spare parts have high costs, or that certain spare parts may no longer be available on the market. Some parts may also only be purchased as part of a larger assembly to which the part belongs. In addition, an international supplier market makes for increased lead time for some parts. An increased regulatory push for sustainability is also found to be a motivation as AM can contribute to extending the life cycle of equipment through 3D-printed parts. AM also opens up the possibility to redesign some parts using AM´s ability to manufacture more complex geometries than traditional manufacturing.

A key finding for this research question was the intention to outsource AM activities to an AM service provider in the future. While the current in-house implementation has seen several effects related to design improvements and costs, the main intention has been to build AM competency and familiarity with the technology before initiating a partnership with an AM service provider in the future. In terms of the preferred characteristics of the AM provider, geographical proximity is preferred, at least in an initial phase. It is in the case company´s interest that the AM provider has customers beyond just their plant, given that the demand will likely be variable. A certain level of expertise related to legal aspects such as intellectual property rights is also expected.

To answer the research problem, AM of spare parts may improve maintenance and support in asset management by providing an alternative supply source and potentially alleviating some of the challenges faced in the supply of spare parts. For instance, some spare parts may potentially be produced cheaper with AM than what traditional suppliers can offer. AM may also be used to produce obsolescent parts that are no longer available on the market. The potential for AM to reduce lead time is also an aspect, in addition to its ability to produce more complex geometries and facilitate design improvements for certain spare parts.

7.2 Managerial Implications

As discussed in this thesis, some decision-making aspects related to the organization of AM capacity include the decision to outsource or implement in-house and whether to have a centralized or decentralized supply chain configuration. Decision-makers need to consider the implications of these aspects. For instance, a centralized configuration would make transportation costs the dominant factor (Li et al. 2017), while a decentralized configuration would mean high manufacturing costs (Liu et al. 2014).

Further implementation of AM would likely imply a stronger need to implement a way of classifying spare parts based on their suitability for AM. In addition, it would be necessary to have CAD files readily available, as well as original drawings, as this was found in the literature to be a major barrier (Ballardini, Ituarte, and Pei 2018; Khajavi, Holmström, and Partanen 2018).

7.3 Limitations

The single case study approach has been discussed previously in the methodology section. The use of the single case study limits the ability to generalize your findings, but gives more detail about a single case than a multiple case study (Thomas 2010). By virtue of this, the findings of this case study may not necessarily be generalizable to other industries. Conducting a multiple case study could have helped improve the generalizability of the study, however, that could have meant gaining less detail about each individual case.

This study has concentrated on the application of AM in spare parts logistics. However, the legal landscape of AM remains a challenging topic characterized by a great deal of uncertainty. This has been discussed in depth by relatively few authors and is considered one of the biggest research gaps in AM literature by Mecheter, Pokharel, and Tarlochan (2022). The legal aspects of AM have namely been studied by Ballardini, Ituarte, and Pei (2018). To narrow the scope of this study, this perspective, including issues such as intellectual property rights, has not been discussed in great detail. Naturally, the legal side is a vital aspect when discussing AM implementation. Therefore, it becomes one of the main limitations of this study.

The fact that AM is a rapidly developing technology also indicates a limitation of the findings in this thesis. The AM industry is growing 22% annually according to Bromberger, Ilg, and Maria (2022), meaning that the technology could change significantly in just a few years.

As highlighted in Figure 10, this case study has concentrated on the use of AM for the production of simple polymer parts with lower volumes, and not assemblies or metal parts. The study´s findings may therefore not be generalizable to these other contexts not examined in the study.

7.4 Suggestions For Further Research

This study has examined issues related to the organization of AM capacity, discussing the outsourcing approach vs. the in-house approach, as well as the centralized configuration vs. the decentralized configuration. This has been examined through qualitative research. A suggestion for further research may be to concentrate on quantitative aspects, for instance by comparing the costs or environmental sustainability performance of a centralized SC configuration vs. a decentralized SC configuration. As mentioned in the previous chapter, the uncertain legal environment surrounding AM is also an area where a better understanding is needed.

8.0 References

Achillas, Ch, D Aidonis, E Iakovou, M Thymianidis, and D Tzetzis. 2015. "A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory." *Journal of manufacturing Systems* 37: 328-339.

Araújo, Nuno, Vânia Pacheco, and Leonardo Costa. 2021. "Smart Additive Manufacturing: The Path to the Digital Value Chain." *Technologies* 9 (4): 88.

Attaran, Mohsen. 2017. "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing." *Business horizons* 60 (5): 677-688.

Ballardini, Rosa Maria, Iñigo Flores Ituarte, and Eujin Pei. 2018. "Printing spare parts through additive manufacturing: legal and digital business challenges." *Journal of Manufacturing Technology Management*.

Barreto, Luis, Antonio Amaral, and Teresa Pereira. 2017. "Industry 4.0 implications in logistics: an overview." *Procedia manufacturing* 13: 1245-1252.

Baumers, Martin, and Matthias Holweg. 2019. "On the economics of additive manufacturing: Experimental findings." *Journal of Operations Management* 65 (8): 794-809.

Beamon, Benita M. 1998. "Supply chain design and analysis: Models and methods." *International journal of production economics* 55 (3): 281-294. https://doi.org/10.1016/S0925-5273(98)00079-6.

Belhadi, Amine, Sachin S Kamble, Mani Venkatesh, Charbel Jose Chiappetta Jabbour, and Imane Benkhati. 2022. "Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view." *International Journal of Production Economics* 249: 108516.

Bogue, Robert. 2013. 3D printing: the dawn of a new era in manufacturing? Bradford, England.

Boon, Wouter, and Bert Van Wee. 2018. "Influence of 3D printing on transport: a theory and experts judgment based conceptual model." *Transport Reviews* 38 (5): 556-575.

Bromberger, Jörg, Julian; Miranda Ilg, and Ana Maria, 15. March 2022, 2022, "The mainstreaming of additive manufacturing," https://www.mckinsey.com/capabilities/operations/our-insights/the-mainstreaming-of-additive-manufacturing.

Butt, Javaid. 2020. "Exploring the interrelationship between additive manufacturing and Industry 4.0." *Designs* 4 (2): 13.

Calignano, Flaviana, and Vincenza Mercurio. 2023. "An overview of the impact of additive manufacturing on supply chain, reshoring, and sustainability." *Cleaner Logistics and Supply Chain* 7: 100103.

Cavalieri, Sergio, Marco Garetti, Marco Macchi, and Roberto Pinto. 2008. "A decision-making framework for managing maintenance spare parts." *Production planning & control* 19 (4): 379-396.

Chekurov, Sergei, Sini Metsä-Kortelainen, Mika Salmi, Irene Roda, and Ari Jussila. 2018. "The perceived value of additively manufactured digital spare parts in industry: An empirical investigation." *International Journal of Production Economics* 205: 87-97.

Chen, Ze, Changjun Han, Ming Gao, Sastry Yagnanna Kandukuri, and Kun Zhou. 2022. "A review on qualification and certification for metal additive manufacturing." *Virtual and Physical Prototyping* 17 (2): 382-405.

Christopher, Martin. 2016. *Logistics & Supply Chain Management*. Pearson UK.

Colorado, Henry A, David E Mendoza, Hua-Tay Lin, and Elkin Gutierrez-Velasquez. 2022. "Additive manufacturing against the Covid-19 pandemic: A technological model for the adaptability and networking." *journal of materials research and technology* 16: 1150-1164.

Cooper, Martha C, Douglas M Lambert, and Janus D Pagh. 1997. "Supply chain management: more than a new name for logistics." *The international journal of logistics management* 8 (1): 1-14.

Costabile, G, M Fera, F Fruggiero, Alfredo Lambiase, and Duc Pham. 2017. "Cost models of additive manufacturing: A literature review." *International Journal of Industrial Engineering Computations* 8 (2): 263-283.

Creswell, John W., and J. David Creswell. 2018. *Research Design: Qualitative, Quantitative & Mixed Methods Approaches*. 5th edition. ed. Los Angeles, California: Sage.

Dekker, Rommert, Marcel Jacobus Kleijn, and PJ De Rooij. 1998. "A spare parts stocking policy based on equipment criticality." *International Journal of production economics* 56: 69-77.

DNV. 2023. "Additive Manufacturing and 3D Printing." Accessed 26. March. https://www.dnv.com/services/additive-manufacturing-and-3d-printing-110872.

Ellram, Lisa M. 1996. "The use of the case study method in logistics research." *Journal of business logistics* 17 (2): 93.

Ford, Simon, and Mélanie Despeisse. 2016. "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges." *Journal of cleaner Production* 137: 1573-1587.

Friedrich, Anne, Anne Lange, and Ralf Elbert. 2022. "Make-or-buy decisions for industrial additive manufacturing." *Journal of Business Logistics* 43 (4): 623-653.

Gebler, Malte, Anton JM Schoot Uiterkamp, and Cindy Visser. 2014. "A global sustainability perspective on 3D printing technologies." *Energy policy* 74: 158-167.

Gomm, Roger, Martyn Hammersley, and Peter Foster. 2000. *Case Study Method: Key Issues, Key Texts*. London: Sage.

Handal, Raed. 2017. "An implementation framework for additive manufacturing in supply chains." *Journal of Operations and Supply Chain Management (JOSCM)* 10 (2): 18-31.

Haroun, Ahmed E, and Salih O Duffuaa. 2009. "Maintenance organization." *Handbook of maintenance management and engineering*: 3-15.

Hedenstierna, Carl Philip T, Stephen M Disney, Daniel R Eyers, Jan Holmström, Aris A Syntetos, and Xun Wang. 2019. "Economies of collaboration in build-to-model operations." *Journal of Operations Management* 65 (8): 753-773.

Heinen, J Jakob, and Kai Hoberg. 2019. "Assessing the potential of additive manufacturing for the provision of spare parts." *Journal of Operations Management* 65 (8): 810-826.

Holmström, Jan, and Timothy Gutowski. 2017. "Additive manufacturing in operations and supply chain management: No sustainability benefit or virtuous knock-on opportunities?" *Journal of Industrial Ecology* 21 (S1): S21-S24.

Holmström, Jan, Jouni Partanen, Jukka Tuomi, and Manfred Walter. 2010. "Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment." *Journal of manufacturing technology management*.

Hox, Joop J, and Hennie R Boeije. 2005. "Data collection, primary versus secondary."

Huiskonen, Janne. 2001. "Maintenance spare parts logistics: Special characteristics and strategic choices." *International journal of production economics* 71 (1-3): 125-133.

Hydro. 2021. "On the way to net zero aluminium." Last Modified 15. December 2021. Accessed 21. April. https://www.hydro.com/en/media/news/2021/on-the-way-to-net-zero-aluminium/.

---. 2022a. *Annual Report 2022.* Norsk Hydro (Oslo).

---. 2022b. "Hydro's roadmap to zero-emission aluminium production." Last Modified 29. September 2022. Accessed 21. April. https://www.hydro.com/en/media/on-the-agenda/hydros-roadmap-to-zero-emission-aluminium-production/.

ISO/ASTM. 2021. *ISO/ASTM 52900:2021 Additive manufacturing - General principles - Fundamentals and vocabulary.* West Conshohocken, PA, USA: ASTM International.

Ituarte, Iñigo Flores, Siavash H Khajavi, and Jouni Partanen. 2016. "Challenges to implementing additive manufacturing in globalised production environments." *International Journal of Collaborative Enterprise* 5 (3-4): 232-247.

Johnson, Phil, and John Gill. 2010. *Research Methods for Managers*. Third edition ed. Thousand Oaks, California: Sage.

Kallio, Hanna, Anna-Maija Pietilä, Martin Johnson, and Mari Kangasniemi. 2016. "Systematic methodological review: developing a framework for a qualitative semi-structured interview guide." *J Adv Nurs* 72 (12): 2954-2965. https://doi.org/10.1111/jan.13031.

Kehoe, Dennis, and Nick Boughton. 2001. "Internet based supply chain management: A classification of approaches to manufacturing planning and control." *International Journal of Operations & Production Management* 21 (4): 516-524.

Khajavi, Siavash H, Jan Holmström, and Jouni Partanen. 2018. "Additive manufacturing in the spare parts supply chain: Hub configuration and technology maturity." *Rapid Prototyping Journal*.

Khajavi, Siavash H, Jouni Partanen, and Jan Holmström. 2014. "Additive manufacturing in the spare parts supply chain." *Computers in industry* 65 (1): 50-63.

Khajavi, Siavash H, Mika Salmi, and Jan Holmström. 2020. "Additive manufacturing as an enabler of digital spare parts." *Managing 3D Printing: Operations Management for Additive Manufacturing*: 45-60.

Khorasani, Mahyar, Jennifer Loy, Amir Hossein Ghasemi, Elmira Sharabian, Martin Leary, Hamed Mirafzal, Peter Cochrane, Bernard Rolfe, and Ian Gibson. 2022. "A review of Industry 4.0 and additive manufacturing synergy." *Rapid Prototyping Journal* 28 (8): 1462-1475.

Knofius, Nils, Matthieu C van der Heijden, Andrei Sleptchenko, and Willem HM Zijm. 2021. "Improving effectiveness of spare parts supply by additive manufacturing as dual sourcing option." *OR Spectrum* 43 (1): 189-221.

Kothari, Chakravanti Rajagopalachari. 2004. *Research Methodology: Methods and Techniques*. New Delhi: New Age International.

Kothman, Ivo, and Niels Faber. 2016. "How 3D printing technology changes the rules of the game: Insights from the construction sector." *Journal of Manufacturing Technology Management* 27 (7): 932-943.

Kunovjanek, Maximilian, and Gerald Reiner. 2020. "How will the diffusion of additive manufacturing impact the raw material supply chain process?" *International Journal of Production Research* 58 (5): 1540-1554.

Lasi, Heiner, Peter Fettke, Hans-Georg Kemper, Thomas Feld, and Michael Hoffmann. 2014. "Industry 4.0." *Business & information systems engineering* 6: 239-242.

Lastra, René, Alejandro Pereira, Miguel Díaz-Cacho, Jorge Acevedo, and Antonio Collazo. 2022. "Spare Parts Made by Additive Manufacturing to Improve Preventive Maintenance." *Applied Sciences* 12 (20): 10564.

Li, Yao, Guozhu Jia, Yang Cheng, and Yuchen Hu. 2017. "Additive manufacturing technology in spare parts supply chain: a comparative study." *International Journal of Production Research* 55 (5): 1498-1515.

Liu, Peng, Samuel H Huang, Abhiram Mokasdar, Heng Zhou, and Liang Hou. 2014. "The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis." *Production planning & control* 25 (13-14): 1169-1181.

Mecheter, Asma, Shaligram Pokharel, and Faris Tarlochan. 2022. "Additive Manufacturing Technology for Spare Parts Application: A Systematic Review on Supply Chain Management." *Applied Sciences* 12 (9): 4160.

Mellor, Stephen, Liang Hao, and David Zhang. 2014. "Additive manufacturing: A framework for implementation." *International journal of production economics* 149: 194-201.

Mentzer, John T, William DeWitt, James S Keebler, Soonhong Min, Nancy W Nix, Carlo D Smith, and Zach G Zacharia. 2001. "Defining supply chain management." *Journal of Business logistics* 22 (2): 1-25.

Meredith, Jack. 1998. "Building operations management theory through case and field research." *Journal of operations management* 16 (4): 441-454.

Min, Soonhong, Zach G Zacharia, and Carlo D Smith. 2019. "Defining supply chain management: in the past, present, and future." *Journal of Business Logistics* 40 (1): 44-55.

Nagarajan, Hari PN, Arvind Shankar Raman, and Karl R Haapala. 2018. "A sustainability assessment framework for dynamic cloud-based distributed manufacturing." *Procedia CIRP* 69: 136-141.

Naghshineh, Bardia, and Helena Carvalho. 2022. "The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review." *International Journal of Production Economics* 247: 108387.

Oettmeier, Katrin, and Erik Hofmann. 2016. "Impact of additive manufacturing technology adoption on supply chain management processes and components." *Journal of Manufacturing Technology Management* 27 (7): 944-968.

Peron, Mirco, and Fabio Sgarbossa. 2021. "Additive manufacturing and spare parts: Literature review and future perspectives." *Advanced Manufacturing and Automation X 10*: 629-635.

Petrovic, Vojislav, Juan Vicente Haro Gonzalez, Olga Jordá Ferrando, Javier Delgado Gordillo, Jose Ramón Blasco Puchades, and Luis Portolés Griñan. 2011. "Additive layered manufacturing: sectors of industrial application shown through case studies." *International Journal of Production Research* 49 (4): 1061-1079.

Pour, Milad Ashour, Massimo Zanardini, Andrea Bacchetti, and Simone Zanoni. 2016. "Additive manufacturing impacts on productions and logistics systems." *IFAC-PapersOnLine* 49 (12): 1679-1684.

Praveena, BA, N Lokesh, Abdulrajak Buradi, N Santhosh, BL Praveena, and R Vignesh. 2022. "A comprehensive review of emerging additive manufacturing (3D printing technology): Methods, materials, applications, challenges, trends and future potential." *Materials Today: Proceedings* 52: 1309-1313.

Rejeski, David, Fu Zhao, and Yong Huang. 2018. "Research needs and recommendations on environmental implications of additive manufacturing." *Additive Manufacturing* 19: 21-28.

Rinaldi, Marta, Mario Caterino, Marcello Fera, Pasquale Manco, and Roberto Macchiaroli. 2021. "Technology selection in green supply chains-the effects of additive and traditional manufacturing." *Journal of Cleaner Production* 282: 124554.

Roda, Irene, Marco Macchi, Luca Fumagalli, and Pablo Viveros. 2014. "A review of multi-criteria classification of spare parts: From literature analysis to industrial evidences." *Journal of Manufacturing Technology Management* 25 (4): 528-549.

Rogers, Everett M, Arvind Singhal, and Margaret M Quinlan. 2014. "Diffusion of innovations." In *An integrated approach to communication theory and research*, 432-448. Routledge.

Rogers, Helen, Norbert Baricz, and Kulwant S Pawar. 2016. "3D printing services: classification, supply chain implications and research agenda." *International Journal of Physical Distribution & Logistics Management* 46 (10): 886-907.

Ruffo, Massimiliano, Chris Tuck, and R Hague. 2006. "Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 220 (9): 1417-1427.

Rupp, Mario, Manuel Buck, René Klink, Markus Merkel, and David K Harrison. 2022. "Additive manufacturing of steel for digital spare parts–A perspective on carbon emissions for decentral production." *Cleaner Environmental Systems* 4: 100069.

Rüßmann, Michael, Markus Lorenz, Philipp Gerbert, Manuela Waldner, Jan Justus, Pascal Engel, and Michael Harnisch. 2015. "Industry 4.0: The future of productivity and growth in manufacturing industries." *Boston consulting group* 9 (1): 54-89.

Salmi, Mika, Jouni Partanen, Jukka Tuomi, Sergei Chekurov, Roy Björkstrand, Eero Huotilainen, Kirsi Kukko, Niklas Kretzschmar, Jan Akmal, and Kalle Jalava. 2018. "Digital spare parts."

Saunders, Mark N. K., Philip Lewis, and Adrian Thornhill. 2012. *Research Methods for Business Students*. 6th ed. Harlow: Pearson.

Song, Ruoyu, and Cassandra Telenko. 2017. "Material and energy loss due to human and machine error in commercial FDM printers." *Journal of cleaner production* 148: 895-904.

Srivastava, Manu, Sandeep Rathee, Vivek Patel, Atul Kumar, and Praveennath G Koppad. 2022. "A review of various materials for additive manufacturing: Recent trends and processing issues." *journal of materials research and technology* 21: 2612-2641.

Stake, Robert E. 1995. *The Art of Case Study Research*. Thousand Oaks, California: Sage.

Stebbins, Robert A. 2001. *Exploratory Research in the Social Sciences*. Vol. 48. Thousand Oaks, California: Sage.

Thomas, Gary. 2010. *How to Do Your Case Study: A Guide for Students*. Los Angeles: Sage.

Tziantopoulos, Konstantinos, Naoum Tsolakis, Dimitrios Vlachos, and Loukas Tsironis. 2019. "Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era." *Production Planning & Control* 30 (7): 510-521.

Vafadar, Ana, Ferdinando Guzzomi, Alexander Rassau, and Kevin Hayward. 2021. "Advances in metal additive manufacturing: a review of common processes, industrial applications, and current challenges." *Applied Sciences* 11 (3): 1213.

Voss, Chris. 2010. "Case research in operations management." In *Researching operations management*, 176-209. New York: Routledge.

Westerweel, Bram, Rob JI Basten, and Geert-Jan van Houtum. 2018. "Traditional or additive manufacturing? Assessing component design options through lifecycle cost analysis." *European Journal of Operational Research* 270 (2): 570-585.

Wohlers, Terry. 2019. *Wohlers Report 2019: 3D Printing and Additive Manufacturing State of the Industry*. Wohlers Associates.

Wu, Dazhong, David W Rosen, and Dirk Schaefer. 2014. "Cloud-based design and manufacturing: status and promise." *Cloud-Based Design and Manufacturing (CBDM) A Service-Oriented Product Development Paradigm for the 21st Century*: 1-24.

Yin, Robert K. 2018. *Case Study Research and Applications: Design and Methods*. Sixth edition. ed. Los Angeles, California: Sage.

Zijm, Henk, Nils Knofius, and Matthieu van der Heijden. 2019. "Additive manufacturing and its impact on the supply chain." *Operations, logistics and supply chain management*: 521-543.

9.0 Appendices

9.1 Appendix 1: Interview Guide 1

The following interview guide was used in the semi-structured interviews conducted with representatives from the case company. The interview guide was sent to the respondents in advance so they could adequately prepare for the interview.

General questions:

1. Which department do you work in?
2. What are your main duties/activities?
3. Have you been involved in the introduction of 3D printing technology in the company? If so explain how you have been involved.
4. What is the long-term plan/goal for using 3D printing in your company

Spare parts inventory

1. What types of spare parts do you have?
2. Can you describe the general stocking policy for spare parts inventory?
3. What are currently the biggest challenges with spare parts logistics in your organization?
4. What types of spare parts could benefit from being 3D printed?
5. Is a digital inventory system something you have considered implementing?
6. To what extent is the procurement process different with 3D printing?

Current handling of spare parts logistics

1. Describe the process of acquiring the spare part. What do you know about the following for the spare part in question?

    a. What triggers the demand/need for the spare parts order?
    b. How did the process start?
    c. Which actions were performed, and when were they performed?
    d. Describe the information flow (between employees, between external companies, through IT-system)

    e. Where is the supplier located? How is the spare part transported to the plant?

2. Can you describe the stocking policy for this spare part?
3. How many suppliers do you have for the spare part? Just one or multiple?

3D printing

1. Do you 3D print parts yourself or does a 3D printing service provider perform that for you?
2. For the current crop of spare parts produced with 3D printing, which of the approaches in the last question do you consider superior?
3. If you increase the proportion of 3D-printed parts in the future, will the approach change?
4. Which spare parts are currently produced with 3D printing and what have been the changes when compared with purchasing these parts from a traditional supplier? with respect to:
    a. Costs
    b. Lead time
    c. Emissions
    d. Machine downtime
5. What does your 3D printing production capacity look like?
6. Are there any challenges related to the quality of a 3D-printed part vs. a traditionally manufactured part?
7. Is the supply chain changed with regard to its length (number of companies involved) when comparing 3D printed parts with traditionally manufactured parts?
8. What is the level of 3D printing competency within the organization?

9.2 Appendix 2: Interview Guide 2

1. Regarding the market for AM service providers, what kind of knowledge and capabilities do you envision the service providers having in order to suit your needs?
2. Ideally, where should they be located?
3. What kind of relationship do you envision having with AM service providers?