Additive Manufacturing for Maintenance, Repair and Operations within the Aerospace Industry at GKN

A research study on how to overcome the challenges of implementing additive manufacturing for maintenance and repair purposes.

Master's thesis in Production Engineering

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Cover: Schematic image showing a symbol representing AM within the aerospace industry in the middle, between a symbol representing the manufacturing industry to the left and sustainable recycling to the right.

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Abstract

The aerospace industry is known to manufacture expensive components, which are critical to safety and exposed to wear. This has led to an increased need for a circular business model, which has become attractive in several manufacturing organisations, where repair and maintenance of components is offered. As the aerospace industry is product-oriented, Additive Manufacturing (AM) in repair is considered to be an optimal manufacturing method to eliminate waste and achieve a more sustainable organisation. Guest Keen and Nettlefolds (GKN) Aerospace is constantly working on their sustainable development and has today come a long way, however, the road has not been easy.

The research study is based on three research questions where the current state of AM repair is analysed at the company. The challenges related to the implementation of AM repair are then investigated and alternative solutions and opportunities for overcoming these are suggested. Finally, relevant cost parameters are identified in order to present a product cost guideline for AM repair. The thesis answers these research questions through four primary research methods. A qualitative study in the shape of a pre-study at the company and an interview study with employees. A literature study where the identification of alternative solutions and opportunities was discovered. A benchmark study with two external actors within the AM field and finally, a case study on different cost models for AM repair.

The current state analysis showed that GKN is in the early development phase with the implementation of AM repair. The implementation of AM with specific materials, component-geometries, and -sizes for repairs is still being evaluated. The challenges related to the implementation of AM repair, identified at GKN, are in the areas of Strategy, Communication, Qualification and Verification, Experience, AM Competence, AM Equipment, Material aspects, and Cost. To overcome these challenges, alternative solutions and opportunities are proposed in the areas of Organisational structure, Interdepartmental collaboration, Internal organisational communication, Design Methodologies, Inspection, and Analysis as well as Application and Standards. Finally, the results of the case study showed that Pre-processing, Set-up, AM-build, Removal & Cleanup, Post-processing as well as Inspection and Testing are relevant areas to consider when designing a product cost guideline for AM repairs.

Keywords: Additive Manufacturing, Aerospace, Cost, Maintenance, Repair and Sustainability.

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Abbreviations

Abbreviation	Definition
2D	Two-dimensional
3D	Three-dimensional
AIM	Affinity and Interrelationship Method
AT	Acoustic Emission Testing
AM	Additive Manufacturing
ASTM	American Society of Testing and Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CT	Computed Tomography
DED	Direct Energy Deposition
GKN	Guest Keen and Nettlefolds
GOM	Geometric Optical Measurement
GTC	Global Technology Centre
HIP	Hot Isostatic Pressing
ICME	Integrated Computational Materials Engineering
IR	Infrared
LMD	Laser Metal Deposition
LPBF	Laser Powder Bed Fusion
MRO	Maintenance Repair and Operations
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
PBF	Powder Bed Fusion
PCRT	Process Compensated Resonance Testing
PTC	Production Technical Centre
R&D	Research & Development
SEM	Scanning Electron Microscopy
SLM	Selective Laser Melting
TEM	Transmission Electron Microscopy
TO	Topology Optimisation
TRL	Technology Readiness Level
UT	Ultrasonic Testing

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1 Introduction

In this chapter the research background is presented, along with the aim, research questions, and delimitation of the thesis.

1.1 Background

For many years, the main strategy for many manufacturing companies has been the traditional linear take-make-dispose model. However, this linear consumption model is not sustainable in the long term when signs of resource depletion start to show. The linear model then leads to higher resource prices and costly disturbances along the supply chain, which make companies vulnerable due to tighter profit margins and longer lead times. The circular flow model however, is based on the concept of reducing waste and becoming resource efficient by designing products for reuse. It is considered to be a more sustainable model to work with, which allow companies to take social, economic and environmental responsibility of their production while avoiding the risks associated with the linear model mentioned above (Ellen MacArthur Foundation, 2013).

In order to achieve a circular flow, it is important to consider offering services, which give the customer the opportunity to choose to reuse the product. This promotes sustainable consumption by giving the customer the right to repair the product rather than simply purchase a new one. Not only may companies wish to do this, in their own interest to become more sustainable and resource efficient but as the efforts to mitigate climate change and environmental damage increase, it may be required of them. In October 2019, the European Union launched a "right to repair" directive, which aims to strengthen the repair-ability of products within certain industries and encourage circular economies (Hernandez, Miranda & Goñi, 2020). Statistics also show that the aircraft Maintenance Repair and Operations (MRO) market is a rapidly growing market with an expected industry revenue growth of approximately 27.1 billion US$ within the next ten years by 2031 (Wyman, 2021). Thus, as customers wish to retain their right to repair products it is vital that companies gain experience within MRO in order to offer services such as repairs in the future.

GKN is a company, which has worked as a production, competence and resource center for the aerospace industry since 1930. The company works within four different sectors in the aerospace industry, which are: engines, aerostructures, special technologies as well as aftermarket services & MRO. The components produced by the company can be found in over 90 % of all new passenger planes delivered across the world (GKN Aerospace, 2021a).

While the company has generated various solutions as well as methods of service and maintenance when it comes to repairing parts, aerospace components are today often expensive and complex, which means repairs can become very extensive and expensive operations. Therefore, in an effort to enforce a circular sustainable flow, a cheaper maintenance service is sought, which can be offered to customers as an alternative option to newly manufactured components.

Today, the company has realised that there is potential for the use of AM in the aerospace industry for repairs. The technology has already been implemented for one component repair/modification successfully. Because the process of repairing with AM can be quite time consuming, it is not suitable for all industries (Interviewee C). GKN however, has a greater product focus than process focus with one-piece production, the technology is therefore considered to be suitable for the company. The next step for the company is therefore to investigate and identify how AM can be implemented for repair purposes and where the company needs to develop new solutions to deal with current challenges. The end goal for the company is to develop a process that is sustainable, safe and cost-effective where the certainties and uncertainties of AM are taken into consideration for the development of a repair process, utilising the technology (Interviewee C).

1.2 Aim

The purpose of this thesis project is to investigate and evaluate the current state of AM at GKN with a focus on maintenance and repair operations within the company. The primary goal is to identify the challenges related to AM repair as well as indicate and suggest solutions, opportunities or methods, which can be employed in order to overcome those challenges. Additionally, guidelines for a product cost estimation of the repair process will be provided with the aim of providing insight into important cost parameters for AM repair.

1.3 Specification of issues under investigation

RQ1: What AM technologies does the company have today? What is the current state of knowledge pertaining to AM repair within the company? Where and how has AM repair been applied based on component size, material and geometry?

RQ2: Where can challenges within the implementation of AM repair be identified and what are the alternative solutions for potentially overcoming these challenges?

RQ3: How could a cost model for AM repairs be constructed and which parameters should be included in the guideline?

1.4 Delimitations

- The report will only take into consideration the AM technologies and materials, which are utilised for repair at GKN today.
- The report will not examine or measure how well different combinations of component- and repair materials combine.
- The report will only examine AM in the context of maintenance and repair. The technology will not be examined in terms of new production.

- The current state analysis will only take into consideration GKN products or projects, which are considered AM repairs or modifications at the company.
- The product cost management guideline created during the thesis will not take into consideration the costs related to the lead time, depreciation and transportation to and from the company site.

2 Theoretical Framework

The theoretical framework below aims to serve as an introduction, providing insight into important concepts and technologies, which are relevant to the thesis.

2.1 Circular Economy

The concept of a circular flow is according to the Ellen MacArthur Foundation "Based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems" (Ellen MacArthur Foundation, 2017).

A circular economy focuses on decoupling the growth of a business from the consumption of resources by transforming a take-make-waste model, which is linear, into a regenerative circular flow (Ellen MacArthur Foundation, 2017).

A circular economy aims to eliminate the impacts of linear take-make-waste models in order to reduce the negative impacts on human health and natural systems, which such models have caused. Thus, a circular economy aims to reduce waste and pollution such as the pollution of air, land, and water as well as structural waste by avoiding non-renewable resources for example and supporting the regeneration of natural systems. A large part of reducing waste with a circular economy is built on the principle of keeping products and materials in use by designing for longevity, reuse, re-manufacturing and recycling for example (Ellen MacArthur Foundation, 2017).

2.2 Technology Readiness Level

Technology Readiness Levels (TRL) are used to describe the technical maturity of a technology. The method was developed by the National Aeronautics and Space Administration (NASA) and is currently used as a tool by engineers to measures the maturity of a technology throughout its development. The TRL scale ranges from one to nine, where 9 is the point at which the technology has reached full maturity. To view the TRL, see figure 1 below (TWI, 2021a).

Level 1-3: The first three levels of the TRL are focused on the research phase and describe the maturity of the research completed to develop the technology. The first level focuses on the basic principles, on which the technology is built. The second stage is focused on the application possibilities and the third stage on experiments, which can provide a proof of concept (TWI, 2021a).

These stages are mainly the focus for universities and government funded sources as there is a greater focus on the research phase (TWI, 2021a).

Level 4-6: Level four up to six are focused on the development of the technology, such that it can be validated and demonstrated in a lab and eventually an environment relevant to the function. During stage 4 for example, the technology is validated in a lab, where it can be analysed to determine the parameter operating range. The fifth stage is the stage, at which the technology could be validated through a simulated environment and the sixth stage is focused on demonstrating the technology in such an environment (TWI, 2021a). Level four, five and six are often referred to as the "Valley of Death", as academic organisations and the private sector rarely wish to invest in these stages in order to ensure the technologies maturity (TWI, 2021a).

Level 7-9: The last stages of the TRL are stage seven up to nine, which focus on the implementation of the technology. At the seventh stage a prototype of the system is implemented in a functional environment and in the eight stage, the technology has been qualified for the final stage. The final stage is the stage, at which the technology is then proven in its functional environment and ready for commercial deployment (TWI, 2021a).

Figure 1: Technology Readiness Levels.

2.3 Additive Manufacturing

AM is an approach to industrial engineering, more commonly known as Three-dimensional (3D) printing. The technology utilises data from models created in software such as Computer Aided Design (CAD) or with 3D scanners to create the hardware defined in the models through the deposition of material. The material is deposited in layer upon layer until the object is complete (General Electric, 2021).

The technology can utilise materials such as biochemicals, ceramics, thermoplastics and metal to create 3D objects. It can also provide a higher digital flexibility and efficiency to manufacturing operations while minimising waste, enabling the creation of complex geometries, and improving performance. Examples of AM processes are Laser Powder Bed Fusion (LPBF), Binder Jetting, Direct Energy Deposition (DED), Material Extrusion, Material Jetting, Sheet Lamination and VAT Polymerisation (General Electric, 2021).

2.4 Additive Manufacturing Technologies

AM is a manufacturing technology that consist of several different processes. The three AM technologies, which have been mentioned during this thesis are LMD (Laser Metal Deposition) -powder and -wire as well as LPBF. Therefore, these three AM technologies are presented further below.

2.4.1 Laser Metal Deposition Powder

LMD-powder is an AM process, which is classified as a DED process. The technology is used for building up volume by adding layer by layer of material. LMD-powder utilises a laser beam to form a melt pool on the surface of a metallic substrate, into which metal powder is injected using a gas stream. The laser beam exits through the center of a nozzle and the powder is injected into the laser through powder channels in the same nozzle. When the powder hits the laser, it melts and is thus, deposited on the substrate. The nozzle i.e the deposition head is moved during the operation, to enable the creation of a single line deposit. To enable the creation of layers multiple lines are added on to each other, which can create the complete desired structure. To ensure that a metallurgical bond is created between the coating and the base material, a thin layer of the base material is first melted by the laser heat source in a checked way (SPI LASERS, 2021). This AM method enables the utilisation of different materials in AM since several containers where the powder is applied could be active at the same time. Thus, the possibility of building structures with different materials is conceivable (Hönl, 2019). In figure 2 below, the basic principle of an LMD-powder machine is demonstrated.

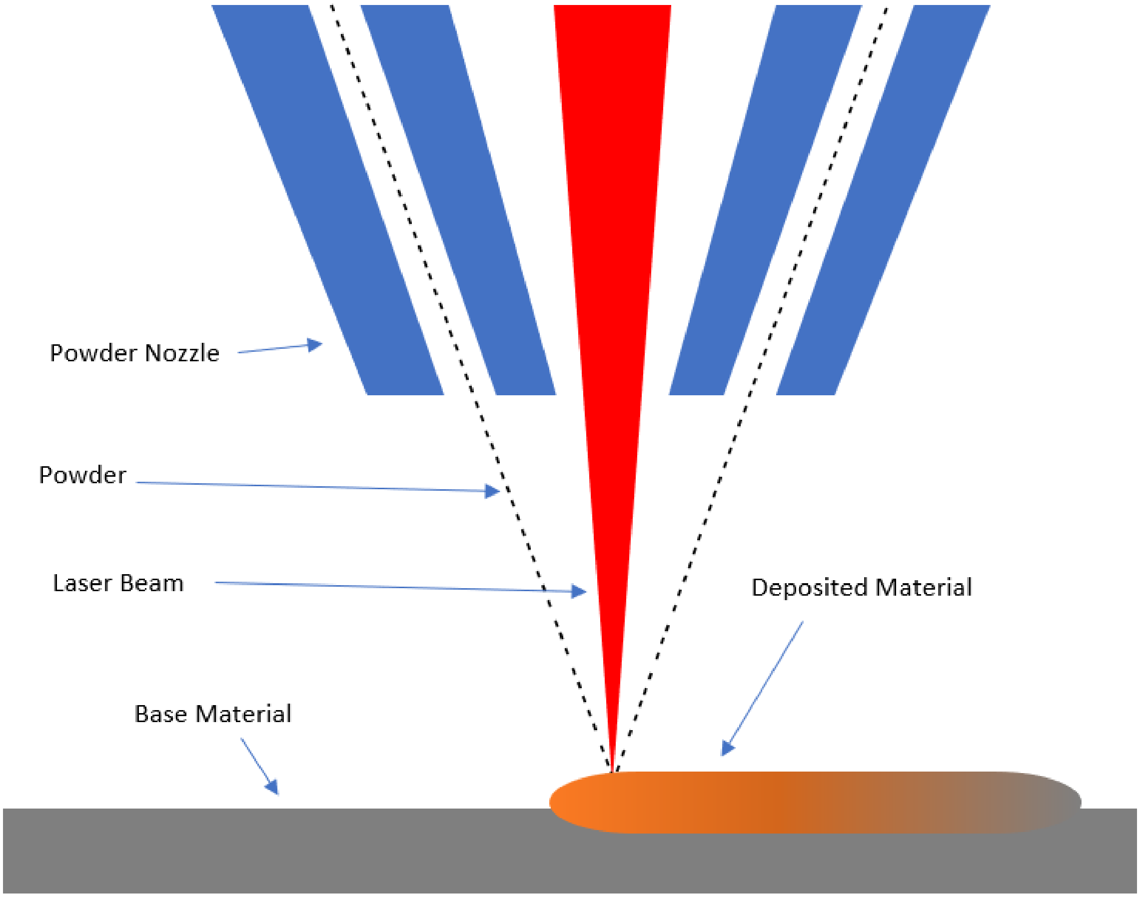

Figure 2: Laser Metal Deposition Powder.

2.4.2 Laser Metal Deposition Wire

LMD-wire is an AM process that utilises a laser beam in order to melt a metal wire and fuse it together with another base material. The laser beam enters through multiple fiber coupled diode laser sources, which can be located around the nozzle for example. The wire material is then fed through the center of the nozzle where it melts once it has come in contact with the laser. The technology is otherwise also classified as a DED process and is used to build up volume, layer by layer (ADDITEC, 2021). This is accomplished when the nozzle is moved over the desired deposition area while melting the wire material. The technology has high deposition rates, 100% material efficiency and utilises shielding gas in a sealed system (CHIRON Group, 2021). In figure 3 below, the basic principle of an LMD-wire machine is demonstrated.

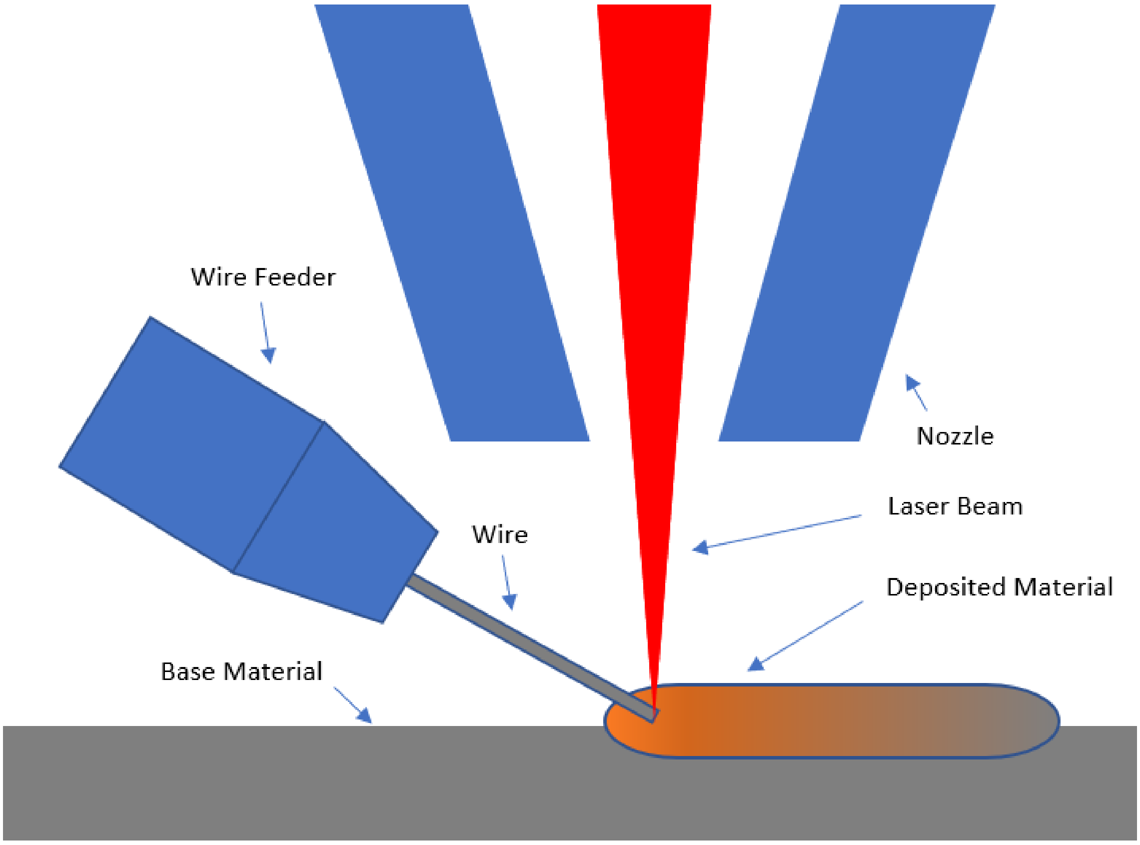

Figure 3: Laser Metal Deposition Wire.

2.4.3 Laser Powder Bed Fusion

LPBF is defined as a Powder Bed Fusion (PBF) technology where the utilisation of a build platform consisting of powder of the materials metals or polymers are utilised to then build/design the component by melting selected sections of the powder (Alexandrea, 2019).

Like several other AM technologies, the creation of a CAD model in 3D is also required in the process of LPBF. The model of the component is then cut into several layers using a slicer so that the component can be built by melting these layers together one after the other. To start the LPBF process, the chamber of the machine needs to be filled with inert gas and heated to a specified printing temperature. A thin layer of powder is then applied to the build platform, where the fiber optic laser then scans the component's cross-section and melts the metal particles together. The component attaches to the build platform with the help of the pressure supports that exist in the machine. When the first powder layer is completed, the platform moves downwards so that another powder layer can cover the first molten layer, this layer is then also molten according to the design of the next cross section and the process is repeated until the desired result is achieved and the component is complete. When the component is finished, the LPBF machine must cool down and the undigested powder must be removed in order to remove the manufactured component (Alexandrea, 2019). To better understand the basic functions of an LPBF machine, please view figure 4 below.

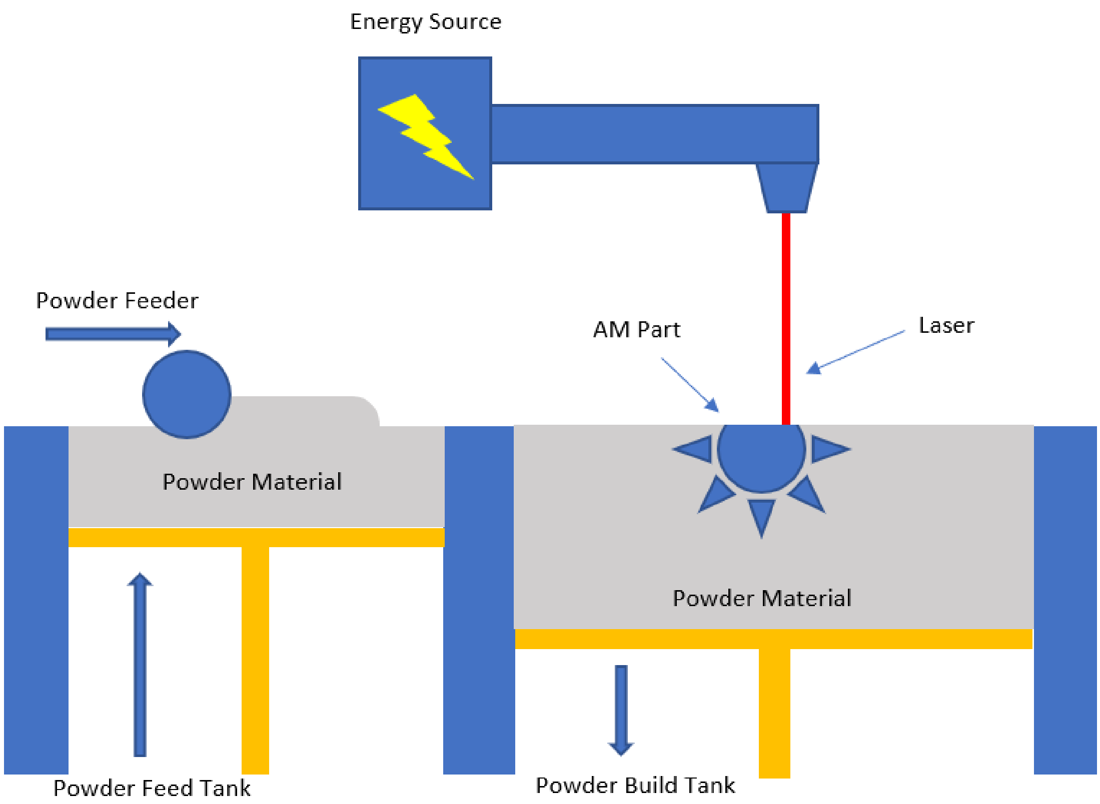

Figure 4: Laser Powder Bed Fusion.

3 Methodology

This chapter describes the methods used during the project to answer the research questions. In order to increase the credibility of the thesis research a few different research methods were used. These methods are further described below.

3.1 Research Design

The research design for this thesis is based on four steps: a qualitative study, a literature study, a benchmark, and a case study. The study followed an exploratory research design. It was determined to be an appropriate approach since the research topic consisted of concepts and techniques, which have not yet been implemented to a great extent (Dudovskiy, 2021).

The research strategy for this project is based on data triangulation, which refers to the use of several different methods in a research project. This supports the development of a comprehensive understanding of the research area, which is necessary for this thesis work (Patton, 1999). The methodology of this research project was also chosen as the exploration of different data sources strengthens the credibility of the research (Denscombe, 2014).

The research began with a pre-study of the company's current work within AM as well as an initial literature study of AM technologies in order to gain some basic knowledge within metal AM repair before initiating the qualitative study.

The qualitative study was initiated with a study of company information on AM repairs and employee interviews. It was partially executed in parallel with the literature study where scientific articles, reports and books were studied. The study was executed in this manner, in order to identify potential knowledge gaps, where further research would be necessary. This was necessary in order to maintain validity during the research.

After the qualitative study and the literature study, a benchmark was executed in order to determine whether the challenges, which GKN were facing were specific to the company or the field of metal AM repair in general. This was also necessary in order to ensure that the results of the qualitative study were valid.

Lastly, in order to answer the third research question a case study was performed on previous AM and repair cost evaluations.

The conclusions drawn once the research had been concluded were presented in the shape of short concise summaries, based on the findings presented in the results and discussion.

3.2 Qualitative study

The thesis project was initiated with a qualitative study in order to evaluate the current state of AM at the company and identify challenges pertaining to AM repair specifically. A qualitative study was considered suitable in this case as the majority of the study is done on a small scale internally at the company. The data collected is also of an interpretive nature, which is another reason why the qualitative approach is more appropriate in this case (Denscombe, 2014).

3.2.1 Study on AM repair at GKN

In order to properly evaluate the current state at the company, a pre-study was initiated where information supplied by GKN was analysed in order to give the researchers a better understanding of what the technology entailed. The information provided by the company was in the shape of documents, reports and presentations on the company's current work within AM. Study visits were also done at workshops: TC, Production Technical Centre (PTC), Space and A at the company. The study visits were helpful in order to identify what the company had been working on so far in terms of AM repair.

The current state study was necessary to perform in order to gain knowledge on AM and AM repairs within the company so that relevant interview questions could be formulated for the second step of the qualitative study. This was important to maintain quality and validity during the qualitative study (Tracy & Hinrichs, 2017).

In order to protect classified information, it was also decided that the components, which are produced by the company would be coded in the report. The components have been coded in a manner where the first component mentioned in the report is component A, the second is component B etc. This was also done to ensure that specific business operations that are active at GKN but not public, would not be revealed.

3.2.2 Interviews

In order to evaluate the current state and potential of AM repair at the company thoroughly, interviews were planned with company employees. The aim was to let employees give their input on AM at the company and express what had been successful as well as unsuccessful with consideration to the development and implementation of AM operations. The information gained during the interviews helped determine how far the company had come while also identifying challenges and opportunities at the company.

The employees targeted and included in the interviews were those that had worked in some regard with different aspects of AM repairs or AM technology specifically.

Some of the employees were suggested as potentially suitable interviewees by the thesis company supervisor at the beginning of the project. Other employees were named by the interviewees when asked for recommendations for further interviews. The selection of employees for the interviews was largely based on their relevance to the thesis subject as well as whether they would be able to provide a new perspective on the subject. Thus, the roles of the employees vary and this was done intentionally in order to capture the challenges the company is facing from as many different perspectives as possible. This approach also helped make the qualitative study more credible since a range of different employees from different departments were included in the analysis.

The employees interviewed covered the three most important departments currently working with AM at GKN, which are: Research and Design (R&D), Production and Construction. The roles of the interviewees are presented in table 1 below.

Table 1: List of interviewees and their respective roles.

Interviewee	Role
A	Process Engineer
B	CAM Engineer
C	Method Specialist
D	Project Manager
E	Materials Application Engineer
F	Process Engineer
G	Engineer Team Lead
H	Materials and Process Engineer
I	Program Manager
J	CoE Director
K	Design Engineer Component Responsible

3.2.2.1 Interview structure

The structure of the interviews was planned ahead of the meetings. It was decided that the interviews would be semi-structured with open questions in order to make sure that the employees interviewed could add their own input during the interview. This was important as there could be information that the employees feel is relevant to the study, yet that is not asked for specifically. To view the questions asked during the employee interviews, see appendix A. (Denscombe, 2014).

During the interviews there were further explanations for questions with non-responses through further development of the questions asked, by providing context to the questions for example. Open-ended questions were also limited in order to focus the answers on the subject in question. The length of the interviews was adjusted based on the in-depth knowledge of the interviewee and their perceived commitment to the subject.

Because GKN works with confidential customer information it was not certain that all audio recordings of the interviews could be retained due to the importance of maintaining critical information within the company. However, the interviewees were asked for their consent to record the interviews purely to maintain a high level of detail in the answers, which would later on be analysed. Collecting information through audio recordings was determined as the main strategy since the interviewee answers would have a higher degree of detail that would make the answers less susceptible to interpretation during analysis than field notes for example. The strategy would therefore also increase the validity of the results (Denscombe, 2014).

It was clarified to the interviewees that all of the interviews would be kept anonymous and that the recordings would be deleted once the project deadline had been met. This was done to facilitate honesty and transparency during the interviews (Tracy & Hinrichs, 2017). It was also agreed that if any of the interviewees did not consent to record the interview, the main strategy for collecting information would be through field notes (Denscombe, 2014).

Due to the current Covid-19 pandemic, not all of the interviews could be completed face-to-face as many company employees were assigned to work from home. Thus, some interviews were done online via platforms such as Microsoft Teams while others were done in person depending on whether the employee was working at the company or from home.

3.3 Literature Study

A literature study was performed during the thesis as the method provides good input in all types of research. Literature studies serve as a basis for knowledge development, and help researchers shape guidelines for specific subjects by comparing results in literature. This methodology is optimal for the evaluation of theories (Snyder, 2019).

The literature study was partially performed in parallel with the qualitative study. This approach was necessary in order to determine whether there was sufficient literature within areas identified as challenging at the company, before suggesting solutions to these challenges.

The literature study then continued on with the purpose of identifying alternative solutions for overcoming the challenges identified during the qualitative study at GKN once the qualitative study had been completed. Different keywords were determined beforehand, connecting to research question two and the scope in order to maintain high quality and validity.

Keywords of interest were: Knowledge, Transfer, Inspection, AM, Repair, Implementation, Qualification, Standards, Collaboration, Communication, Change, Management, Design, Aerospace, Maintenance, Inconel 718, Titanium 64 and Strategy.

Many of the keywords were combined and translated into various search-strings. Screening was made on different articles, scientific papers and books by relevance to the searched topic through Scopus, ScienceDirect, Chalmers Library and other article sources. Relevant literature was picked for the literature study based on the titles of the articles and by reading the summary. If the title was considered relevant and matched the subject of a research question, the literature was read in depth. The information from the literature was extracted if the context of the material was considered relevant by the researchers (Snyder, 2019).

3.4 Benchmark

Benchmarking is a research method used to evaluate and compare products and work processes to facilitate improvement work or strategic decisions. Through the use of external knowledge, the process safety factor increases internally. For the development of improvement processes, a benchmark study is therefore an excellent first step as it facilitates decision-making (Mannan, 2012).

The benchmark methodology was chosen to expand the project's reliability and validity. By making a comparison with an external company that works with AM repair, it was possible to determined whether the challenges at GKN were specific to the company or something identified within other companies working within the same field. A benchmark was also conducted with an AM expert in order to identify an experts insight into the advantages and disadvantages of AM repair.

According to Mannan (2012), the first step is to invest in public data that is available and then perform the benchmark study through e.g., a survey or an interview. This approach was therefore chosen and an online search was conducted to determine the company's current state in term of AM repair experience and research. This study generated relevant questions for an interview where further data, which was considered lacking could be collected. To view the interview questions from the company benchmark see appendix B. An AM expert was contacted, on the recommendation of the thesis supervisor at GKN. The interview questions for this interview were created together with the supervisor. To view the interview questions for the AM expert benchmark, see appendix C. Given the current situation due to the covid-19 pandemic, the interviews were conducted virtually. The interviews were semi-structured, which made it possible to gather some of the interviewees own thoughts and reflections on the subjects (Demscombe, 2014).

3.5 Case Study

As one of the purposes of this master thesis project is to describe and create a product cost management guide. The case study methodology is considered suitable as knowledge can be gained from several similar cases. This methodology examines a specific situation where there are several variables of interest in addition to individual measurement values, therefore, a case study was a suitable method to use when studying processes and changes (Yin, 1994).

The case study started with a collection of data in the shape of cost calculations as well as cost instructions on previous AM operations and repairs of components. This, in order to identify relevant parameters to take into account when implementing a product cost management guideline.

The search for relevant cases was performed internally as well as externally at the company. Some of the companies previous cost evaluations and calculations were used in the case study. The majority of the cases studied were external cases from similar industries. These cases were found through online searches using relevant keywords: AM repair cost calculation, AM cost calculation, repair cost calculation and product cost calculation.

3.6 Data Analysis

In this section, the process and outcomes of the data analysis for each data collecting method are described. The results from the data analysis process are presented in chapter 4, Results.

3.6.1 Qualitative Study

Once the qualitative study had been completed and the necessary information collected through interviews, the data was prepared for analysis. This was done by transcribing the interviews so that important data would be easier to locate (Denscombe, 2014).

When the interviews had been transcribed, the employees answers were analysed. This was done in order to identify information relevant for describing the current state of AM at the company and identify challenges that the employees were facing pertaining to AM repair at GKN.

After data relevant to the study had been extracted from the transcriptions, it was summarised. The Affinity and Interrelationship Method (AIM) was then used to analyse the data further.

3.6.1.1 Affinity and Interrelationship Method

AIM is a problem solving tool for analysing qualitative data. The method is similar to that of Shoji Shiba's 19 step-by-step approach (Alänge, 2009).

The AIM method was chosen in order to sort, structure, organise and analyse the data provided through the interviews. The method made it easier to identify the interrelationships between different challenges mentioned during the interviews.

The method was executed by utilising the challenges extracted from the qualitative study. The challenges were summarised in short concise statements. These statements were then grouped according to how similar they were perceived to be. Once a few larger groups of statements had been identified, challenging areas were defined as different categories.

Once the challenges had been grouped and categorised, interrelationships were then defined where challenges may have originated from other issues in other categories. This made it easier to identify where root causes of some of the challenges were located. As a final step the categories were weighted according to the number of interrelationships identified. Thus, the areas with most outward directed arrows were perceived as root causes of many challenges and therefore imperative to solve first.

3.6.2 Literature Study

A data analysis of the literature was performed based on literature, which described different approaches for such an analysis. (Forsberg & Wengström, 2008).

The literature that had been identified was divided into folders according to the keywords that had been used in the search. This, in order to easily divide the literature according into similar categorical areas and achieve a clearer structure for better data management. The literature was reread carefully in order to mark the relevant data, which could be included in the result. The results identified in the literature were then organised according to the headings of the AIM. This facilitated the use of the right literature for analysis of the different areas defined in the AIM.

3.6.3 Benchmark

The data analysis of the benchmark studies could be conducted once the interviews had been held and recorded. The first step of the data analysis was to transcribe the interview in order to facilitate the analysis and to locate important data, which would be used in the result later on (Denscombe, 2014).

When the transcription had been completed, the answers from the interviewees were reread and a deeper analysis of the transcriptions was conducted. A summary of the extracted data from the transcriptions could be performed when the analysis of the interviews was completed.

3.6.4 Case Study

The analysis of data for the case study started with an in-depth study of the collected cases. Through an in-depth study the relevant parameters could be identified and highlighted. This study was performed in order to facilitate the process of selecting the final parameters. This, in order to define the final cost parameters that were considered optimal for creating a product management guide for AM repairs. The software Excel was primarily chosen in order to define the equations presented in the product cost management guideline. Through this, the equations could be tested and utilised with ease and clarity.

4 Results

In this chapter the result and analysis of the research study is presented. It begins with the current state analysis and continues with presenting the identified challenges with AM repair at the company. Next, the result from the benchmark study with two external actors is presented. Alternative solutions and opportunities to overcome these challenges are then introduced and finally, this chapter ends with a presentation of the product cost management guideline created for AM repair.

4.1 Current State Analysis

This chapter of the report focuses on describing the current state of AM repair at GKN. Today the company strives towards increasing their knowledge within AM and AM repair as a decision has been made to increase the life span of one of their jet engines by 10 years. Since the engine components were not originally designed for this lifespan, it was necessary for the company to increase their knowledge within new repair technologies (Interviewee C).

4.1.1 AM Technologies & Experience

The AM technologies currently considered for AM repair and available at GKN are LMD-powder and -wire. While there are other methods such as LPBF technologies available at the company, which could potentially be used for repair in the future, these are not currently considered for repair operations (Interviewee C). Thus, the two main technologies the thesis has focused on are the two DED technologies mentioned above.

In terms of experience within AM, development and implementation of the technology at the company has shown that suitable applications for AM repair are components where defects in the shape of wear tracks or abrasion for example can be identified (Interviewee K). Repairs and maintenance operations are generally performed in cycles on products during their lifespan within the aerospace industry. Due to this GKN has realised there is a need for component repair with AM (Interviewee J).

4.1.1.1 Laser Metal Deposition Powder

The study visit at the TC workshop at the company revealed that the current LMD-powder machine available at the company is essentially an NC machine from TRUMPF with a laser powder application. The LMD-powder application was chosen because the company saw a need for high accuracy during AM repair, which the application could provide.

The application of powder in the LMD-powder cell is today based on uncontrolled flow surfaces. The repair operation is performed by running tracks of LMD-powder on the surface where milling tracks have been laid out in the program beforehand. The tracks are laid in a manner that aims to minimise the amount of deformation sustained by the component during the operation. It is currently not possible to employ a software that can automatically lay the tracks for the repair operation available at the company (Interviewee B).

Due to this, it has so far been necessary for each repair component to be scanned in order to determine the degree of deformation present, so that the tracks programmed can be adjusted with this in mind. In order to make sure the powder used during the operation meets the requirements set on the process, a test plate is run before the operation. This is necessary to determine the height and width of each track as well as the focal point of the laser and powder deposition rate for example. This was revealed during the study visit at the TC workshop.

The LMD-powder machine was an investment made in order to repair/modify component A (Interviewee J). This repair/modification was suggested when a certain number of manufactured engines had been delivered to the customer and the customer realised that higher traction in the engines was necessary. As the manufacturer of the engine, GKN was therefore commissioned to strengthen certain parts of component A in order to be able to deliver a higher degree of traction. This was done in collaboration with a customer and representatives at GKN to jointly build a plan on how to achieve the desired result. A business case was formed, and calculations were performed to evaluate the profitability of repairing/modifying component A (Interviewee A). The value of repairing/modifying component A turned out to be much higher than buying or manufacturing a new component despite the long lead time. As components A had already been delivered and put into operation by the customers, it was necessary to remove them from the customers turbines and ship them back to GKN in order to perform the repairs/modifications, at which point the components were deformed. The time frame for these repairs/modifications was estimated to be approximately three years (Interviewee J).

Component A is today repaired/modified in three different areas where a total of three kilograms of material is deposited (Interviewees A & J). The component is large and delicate therefore, the choice of LMD-powder was made as it is easier to build up material through AM than conventional welding when the desired result is strengthening (Interviewees B & D) . The material properties were also a driving factor in performing this AM repair process as the base material, cast steel is considered better after the LMD-powder application (Interviewee J). However, component A is not only repaired today with LMD-powder, the conventional methods of plasma and welding are also utilised (Interviewee J). Pre and post-processing steps are also performed on the component, in order to eliminate the defects that arise from the process and to achieve the desired surface smoothness (Interviewee B).

Currently the possibility of repairing/modifying component B with LMD-powder is also being investigated at the company (Interviewee G). Previously, repair of component B has been performed through the conventional method of nickel plating (Interviewee C). Today the company is in the development phase of looking at whether the surfaces where AM repair is required on component B, can be accessed through a new nozzle since access in the LMD-powder cell is limited (Interviewee D). There is currently no assurance from the company that this process will function and succeed in fulfilling all requirements. However, the development work will continue in order to collect data on why this process is not possible if that is the case (Interviewee G).

4.1.1.2 Laser Metal Deposition Wire

In 2008 a decision was taken to introduce the AM technology LMD-wire in a program where a large number of component C had to be attached to an engine component. It was decided that this would be accomplished by utilising LMD-wire to build the component C up directly on the surface of the engine component. The operation was successful and the engine component was thus modified by adding component C to the surface. Currently, this engine component is produced at GKN in Trollhättan, Sweden, and leaves the production facility at a rate of five to six finished components a week (GKN Aerospace, 2021b).

The LMD-wire machine available at the company today is thus mainly used to add component C to another engine component. The LMD-wire machine makes it possible to build up more volume during a repair operation than the LMD-powder machine. Thus, the technology was considered optimal for component C, where quite a large volume of metal is added to a small surface area. The machine is also specifically suited for the application since it is possible to utilise titanium in the machine. This is because the equipment has a plexiglass chamber and a tent, which eliminates the risk of explosion that titanium AM can entail (Interviewee H). A second-generation control system and a development of the process window for the LMD-wire process is something the company hopes to achieve. This in order to enable development of advanced geometric functions as well (GKN Aerospace, 2021b).

Currently, many alternative components are being considered for the LMD-wire machine. The plan is to successfully produce the first AM modified serial component D in the near future (Interviewee F).

4.1.2 AM Repair Parameters

Before a component can be determined as suitable for a repair process there are three parameters, which need to be thoroughly examined, these can be viewed in figure 5 below. These parameters are component material, geometry and size. The parameters are relevant not only before the repair operation has been performed but also after the operation has been completed in order to qualify and verify that the component fulfils all requirements specified. These parameters and the context in which they are relevant to AM repair are presented below.

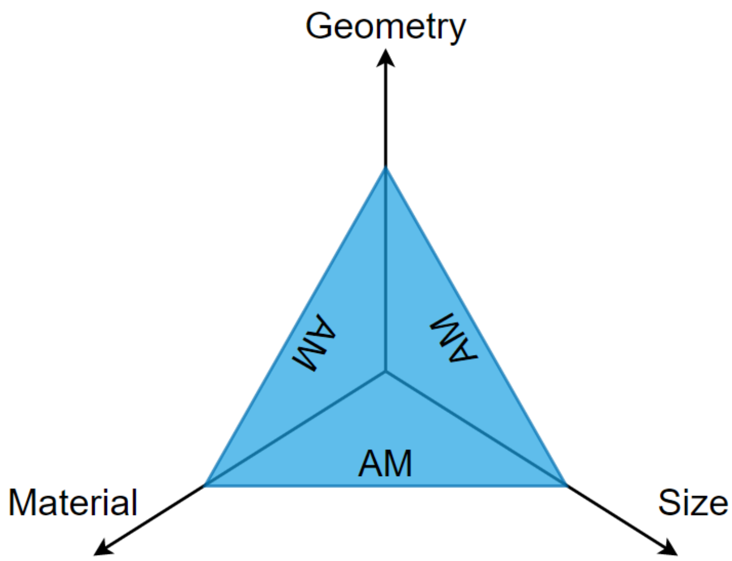

Figure 5: Three important parameters of AM repair.

4.1.2.1 Material

The materials, which are mainly considered for AM repairs at the company today are Inconel 718, Haynes 282 and Titanium 64. Inconel 718 and Haynes 282 are both nickel-based superalloys. Inconel 718 has already been used for a component repair/modification using LMD-powder at the company and Haynes 282 has been tested on component E among other things (Interviewee B). Titanium 64 on the other hand is a titanium alloy, which has been used with LMD-wire and the company desires to work more with the material in the future however, the material is highly explosive and thus requires caution (Interviewee H).

The materials are optimal for adding volume to a component for repair purposes since they are weldable and not prone to cracking. More alloyed materials than the ones mentioned are more prone to developing defects (Interviewee E).

The company works a lot with the development of AM at PTC in Trollhättan. The study visit at PTC revealed that AM technologies entail a certain degree of heat impact on the material, which leads to defects. This is something that is studied closer at PTC where different nozzles and cooling systems are currently considered to eliminate these kinds of defects. However, despite the heat impact, which AM has on materials, the technology is still considered an optimal choice compared to traditional welding, which has a much larger heat transfer in comparison.

4.1.2.2 Geometry

The types of geometry, which have so far been repaired or considered for repair are largely flat surfaces. However, there have been successful attempts to repair component E by applying AM on the inner radius of the component (Interviewee H). Thus, the geometrical complexity of components considered for repair at the company is rather low, which is expected since the technology is rather new in comparison to other traditional repair methods that have been present within the industry for a longer period of time (Interviewee C).

The geometrical complexity of the components is also low as this parameter can limit how well the part can be repaired. If the complexity is high it may mean that the AM machine nozzle cannot reach the areas necessary for repair during the operation (Interviewee B).

4.1.2.3 Size

When an AM machine is considered for repair purposes, one of the first parameters, which needs to be checked, is size. The size of the component is essential to whether the repair operation will be feasible (Interviewee C). If the potential repair component is too large, it may not fit in the AM machine cell or the operation results in machine collision due to that the machine is working in border areas of the cell (Interviewee B). However, if the component is very small it may also cause issues since the amount of heat transferred during the repair operation to the component is concentrated on a smaller body of material, which can lead to deformation (Interviewee C).

During the study visit at the TC workshop it was also expressed that there are certain weight limitations to consider. For example, the LMD-powder cell has a weight limitation on the component table, which can be used to move the component during an operation instead of moving the machines nozzle.

So far the company has focused on finding large potential components for repair with AM since it is easier to create business cases for these components, which are usually very expensive (Interviewee C).

4.2 Identified Challenges

The identified challenges related to the implementation of AM repair at GKN are further presented below.

4.2.1 AIM

The qualitative study resulted in an AIM presented in figure 6 below. The quadratic areas visualised in the figure under each category are further described in the report as specific challenges which were identified during the interview study.

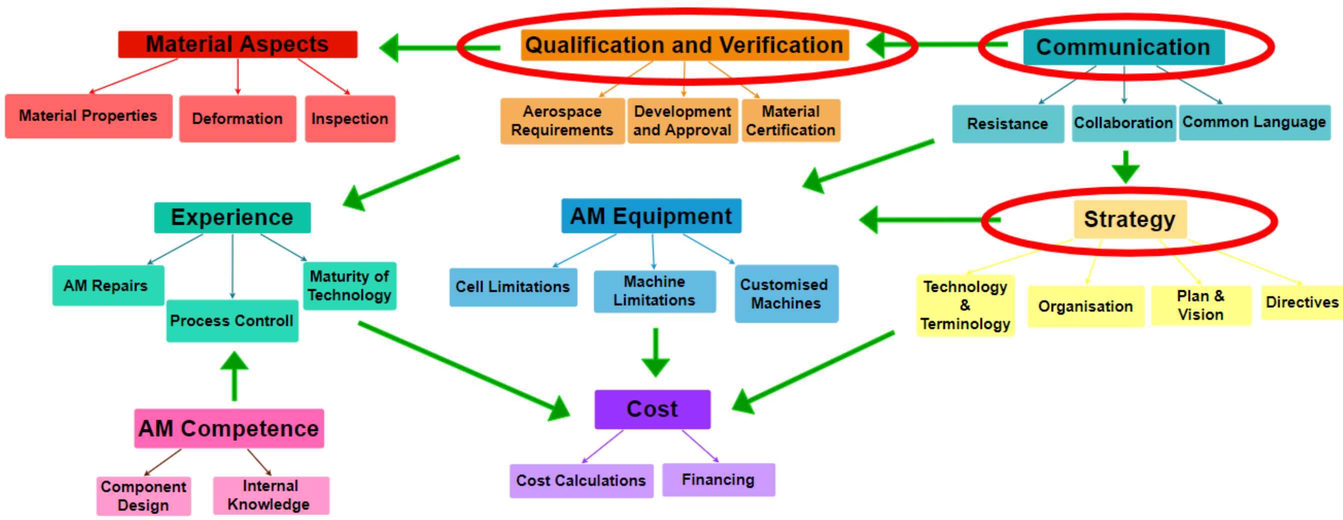

Figure 6: AIM which defines the challenging areas identified at GKN

As visualised in the figure above, three categories are marked with a red circle. When the challenge areas were weighted the categories indicated with a red circle were determined as the areas that are most important to address. This since the categories Strategy, Communication and Qualification & Verification lead to many issues in other categories. Thus the weighting was based on a root cause principle and by overcoming the challenges under the marked categories, it is likely that other challenges may be resolved as well. A presentation of all 8 categories and the specific challenges of each category are presented further below.

4.2.2 Strategy

According to the interview study conducted at GKN, it was identified that the company had challenges within the strategy when it comes to decision-making regarding the implementation of AM. Most of the interviewees expressed that the company did not have a clear strategy for achieving the visions it has within AM repair. Below are presented the identified reasons for why the company has these challenges within their strategy.

4.2.2.1 Technologies with varying maturity and terminology are in the same AM category

After the interviews had been analysed, something that was apparent was that technologies with varying maturity were placed under the same AM category. Below a further explanation of this challenge is given.

Challenge 1

AM is a concept that covers several different manufacturing technologies with different degrees of maturity, this as some technologies have been used and developed more than others.

According to interviewee F, AM technologies, which have been developed to a variety of different maturity levels are placed under the same AM category in the company. Interviewee F claims that this has led to higher requirements being placed on AM technologies that have been around for a longer time such as LMD-powder and LMD-wire. Interviewee F specifically means that LMD-wire and LMD-powder and LPBF are mixed, which is an issue as LPBF is less mature and more difficult to master. This is believed to be a central reason for having a slower development around AM repair at the company (Interviewee F).

4.2.2.2 Outspread organisation for the development of AM repair

Several of the challenges within strategy at GKN, which were identified after the interviews were challenges within the organisations development of AM repair. Bellow these challenges are further described.

Challenge 2

An identified challenge among many of the interviewees is the re-organisation that has taken place at the company among the various corporate departments. Due to Covid-19, GKN has had to restructure the organisation, which has led to the focus on AM being released only to be prioritised once again at a later stage (Interviewee F).

Interviewee D says an example of this is the Technology and Search department, which has been removed. The department worked closely with production and therefore, facilitated a more efficient development of projects as a clearer flow of communication existed between the various departments at the company. Once the department was removed, it was discovered that the development had slowed down, and the focus on specifically AM had been released (Interviewee D). This is believed to be because when the department was removed, it led to the transfer of employees to other departments in the company, which meant the projects initiated in the tech and search department no longer had a specific department responsible for the completion of these projects. Thus, the projects were initiated and then set aside until a new group of employees could take over. Because of this challenge, projects around AM repair are developed slowly and have become more time consuming (Interviewees D and F).

Challenge 3
Today, the company has many different parts of the supply chain externally. This means that, in order to successfully develop AM repair operations, many external business skills are required to succeed in moving forward. This has resulted in the need for expertise from external sources whether it be institutions, companies or PTC for example. The reliance on these external parties has led to long lead times for answers (Interviewee C).

Challenge 4
According to the interview study, there is a need for a central development base for AM. This means that today at GKN there is no clear strategy for how the development work on AM repair needs to be performed.

In accordance with the company's current strategy the development of AM is performed by several different departments at different company locations. The development work takes place among different environments and among different individuals who possess a variety of knowledge about AM specifically. This approach has resulted in a slower development of AM technologies as well as different perceptions of what the technology is capable of (Interviewee D).

4.2.2.3 No common plan or vision for AM repair

During the interviews, it became apparent that the company lacks a common plan or vision for AM repair. A presentation of the challenges within this area are explained more in detail below.

Challenge 5
Several employees agreed that the absence of a uniform plan for how AM repair should be developed at the company is a challenge.

According to interviewee J, there are no clear goalposts for how to develop AM repair. There is a lot of discussion about the implementation of AM repair and the main goal of the introduction is to be become more competitive. At the same time, Interviewee J claims that there are no clear goalposts that describe how this is to be accomplished. Interviewee J also expresses that the current strategy for AM repair is perceived as abstract, which has also been confirmed by interviewee D and H. Interviewee D emphasizes that each department within the company works according to its own road-map. Departments currently work towards fulfilling their goals and visions without any regard to the needs and goals of the remaining departments. This has resulted in ambiguous goals and visions within the departments and the efforts around the implementation of AM repair have been varying.

Challenge 6
According to the interview study, it was identified by employees that many internal initiatives around AM are active at the company. This has led to the perception that there are too many ongoing initiatives, which instead of contributing to development, have led to confusion and unnecessary consumption of resources (Interviewee

D). Interviewee D believes that it is important with internal development around AM and specifically AM repair, but that the type of projects, which are started are not well thought out and adapted to the company's knowledge, experience and customer needs. According to the interviewee D, the company currently has ongoing AM initiatives that aim to develop knowledge within the use of AM with the material Haynes 282. The perception is that these initiatives are unnecessary because the only customer which is interested in components built with Haynes 282 is very conservative and has expressly communicated their disinterest in any and all AM components. This is also confirmed by Interviewee F who also highlights that these internal initiatives require approval from the customer, which is very time-consuming and requires a lot of resources.

Challenge 7

The strategy used in the implementation of the LMD-powder machine in the TC workshop is considered unclear. This is because interviewees D and H believe that there has been no clear plan for how the LMD-powder machine will be used after the current AM repair operations of a specific component have been completed. According to interviewee F, some of the AM equipment invested in is specifically purchased for certain business cases. Interviewee F means that this was the case with the LMD-powder machine, the equipment was bought without a uniform plan for how it would be utilised after the repairs of component A are completed. This makes the identification of new components that could be repaired in the machine very difficult as the equipment has very specific technical parameters, which need to be taken into consideration for any future repairs (Interviewee F).

Interviewee D confirms this and explains that the current strategy is based on adapting the machine to the repair component instead of the other way around. This means that employees thus have to identify components, which can be repaired in very specifically adapted equipment. This complicates the development of AM repair as there will be a need for repeatedly adapting the equipment for each new project (Interviewee D).

4.2.2.4 No clear directives for the development of AM

During the interviews with employees at GKN it was often expressed that clear directives for the development of AM repair were missing. Below the challenges related to this area are further described.

Challenge 8

A clear challenge identified in the interview study is that there is a lack of clear guidance on how and when to choose AM instead of another conventional method. According to interviewee C, currently the choice between AM or a conventional method for repair is based on an experimenting approach. This approach has led to a lack of clear directives and several canceled projects as there is no clear plan to follow.

Challenge 9
The AM repair process currently lacks clear directives for the later stages of the repair operation (Interviewee H). Currently there are no clear instructions for what is included in terms of process steps in a repair operation. This approach complicates efforts to standardise AM repair since no clear process directives can be presented to the customer (Interviewee H).

Challenge 10
According to the interview study, several employees lacked a structured approach to preserving data. Specifically, about previously completed projects and attempts at AM repair.

Interviewee H specifically highlights the repair case for component A. According to the interviewee, there is not enough data from previous AM repair projects as it has thus far only been performed on one component. The interviewee however also explains that there was not enough data preserved from component A repair project either, thus there is not sufficient data available to facilitate future repair cases. This is also confirmed by interviewees E and J, which believe that material data and hardware data are relevant parameters for standardising the implementation of AM repair.

4.2.3 Communication

Some of the most prominent challenges identified at GKN were related to communication between different departments at the company. From the interviews held, it became clear that there is a lack of communication between departments that need to collaborate on projects. The management of the company was also perceived as uncertain because investments and priorities were unclear where it concerns AM.

4.2.3.1 Unperceived resistance between departments

After the interviews had been concluded and the answers had been analysed, something that was quickly apparent was that there is an unperceived resistance between departments that are supposed to collaborate on projects.

Challenge 11
The attitude and approach towards AM at GKN was varied. Some employees such as interviewees C,G and I were very positive towards the technology and its implementation in repair purposes and remarked that this was the general attitude at the company.

Many other employees however such as interviewee B, H and K believe management and the R&D department at the company do not understand the complexity related to implementing the technology in production and are not as positive towards the implementation of the technology. Thus, while some employees perceive there to be an overall positive attitude towards the technology, this is not actually the case.

4.2.3.2 Inadequate collaboration between departments

Many of the challenges within communication at GKN, which were identified after the interviews, were challenges which stemmed from the inadequate collaboration between departments at the company. Departments such as management, R&D, construction and production.

Challenge 12

One challenge, which was identified during the interviews, is between the R&D, design and production departments at the company. According to interviewees F and H, the R&D department works a lot with product requirements but there is not enough collaboration between R&D and production for successful implementation of AM as failure to take important production parameters into consideration cause unnecessary costs and delays.

Interviewee H remarks that the transition for AM between TRL 6 and 7 is a weak link since R&D often deliver an AM project solution to the production department, where production has not been sufficiently consulted. The production department then quickly realise that the solution is not optimal and difficult to implement. Interviewee F also concurs that production is not consulted enough during TRL 1-6, which means it becomes very difficult to raise the TRL for AM, and remarks that this is an issue found between construction and R&D as well.

During the interviews interviewee H for example remarked that production parameters such as machine access, machine nozzle parameters as well as start- and stop sequence effects are something, which R&D rarely take into consideration. Interviewee H explained that this means that the production department can deliver their input only once the project is delivered to the department by R&D at which point, they have to remark on all of the issues with the solution, which makes it unsuitable for implementation. This makes the employees of the production department come across as very pessimistic, which in turn creates further animosity between the departments (Interviewee H).

Challenge 13

Another area, which was perceived as challenging during the interviews was the level of communication between management and other departments such as construction and production. The level of communication between these departments and management is considered lacking by interviewees B, H and K, who remark that there are issues with the maturity and knowledge of AM repair at the company. Due to a lack of communication between the departments however, these issues are not relayed to upper management.

Challenge 14

Due to a lack of collaboration and communication between departments another challenge was identified where interviewee J remarked that the component A project became a hand-over at every arising issue. The interviewee explained that every time a problem related to component A would arise, one department would simply pass it on to the next instead of collaborating to solve the issue together.

4.2.3.3 Lack of common language between departments

During the interviews, it became apparent that many of the employees at the company would use a varying terminology depending on which department they work for. Thus, no common language could be identified between departments.

Challenge 15

One of the first indications that the company lacked a common language between departments was noted when interviewee A explained that while his department considered the component A project at the company to be a modification, many were still referring to it as a repair operation. The interviewee emphasised the importance of a common language at the company, explaining that bunching concepts like repair and modification together in this manner caused confusion and other difficulties related to setting product requirements. According to interviewee A there is a difference between repair and modification, which should be clarified at the company because while it is very important for a repair to fulfil the original requirements of a component, it is not certain that the same is true for a modification. Thus, the requirements set on a modification could perhaps be more lenient or stringent depending on the nature of the operation.

Challenge 16

Another challenge within language at the company is that employees are not certain of what technologies are defined as AM at the company. Interviewees A and H for example believed that Thermal Spraying, which is another technology available at the company was also an AM method. Interviewee C also remarked that nickel plating could be considered an AM method although the company did not consider it as such.

Challenge 17

Employees on management level are very positive toward implementation of AM repair according to interviewee H, who claims that the technology is very alluring in order for the company to keep a competitive edge. However, both interviewees B and H remark that while management are motivated to implement the technology, there is no clear focus in investments.

The motivation for why certain components should be repaired with AM rather than other conventional methods is also perceived as weak by interviewee B who explains that certain components could just as well be repaired with other technologies available at the company where a certain amount of experience has already been gained.

4.2.4 Experience

AM as previously mentioned is a new technology on the market and therefore there is still a general lack of experience within its implementation. The interview study confirmed this, as several employees claimed that today GKN lack experience in AM repair.

4.2.4.1 Few AM repairs performed

So far, there are very few AM repairs that have been performed at the company and thus there is a lack of experience within this area. The small number of repairs that have been performed at the company have led to a number of challenges, which are presented below.

Challenge 18

As previously mentioned, what the company classifies as AM repair has only been performed on one component, component A. As this is a new process for GKN, several unexpected issues appeared during the implementation. According to interviewee J it was not known how long certain process steps would take. This was also confirmed by interviewees B and I who have both worked with the implementation of AM repair and are still working with the component A project. These unexpected sub-operations complicated the implementation and subsequent implementations of projects within AM repair, mainly since the experiences within AM repair is limited (Interviewees B and I).

Challenge 19

The lack of experience within AM repair results in difficulties when attempting to increase the reliability of the process within the organisation (Interviewee H). Fear due to previously unsuccessful projects among the employees was identified during the interview study through interviewees H and J. The little experience in what GKN classifies as AM repair has resulted in a fear of investing time and resources in the implementation of the technology and the process (Interviewee H). The development work of the technology has been slowed down and this is mainly due to the fear that has been built up from previous experience and failures (Interviewee J).

Challenge 20

The knowledge and experience the company currently has within AM technologies that already exist in the facility is considered to be lacking, which was identified in the interview study among several employees. Specifically, the limitations of these technologies are something that several employees lack experience and knowledge within, explains interviewee A. According to interviewee A, this is mainly due to the lack of communication between the departments at the company. It is believed that many of the answers one is looking for are already available within other departments, but due to the communication issues, which exist internally at the company, not all information and data is shared (Interviewee A).

4.2.4.2 Lack of knowledge within process control

The issue of lack of knowledge within process control was clearly identified after the analysis of the interviews. Below a further description of these challenges within this area is presented.

Challenge 21
The employees at GKN express that there is a lack of experience and knowledge within process parameters obtained from the process control for AM repair (Interviewees F and G). Interviewee F also explains that even with a set of identified process parameters of AM repair, there is no standardised working method available that can show whether these parameters meet the requirements for the component and the process (Interviewee F). It is assumed that the deposited material of AM must be better than the original material of the component, to ensure that the component meets the requirements (interviewee G). However, the challenge is to investigate whether the identified process parameters provide deposited material, which meet component requirements without achieving the same material properties as the original component.

Challenge 22
In component repair with AM, it is required that the process can be constantly controlled to ensure that the component meets the established requirements (Interviewee F). An identified challenge among the employees is the lack of experience about how the process for AM repair should be controlled. Both interviewees D and F explain that today there is a lack of knowledge and experience in how to control this type of process. Interviewee C concurs and adds that this is crucial for standardising the AM repair process. It is believed that in order to exchange a conventional method for an AM repair, it is necessary to know exactly what happens during the operation. This is because process control can help prove that the repair meets the established requirements, if during monitoring it does not deviate from an established set of parameters just like in a conventional method (Interviewee C).

4.2.4.3 Immature manufacturing technology
AM is today still considered an immature manufacturing technology. This has resulted in challenges within the company. A further explanation of these challenges is presented below.

Challenge 23
The interview study showed that many at the company consider there to be higher requirements on AM technologies than other conventional methods. According to interviewee A, this is mainly because the technology is still new and that there is a lack of experience. These high requirements are applied because the aerospace industry is a very conservative industry, which then further complicates the standardisation of AM repair.

Challenge 24
Several employees expressed that currently it is unclear, which materials are accepted in AM repair process. Interviewee E specifically highlighted the case of castings. It is assumed that castings are faultless, even though it is known that this is not the case. However, casting have been utilised within the industry for a much longer period of time than AM and thus the technology has withstood the test of time. Interviewee E expresses that the problem here is in how mature the process is. A

more mature process does not require as much inspection and control, which leads to more lenient requirements on the materials.

4.2.5 AM Competence

AM as previously mentioned is a large area that covers several different technologies. Mastering component design and increasing the internal company knowledge within AM repair are challenges that were identified at GKN during the interview study. Below these challenges are further described.

4.2.5.1 Lack of component design for AM

The issue of lacking components designed for AM repair is something that was clearly identified when analysing the interviews. In the section below a further description of this is presented.

Challenge 25

Another identified challenge from the interview study is that the components available at the company today are not designed for AM repair. According to interviewee F, the company is planning repairs on components designed before AM was relevant as a repair method. This complicates the reliability of the process as components that are not designed for AM have a different type of design and structure. Due to this, repair with AM becomes a less attractive choice.

4.2.5.2 Lack of internal knowledge

A lack of internal knowledge has given rise to a few different challenges within GKN. The nature of these challenges is further described below.

Challenge 26

A challenge identified by interviewee J is the development curves that are formed with each change or development in the AM repair process. It is believed that the AM repair methodology is very component and process adapted and with each specific component repair, a specific case is formed. These cases create new development curves that never really end. This has resulted in high costs for each case where the knowledge gained from the case has not been useful for the next AM repair project because the operations are highly customised to the component (Interviewee J).

Interviewee A also explains that for AM unlike other technologies the interviewee has worked with, as soon as something changes in the process, the TRL decreases from TRL 7 or above to TRL 4. It is claimed that as soon as a new AM repair operation is created, the TRL drops and the development project is sent back to Global Technology Centre (GTC) and R&D, which then have to raise the TRL of the operation back up so that it can be implemented. Thus, every time the repair process needs to change a new development curve is initiated.

Challenge 27

The internal knowledge about how all AM equipment works at GKN is currently perceived by employees as lacking. The interview study specifically identifies a lack of knowledge about the calibration of AM machines. This is mainly due to that machine developers often tend not to want to share knowledge about their equipment (Interviewee F). Machine manufacturers have patents on their machines and therefore GKN employees are not allowed to perform all types of calibration and maintenance internally. According to Interviewee F, this limits the possibilities for developing internal knowledge about the AM equipment, which also then complicates the development of the technology further at the company.

Challenge 28
Today, GKN relies a great deal on a research institute, which is very knowledgeable with consideration to the nozzles utilised for the laser machines at the company. The knowledge pertaining to the nozzles is currently lacking internally at the company, hence the company turns to the research institute for this (Interviewee H). This means that each time a nozzle is in need for repair or a new nozzle is to be introduced, the nozzles have to be sent to the research institute for maintenance or parameter development. As GKN is collaborating with this research institute, it means long lead times and production stops for the company before results have returned from the institute (Interviewee G).

4.2.6 AM Equipment

There is a variety of AM equipment at GKN, but the two technologies that have been mentioned most during the interviews are LMD-powder and LMD-wire. Thus, the challenges identified during the interviews is focused on this particular AM equipment.

4.2.6.1 AM cell limitations

During the interviews with employees at the company, it was often expressed that there were a few different challenges at the company related to the limitations of the AM machine cells. These are further described below.

Challenge 29
An important limitation related to the AM equipment at the company is the available space and access to the component in the AM cells. According to the interviewees B, G and I, repairing large components is currently very challenging because the AM machine has to work in end-limit areas. Interviewee B clarifies that when this is the case, it is necessary to contact a research institute for further instructions on how to run the machine in order to avoid collisions with the nozzle. This, in particular is described as a very time consuming step.

Interviewees B and G also explain that the same challenge arises when the machine needs to work in different angles and perform AM in 360 degrees around cylindrical components.

Challenge 30
Another limitation that is important to consider since the company is focused on repairing larger components where it is easier to find business cases, is weight. The LMD-powder cell specifically has a weight limitation according to Interviewee B that thus determines how heavy the components to be repaired can become before they are no longer feasible for repair in the AM cell.

Challenge 31
According to interviewee H, there is also no indication in the AM cells for when machine nozzles are running out in inventory. This, means that when a collision occurs with the nozzle, there may not be any spare nozzles available, which will cause a stop in production. This is a challenge as it could potentially increase the lead time of repair operations.

Interviewee H also expressed that had it not been for the Covid-19 situation, during which production has slowed or stopped completely for some components, then there would have been a stop in production regardless as the necessary AM nozzle has been sent for parameter development at a research institute and has been delayed by approximately a year so far.

4.2.6.2 Limitations of machine

The technology, which was discussed most during interviews, was the limitations of the LMD-powder equipment. The limitations of the machine that were brought to attention during the interviews are further described below.

Challenge 32
According to interviewee B and H, the current LMD-powder machine lacks height control, joint tracking and localisation. It was expressed during the interviews that these abilities are essential for better process control. Interviewee D also concurred that there is a need at the company for a more flexible LMD-powder machine specifically.

Without these abilities, set-up operations such as programming take more time as all components need an individual program based on the component scan because the machine cannot adjust the program to the component automatically. This also means that the programming needs to be executed with a high degree of detail according to interviewee B.

Challenge 33
A challenging limitation of the LMD-powder machine, which is very time consuming according to interviewees B and D is the programming needed for each component. The LMD-powder machine currently available at the company cannot handle greater programming files than 740 kB. Therefore, the program has to be run in smaller sequences in the machine in order to perform a complete repair operation.

Interviewee B explained that for the repair operation linked to component A, 40 programs had to be run for each component repaired because of this limitation where each individual component requires completely new programs adjusted to their specific deformation.

Challenge 34
One of the more costly limitations of the LMD-powder machine is linked to the nozzles of the machine. Interviewees B and H explained that the nozzles currently used are very sensitive to reflection, which can damage the lens of the nozzle and collisions, which can disrupt the distribution of powder through the nozzle for example. The parts in question are also very expensive, as there are very few suppliers on the market for AM nozzles with high accuracy and quality.

4.2.6.3 Customised machine

Some challenges related to the AM equipment is a result of how highly customised the equipment is to specific components. This has made it difficult to adjust the equipment to new projects and initiatives.

Challenge 35
Interviewees B and H explained during the interviews that the current LMD-powder machine has been specifically built for the component A project. This has made it difficult to find other components that can be repaired in the machine. Interviewee H claims that among other things, the size of the components pose a challenge as access to the components becomes an issue if they are larger than component A.

Interviewee G concurs and explains that there is a need for components, which are viable for the machine but also that there are business cases for. This along with size and access limitations make the options for repair components very limited at the company.

Challenge 36
Another challenge that interviewee G remarked on was that, if the LMD-powder machine is to be rebuilt to accommodate other repair components, the machine still has to be suitable for component A as well because it is an ongoing repair project. Thus, the challenge is to increase the flexibility of the machine without disrupting any currently important parameters for the component A repair.

Challenge 37
Interviewee K claimed that increasing the flexibility of the machine will be very difficult and the equipment may never become suitable for several different components. The interviewee explained that this is because the repair operations considered viable are all very specific when it comes to process requirements. Thus, it is will be a challenge to make the LMD-powder machine highly customised to several different components and rebuild it each time another repair component is added to the company's list of repairs.

4.2.7 Qualification and Verification

During the interviews with company employees, it became clear that the company has a lack of qualification and verification methods for AM repairs where it concerns the process as well as the component. The challenges within qualification and verification are largely found within three areas, which can be seen below.

4.2.7.1 Conservative industry with high security demands

One of the first challenges expressed within the company during the interviews was related to the aerospace industry as a whole. Thus, it concerns not only GKN but their customers as well.

Challenge 38

The aerospace industry is considered a very conservative industry by the employees at the company, with high demands on safety. This is a result of the high demands and requirements set on the company by government authorities. GKN is not the only company, which has to comply with these requirements though, since their customers are also under the same obligation. This leads to a lack of business cases within AM repair at the company, which further slows down the process development for AM (Interviewees D, G and K).

4.2.7.2 Slow development and approval of methods

The development and approval of new methods at the company is currently considered very slow and the issue seems to be linked to a few challenging areas.

Challenge 39

The methods developed within the company are categorised according to their respective TRL. Once a method reaches TRL 4, it is developed through GKN's GTC until it has reached TRL 6 where it is then handed over to the production team at the company. Thus, the process development is performed internally as well as externally (Interviewee A).

The AM process development therefore becomes very time consuming since there are research institutes included in GTC, which may have different lead times and priorities and the development process is performed in a manner which means that, as soon as the process changes, the TRL may need to be dropped back down to 4. Thus, the development curve needs to start all over again at the company (Interviewee A).

Challenge 40

Another challenge identified during the interviews was related to the organisation. According to interviewee H, it is unclear, which methods should be used for qualification and verification of a repair process. There is no standardisation for qualification, and it is unclear when a process is approved since there is no clear process ownership.

During the interviews, interviewees E,G and I claimed that it is unclear how many tests need to be performed in order to qualify a process for repair and determine that it fulfils all requirements.

Challenge 41
A lack of design responsibility was also pointed out as a challenge by interviewee E, who claimed that it is unclear whether anyone has a design responsibility for the components since there are no dimensional criteria. This is necessary since someone needs to approve the component design and specify whether it is acceptable for the dimensional characteristics to change somewhat due to the repair process as long as the component complies with the base requirements set by the customer. Without design responsibility it becomes more difficult to qualify a process for repairs.

4.2.7.3 Uncertainty in how product materials are certified
The third issue within qualification and verification, which poses challenges for the company is related to the manner in which product materials are certified for repair purposes.

Challenge 42
An uncertainty that the company employees are currently working with relates to material certification. According to interviewee F there is currently a lack of knowledge in how materials produced in AM should be implemented and certified. Interviewee E agrees with that, claiming there are uncertainties on how to verify that certain material properties meet requirements. For example, it is unclear how one should verify that the AM material complies with service life requirements.

Challenge 43
After the AM process has finished, one of the challenges identified pertains to how material properties should be verified. Interviewee F explained that it is difficult to tell which material is being built to begin with since the AM process does no necessarily produce the same set of material characteristics during each process. This is because certain parameters in the repair process, such as temperature can vary. Thus, it is very important to consider bringing inspection methods into the building process as early as possible.

Challenge 44
The post-processing of components repaired in AM also pose some challenges. Interviewee F points out that since it is still very difficult to verify what happens after the AM weld process is finished, it also becomes difficult to choose an appropriate post-processing method.

4.2.8 Material Aspects

In AM and specifically AM repair, the material aspects and properties created by the process are very important to be able to identify. Due to the fact that the technology is still new and in the development phase, unrealistic requirements are placed on the material that is deposited on the component. These requirements are also imposed on the repaired component. According to the interview study, this is mainly due to the uncertainties linked to how to achieve the desired material properties within AM repair. Below the challenges regarding material aspects of AM repair are described.

4.2.8.1 The application of material can change material properties

By depositing AM material, one tends to change the material properties of the component, which was expressed by the employees during the interviews. GKN today has challenges within this area, these are presented further below.

Challenge 45

Several employees expressed that the post-processing required after the AM repair process has been completed, can change the material properties. This is because the component has already been processed during the original manufacturing procedure. In the event of further post-processing after the deposition of the AM repair material, material properties are changed and cannot be controlled. It is not known today what material properties are formed in each specific finishing method. The challenge is to identify whether these material properties are the same each time this finishing method is utilised (Interviewee F).

Interviewee F specifically highlights the post-processing method, local heat treatment, where it is expressed that the desired material properties cannot be achieved when local heat treatment is performed on a component that has already been through heat treatment in the previous manufacturing procedure. Residual stresses are formed in the material, which are difficult to eliminate. Interviewee G also confirms this and expresses that the material properties change during local heat treatment. It is explained that it will therefore be difficult to repair components that have already been through heat treatment.

Challenge 46

Several employees confirmed during the interviews that the requirements one has today on the material properties are unrealistic. What was specifically highlighted was that the departments can strive for forging properties when welding in castings (Interviewee D). Interviewee D expresses that one cannot expect properties such as those of forging when depositing AM material on a component that is a castings. According to interviewee D, these unreasonable requirements are mainly due to the uncertainty surrounding the material properties that are formed after the AM material has been deposited on the component. But also, the uncertainties that come with all the finishing methods that should performed on the component after the AM repair process.

4.2.8.2 Difficult to predict deformation

The issue of predicting deformation is tackled by GKN today. Below is a description of the challenges GKN has and is trying to overcome within this area.

Challenge 47
At what GKN classifies as an AM repair of component A, the programming of the AM process has been adapted to each specific component (Interviewee K). This has resulted in that it becomes difficult to predict what the component deformation looks like after the process has been completed (Interviewee K). Thus, it cannot be ensured that the deformations that appears after the AM repair process are the same for every component A. This complicates the planning of the entire AM repair process as the resulting component properties do not look like the desired outcome (Interviewee K).

Challenge 48
Another challenging area is the residual stresses, which result from the AM repair operation. The issue is that residual stresses are formed on the surface of the component, which must then be treated locally with heat after the AM repair process has been completed. Although this local heat treatment has been carried out, it is not possible to completely eliminate the residual stresses that may remain in the phase transition, between the materials deposited and the original material.

4.2.8.3 Lack of inspection methods
The inspection method used at GKN today has challenges within inspection and analysis of material as well. These challenges are explained in more detail below.

Challenge 49
The inspection methods available today at GKN do not work for AM repair. Cracks that form in the component directly during manufacture are difficult to identify. Minor defects that arise from the AM repair process are thus not detected with the inspection methods that are currently available at the company (Interviewee F).

Crack propagation is an inspection method that is currently used in conventional repair methods and does not work as a method for AM repair, says interviewee F. By this, interviewee F means that it cannot be ensured that the component is as thin, fine, and light as it needs to be after an AM repair process has been performed. This is because it is difficult to know what material properties the material deposited has from the beginning with the AM repair process.

4.2.9 Cost

When it comes to the cost of AM repair, there is no clear view of the cost parameters linked to AM repair operations, financing and resources at the company according to employees. These challenges are further developed and explained below.

4.2.9.1 Inadequate cost calculation
Where cost calculation are considered for AM repair at the company, the challenges identified are related to an uncertainty in what cost parameters should be considered for a cost evaluation.

Challenge 50
According to interviewee J, so far, the company has performed a cost calculation on one component repair, component A. The business case created based on this however did not hold up at the end of the project as the total cost of the repair exceeded the estimated cost calculated. Interviewee J claimed this was because unexpected costs can arise from the implementation of a new technology. According to interviewees H and J these costs are among other tool costs, re-work costs, certificate costs and costs brought on due to unique component deformations etc. Interviewees D and E also concurred that there is a difficulty with predicting these kinds of costs at the company.

4.2.9.2 Difficult to find financing

The financing of AM initiatives and projects is also a challenging area at the company, which the employees have pointed out. There are several factors that cause issues within the area of financing for AM from the number of active AM initiatives at the company to the lack of business cases and customer requirements.

Challenge 51
According to interviewee J, one of the major challenges linked to financing is that it is a technology difficult to sell to customers because it is relatively new in the industry. Interviewee C agrees and further states that because the technology is still expensive in the development phase and there is no clarity concerning the costs related to the technology, it may not come across as an alluring option for customers.

Challenge 52
According to interviewees C and J, another challenge that employees and departments at the company face when seeking financial resources from management at the company is that unless the initiative can be linked to a profitable business case or potential future business cases, it is unlikely the initiative will receive the necessary funding.

Challenge 53
The third challenge within financing for AM at the company is linked to the number of active initiatives. Interviewee D explained that there are a lot of AM initiatives currently active and waiting for funding at different departments within the company. This means that all of the initiatives are competing for the same resources, which causes a lack of focus in investments according to the interviewee, which then result in a very slow development pace for the technology.

4.3 Benchmark within AM repair

To get an idea of how external actors view the area of AM repair, two benchmark studies were conducted. One with Siemens Energy AB Finspång and one with an AM expert. Below are the results of the benchmark study and the external actors' views on AM repair.

4.3.1 Siemens Energy AB Finspång

The benchmark study with Siemens resulted in an interview with a manager at the company who works within the department R&D for AM. Siemens is today one of the leading companies when it comes to AM repair. This since they have established AM repair on three components and are constantly working to develop and implement repair and maintenance methods on several other components. The company currently performs AM repairs on the gas turbines that are manufactured internally at the company. The AM technology used in the repairs is LPBF. Today, the company designs components for AM repair that are known to have been subjected to wear. The interviewee explains that since the company mainly manufactures gas turbines, which is a well-known product within the company, it is clear to them that the component has a limited service life and will eventfully need repair. Thus, for components like these, the part is designed right from the start to cope with an AM repair later on.

The interviewee believes that today, a better flow of communication could eliminate many of the limitations with the LPBF technology within the company. Today it has been made clear to all organisations at the company what restrictions there are in terms of what the equipment can handle, what sizes are allowed, what materials to use, and what to expect from the equipment. On the other hand, Siemens has a large R&D department, which complicates the communication of such restrictions to the remaining departments. There is great potential for development and improvement in the communication between departments. According to the interviewee, large differences have been seen in the results of successful communication and knowledge transfer between the various departments. The example of designers and production technicians is given, where it is explained that with a lacking collaboration early in the development work, the desired result is not achieved. In some cases, unfortunately, designers have stated that it is possible to produce or repair in AM, the developed concept has been released to the production department, which then state that this is not the case. This adds unnecessary costs and time that would have been eliminated if a closer collaboration between R&D and production had been achieved claims the interviewee.

When it comes to the flow of communication between management and the remaining departments, it is also confirmed here that today there is an existing gap. The interviewee believes that within a company there are always some types of groupings. Where some are technology enthusiasts while others are more hesitant about new technology. In addition to this, there is a divide in management, where some aim to contribute to more development and implementation of new technology or/and do not dare to take any risks regarding investments. However, the interviewee highlights that within Siemens, management has been very positive about the implementation of AM in repair and maintenance. It is explained that the managers who have been in the right position to make financial decisions have chosen to invest within this area.

The common language used within the company for AM repair is considered by the interviewee to be clear, specifically when it comes to what is defined as AM. Distinctions on repair, modification, and new production are also clear. On the other hand, it is felt that the languages when it comes to the technology itself is unclear among several employees. That is, what is the technology called and what are the different elements within AM called. This is believed to be due to the fact that the technology is still new, and the experience is not high. The interviewee explains that just a few years ago the technology was called Selective Laser Melting (SLM), but today it has been internationally decided that the technology should be called LPBF. Official name changes of the technologies make communication more difficult for individuals and it is therefore experienced that many choose instead to not speak about the technology.

The AM repair process currently has what the interviewee considers to be higher requirements than conventional methods utilised for repair. According to the interviewee, more questions are added during an AM repair, which is mainly due to the lack of experience and because in comparison with conventional methods, AM is still considered a new technology. However, the interviewee explains that the high requirements are utilised to motivate both customers and employees internally that the technology is optimal. This is because skepticism always appears during the implementation of new technology. By demonstrating the technology's advantages and proving that it can meet the high demands set, a possibility to prevent much of this skepticism is created. People who are skeptical about new technology will always find reasons to argue against the implementation and therefore, it is important that a company can demonstrate the benefits, explains the interviewee.

When qualifying and verifying a repair process with AM, Siemens uses a standard established product development process that is similar to most companies. However, in this case, a special focus is placed on technical issues such as what risks are seen with these repairs and how to control them. According to the interviewee, the company possesses great knowledge in how product materials are to be certified. Siemens today has a team of competent materials engineers with laboratory resources who constantly ask critical questions and test all materials before they are used on the final product. On the other hand, when it comes to official certification, a gap has been identified as the official standards have come in as late as 2020. The interviewee says that the company knows how the certification should be executed, but there have been no official standards to support it. When it comes to the requirement set on material properties, the same material properties are not expected in the repair as the original component. According to the interviewee, it is unreasonable to assume that it is possible to achieve the same characteristics. It is necessary to know what properties the repaired material has however, and calculations need to be performed to prove that it will hold up in terms of strength. The interviewee explains that when inspecting the repaired component with AM, Siemens utilises risk analysis. Where the company performs a specific risk analysis for each component in order to identify what defects could possibly occur, and how an inspection of the component can be performed. Among the inspection methods utilised internally are: classical penetrating fluid testing, Ultrasonic Testing (UT), or other alternative conventional methods.

Today, Siemens does not follow a uniform plan in terms of a development plan for AM repair projects. Instead, the company works in line with the concept that ideas are created when a repair is needed, which then leads to an investigation of whether AM is an alternative or not. When identifying whether AM is a suitable repair method, it is necessary to go back to the people who developed the first repair methods at the company and follow their experience and utilise their competence. In other words, the interviewee explains that there is no fully documented process for this stage of the development phase. However, Siemens works according to the principle that each project group is required to document what is done, both in development, testing, and the remaining phases of a project. The interviewee mentions that it is unfortunately very individual how carefully this documentation is performed. A report however must always be written, which then must be archived according to company rules. Siemens has today built up an AM Wiki, which is a website that has the same function as Wikipedia. Each user can contribute with their knowledge on the platform. The platform was implemented since the company has a global network mainly within Germany, England, the USA, and Canada. To succeed in exchanging experiences and knowledge between project groups, the company therefore chose to implement the Wiki, in which employees can briefly describe the projects that have been performed and refer to the complete final report for further in-depth investigation.

At Siemens, no unexpected costs are considered today during the calculation of an AM repair. The interviewee believes that this is something that is necessary as costly surprises often arise from this type of repair projects. However, the interviewee mentions that in some occasional cases it can be seen that the cost of repair with AM is significantly cheaper than the cost associated with a conventional method. In these cases, a buffer is automatically built since, all the costs are rounded of upwards. In many cases however when there is a border case in terms of what technology is more profitable, AM or a conventional method, the company is pressured to prove that AM is a cheaper alternative. The interviewee explains that it can therefore be difficult to account for buffers, which often generate unexpected costs in cases like these.

4.3.2 AM Expert

The second benchmark study was based on an interview with an AM expert who currently works as a lecturer at University West in Trollhättan. The interviewee has previously worked with AM repairs of industrial tools and specifically has experience with different laser manufacturing methods, which do not differ much from DED as well as AM technologies. As laser is the interviewee's area of expertise, the interviewee decided to collaborate with University West in developing a course within AM, where AM repair is one of the subjects taught.

The interviewee begins by explaining that the tools, which he has experience in repairing are used to produce other details. When qualifying this AM repair process where the interviewee previously worked, the employees were expected to look at the process outcome during the procedure. This was done in order to ensure that the details, when finished, had the correct shapes and that the components met the requirements set. An analysis was also performed on the repaired components where data was collected, that proved the AM repair operation was a competitive solution in terms of sustainability and cost in comparison with the previously utilised conventional methods. Unlike the utilisation of AM in the aerospace industry, the expectations on performance and requirements are therefore not as high as might be expected for an aerospace component. The interviewee claims that in terms of knowing how the process should be utilised and approved, there are many challenges today for the aerospace industry. The example of forging and castings versus AM is given, where it is explained that for forged or cast details, the desired strength, yield strength, and ductility of the material has already been specified when the component is ordered. However, during AM repair, all the process parameters used during production have an impact on the final result. The interviewee explains that the most sensitive components may not be suitable to repair with AM within the aerospace industry. Instead, the interviewee believes that the company should start by looking at less sensitive details where experience and knowledge can be built within the technology.

The interviewee also expresses that the materials utilised at GKN, are not easily weldable, which also makes the repair with AM difficult. It is explained that it is important to find the right process parameters to succeed in overcoming these challenges. In cases where there is a need to build key structures, i.e., where several layers of AM powder need to be deposited, it has also been identified that different micro-structures are obtained in the material. This is due to the fact that layer upon layer is built, which then becomes heat upon heat that creates defects in the original component and the deposited material on the component. Here, the interviewee suggests that it can be beneficial to sometimes deposit a powder layer, melt it down, pause the process for 1-2 minutes and then proceed with the next layer. This methodology avoids the anisotropic behavior that is otherwise obtained at high temperatures in different areas of the application.

The interviewee emphasises the importance of understanding that if the company aims to repair details with AM, it is necessary to be aware that the repair method consists of a long chain of procedures. If the damaged part has the wrong shape, or does not look like the CAD drawing for example, this means it is necessary to first scan the part and examine how defective it is. It can then be determined how much powder should be deposited on the component. There will always be some damage to the surface if the AM material is directly deposited and melted down. Therefore, post-processing methods on the component tend to be necessary in most cases for AM repairs. This is because the process cannot be expected to achieve the desired component characteristics with only the molten powder deposition of AM. For example, if the desired result is to increase the density of the applied material or achieve specific surface measurement, a suitable post-processing method is required. These finishing operations on the component are also favorable for the purpose, since they can introduce tensile stresses in the component that can lead to an increase in strength.

The differences between conventional repair methods and AM repair are discussed during the interview. The interviewee specifically highlights the advantages of AM repair where it is claimed that the heat transferred during the AM repair is significantly lower and the risk of defects such as shape changes during the repair is thus lower compared to conventional repair methods. The example of welding is given, which is a conventional repair method that uses gas metal arc welding equipment. The finishing time is noticeably affected with this conventional method, which increases since it is necessary to go back into the CAD drawings and re-align the part according to the defects that have appeared. These problems are avoided in AM powder application as the heat transferred is significantly lower because the process is much faster in comparison to welding. The shape accuracy achieved with AM laser is also a great advantage compared to conventional methods. The interviewee claims that the problems that are often discussed around the reliability of the final result for AM repairs are exactly the same for conventional repair methods. The method does not contribute to the creation of homogeneous component material, as it will always differ between the repaired part and the original part, regardless of the choice of method.

According to the AM expert, companies today are afraid of AM technology, which is mainly due to the limited information and education. It is important to highlight all the benefits achieved with an AM repair implementation, specifically to people who have authority to make decisions within a company. This can be done by demonstrating the lead time reductions, higher productivity, less environmental impact, and highlighting the profitability of AM repair compared to conventional methods. However, there are several questions surrounding AM technology. Many still associate AM with a 3D printer for plastic, which sets the level for how reliable people think the AM process is. In addition, many today claim that there are no standards for what requirements to set on a repaired product and how the repair procedure itself should be performed. However, this is a bit of a myth today, explains the interviewee, as several organisations have begun to produce standards within AM metal and AM repair. These standards have been very driving from the American side as they were early in the AM world and realised the lack of standards in the field. So currently there are a lot of standards within the American Society of Testing and Materials (ASTM). The interviewee believes that many companies should use the ASTM standards to start with in order to build up their business around AM and AM repair.

Another important factor that also affects the motivation around AM and AM repair are the large investment costs, where it is expressed that the equipment for the implementation of AM is very expensive. A laser source is very expensive and it is important to be prepared for the costs associated with the technology. Companies also need to have an online monitoring function to enable continuous monitoring of the process.

The interviewee also claims that this may be why AM, has ended up within the larger companies such as Volvo, GKN, and Siemens primarily, in Sweden. These companies have the financial means to invest in this innovation. However those who might have benefited most from AM technology are companies that manufacture smaller components with lower requirements. The downside is that these companies can rarely afford the AM technologies.

In addition to the investment that come with the implementation of AM, a large investment is required in education (AM expert). According to the interviewee, it is important to be aware that the AM process will never be a matter of simply inserting a component in to a machine and pressing a button. As with traditional welding, a lot of operator knowledge is required, hence the education costs mentioned above. It is imperative that employees understand what happens to the material when process parameters are tailored in repair operations. Because there is also an educational cost linked to AM repair, it becomes a challenge to make a cost compression between AM repair and other conventional methods.

4.4 Alternative solutions and opportunities

Below the identified alternative solutions and opportunities for the challenges previously defined are presented. Note that many of the methods mentioned below can be utilised to resolve several of the challenges mentioned earlier in the report.

4.4.1 Organisational Structure

The organisational structure within a company plays a major role in how the implementation of new technologies and projects takes place. Organisational structure is a broad word, it is defined as the rules, policies, procedures, and processes that have been established internally at a company. These are created by management and facilitate a company's way of working and direction. A clear and well-defined organisational structure eliminates challenges surrounding undefined roles for responsibility. A well functioning organisational structure can also reduce issues linked to unclear visions, goals and directives. Every company today adapts its organisational structure according to its market and needs. Therefore, it is important that the company define these, to build an organisational structure, which is suitable for the organisation (Jacobsen, Grunert, Søndergaard, Steenbekkers, Dekker & Lähteenmäki , 2014). Below different approaches and methodologies are presented on how to build a well functioning organisational structure.

4.4.1.1 Selecting suitable business model

AM is a new technology on the market that requires changes in companies' existing business models. To succeed in implementing the technology, it is recommended that leaders adapt the company's business model. Companies must take a strategic position on how AM repairs are specifically defined within the organisation and define a suitable business model for AM. The authors Martens, Fan & Dwyer (2020) claim that companies need to focus on the advantages of the technology by adapting their business models to cope with the opportunities and benefits of it in order to stay competitive. This is necessary for projects to be developed and considered worthwhile (Martens et al., 2020).

When introducing a new technology or process such as AM in repair, it is important that companies identify their customers' needs. It is important to know that the customer wants to utilise the technology for their components and that they accept both the advantages and disadvantages that the process may entail. Therefore, as a company, it is important to identify a market segment that values the introduction of the technology and create capacity that customers and competitors can not replicate (Martens et.al., 2020).

It is important to have a business model that supports taking on risks and challenges in order to build experience within the implementation of new technologies. When a company has determined that the technology in question is in demand by customers, investment costs and development costs should be addressed in order to succeed with the implementation (Martens et al., 2020).

The authors Martens et.al. (2020) also emphasize that employees' knowledge should be developed and the focus on training staff in the area should be considered. A leader also needs to recruit operators and engineers with the right area of competence and experience to succeed in advancing, if specific knowledge is considered lacking. This can eliminate the need to rely on external parties by increasing internal knowledge within the organisation (Martens et.al., 2020). Interviewee A also concurred with this approach and claims that technical knowledge pertaining to calibration for example could be developed internally as the resources necessary for this are available at the company.

4.4.1.2 Platforms for knowledge transfer

Preservation of knowledge and data is necessary in a company to enable the implementation of new technologies. Knowledge of previously performed projects, identified parameters and specific working methods within a company need to be preserved in a structured and easily accessible way to facilitate any re-organisations within company departments (Thomas & Prétat, 2009).
Data and previous experiences of completed projects should be easily accessible to anyone who wishes to utilise it for future projects and implementations. IT-based systems are great tools for preserving knowledge and data in a sustainable and structured way. The introduction of IT-based systems includes the implementation of computer systems, which contain databases with search tools to make data easily accessible to all corporate departments. It is important that these systems are used correctly and fully to succeed in achieving the desired result. Similar systems are often found in companies but the utilisation of these is limited. In other words, it is important that the preservation of data and knowledge is documented clearly and in a structured manner. This in order to facilitate and ensure the utilisation of the system (Thomas & Prétat, 2009).

4.4.1.3 Decentralised decision making

To facilitate the transfer of goals, visions and requirements established by the management to the remaining departments, the principle of decentralised decision making is recommended. This since the principle simplifies the information sharing between the various corporate departments and the hierarchies at the company. Challenges such as unrealistic requirements and unclear plans for further development can be eliminated with decentralised decision making. The principle facilitates diversification of new activities since the management's goals and visions have been presented clearly and structured for all the corporate departments (Thomas & Prétat, 2009).

Better control and monitoring of the implementation of AM repair is also achieved as the entire company's goals and visions have been presented and discussed with the remaining departments. If any corrective measures need to be taken within company departments it is then clear that these decisions are approved. Through decentralised decision making, employees also have the authority to make independent decisions, which results in decision-making being determined in a simpler and faster way (Thomas & Prétat, 2009).

4.4.1.4 Management support

Implementation of new technology requires clear support from the management of the company to be successful (Leonard-Barton & Kraus, 1985). Management support motivates employees and departments to want to work towards this implementation. Often it is perceived that leaders are very optimistic about the introduction of new technology, but that no support is given in the shape of resources, processes, and facilities (Murthy, 2007). In order to ensure that employees are working towards a successful implementation and the goals set, it is therefore very important that this type of support is perceived to be provided by the employees (Tavakoli, 2010). Management should identify where priorities and investments should be placed and thus avoid starting too many internal initiatives (Lee & Kim, 2020).

By implementing tools such as involvement, engagement, reward and recognition programs the management can be perceived as more supportive and this could lead to a more efficient implementation of new technology within the organisation (Lee & Kim, 2020). Management should also emphasize the benefits of implementing the new technology so that the employees feel that the implementation will benefit them. This will reduce the risks associated with creating a fear of failure, contradiction and unclear visions within the organisation (Lee & Kim, 2020). The management should also understand the differences in employees' feelings. The resistance to change model explained by the author Murthy (2007) clearly describes the different factors associated with employees resisting change. By following this kind of model, the management could understand their employees better and know exactly what type of tool is needed for that specific employee's reason to resist (Murthy (2007).

The support that management must generate is in the form of being available to the needs of employees, showing that what they have to say is important and that they are considered in their decision making. According to the authors Lee & Kim (2020), this achieves several advantages within the company. Employees will work towards set goals and the support received will generate higher commitment around individual work, which will lead to better productivity and results. In other words, leaders who are considered role models by their employees, will have employees that are motivated by their work since they have a clear sense of how their work benefits the company and themselves. (Lee & Kim, 2020).

4.4.1.5 Failure tolerant management

When introducing new technology, it is important to have a management that is stable enough to cope with any failures that may arise. The authors Farson & Keyes (2002) highlight the approach of leaders that engage in specifically the projects that are known to contain challenges and risks, since according to the authors, these are the pathways that lead to success. These types of leaders go in and show their support and commitment in order to eliminate emerging fear and contradiction among employees. Fear from previously unsuccessful projects and the contradiction from employees is very dependent on the management's response to these challenges. With management that does not tolerate failure, an organisation that fears failure is automatically created. This results in an organisation that is fearful of taking on challenges and opportunities and an organisation with limitations in innovation and development is instead formed (Farson & Keyes, 2002).

The authors Farson & Keyes (2002) discuss the importance of having a leadership that tolerates failure and highlight the failures as a learning lesson. The authors believe that management should take on the implementation of technologies that entail risks of failure and view the lessons learned from those failures as experience that is built within the company. This approach helps employees overcome their fear of failure and instead creates a culture of intelligent risk-taking that leads to sustainable innovation. These leaders break the barriers that exist between the different hierarchies and instead engage on a personal level (Farson & Keyes, 2002).

4.4.2 Interdepartmental Collaboration

Having well functioning interdepartmental collaboration within a company, leads to an organisation working towards the same goals and vision, which results in a higher degree of efficiency and productivity. This approach can eliminate the need for departments to place blame and responsibility in specific areas on other departments or individuals. A well functioning collaboration between departments can instead help create, share, and develop knowledge between different individuals that come from different backgrounds. Individuals and departments always possess different areas of knowledge, and through well functioning collaboration, these can be combined and thus contribute to the entire organisation's performance (Thomas & Prétat, 2009). Below, methodologies on how to achieve interdepartmental collaboration and thus eventually eliminate several of the challenges discussed under the AIM are presented.

4.4.2.1 Meetings

Meetings are constantly held within companies, despite this, there are challenges in the transfer of knowledge between different departments. The authors Thomas & Prétat (2009) discuss how different types of meetings can facilitate successful knowledge transfer. The authors highlight, for example, information meetings, brainstorming meetings, and face-to-face meetings. These meetings between different departments and teams lead to employee's sharing their different areas of expertise, which can create a clearly defined language for the final project goal.

Meetings could also generate a better understanding of departments' needs and clearer solution proposals could be formed jointly that solve all issues and take into consideration the important aspects linked to all steps in the manufacturing chain. To achieve these benefits, it is required that the organisation decides on scheduled face-to-face meetings between different departments that work with the same project and in this way "forces" the departments to share their knowledge and experience. Through this approach, a stronger relationship is built between the departments, which also leads to tools such as spontaneous sharing and e-mail exchange taking place automatically later on (Thomas & Prétat, 2009).

4.4.2.2 Implementation teams

Implementation teams are teams that work collaboratively to ensure and support the implementation of new technologies for example. The team can include employees, researchers and experts, which are knowledgeable about a certain innovation to support and facilitate its implementation (NIRN, 2021).

Implementing new technology today can be a long process as there is a clear difference between investing in new technology and being able to utilise it efficiently. This gap is due to a few key challenges related to the managers responsible for implementing the innovation, which have a very important role in facilitating technology utilisation (Leonard-Barton & Kraus, 1985).

The key challenges that are imperative for an implementation manager to overcome is their dual role, the variety of internal markets served, the resistance to change, the degree of promotion, choice of implementation site and the need for one person to take overall responsibility. Managers responsible for the implementation of a technology tend to be better equipped at guiding the development of the technology rather than its implementation. (Leonard-Barton & Kraus, 1985).

It is especially important for the implementation managers to create a smooth framework for information by coordinating an iterative process where relevant information is gathered. To deal with internal markets it is also important that challenges and needs be defined in order to succeed with implementation. Different approaches should also be used to gain acceptance from different organisational levels where the motivation of each individual or group is first identified and then utilised to drive implementation forward. Thus, it is up to the implementation manager to "sell" the technology to the organisation. This can also be accomplished by choosing an appropriate implementation site, where the technology is utilised in order to prove feasibility (Leonard-Barton & Kraus, 1985).

Accomplishing all of this work, requires involvement not only by one individual. The implementation manager should have a team to work towards the goal of implementation together with. To succeed, the team should ideally consist of at least four other team members:

- **A sponsor** that ensures that the implementation project can receive the funding and resources necessary. The sponsor tends to be someone who works at a higher level within the organisation.
- **A champion** who acts as mediator and problem solver for the technology.
- **A project manager** who oversees the work being done and is in charge of administrative tasks.
- **An integrator** who is in charge of communication and priority conflict handling.

It is imperative that at least one of these members has enough authority to drive the implementation forward and mobilise employees as well as resources. Something that is important to keep in mind is that members of an implementation team tend to have a clear view of the benefits of the technology they are working with and thus, when resistance appears in the shape of uncertainty for example, it can often be shrugged off as irrational fear. However, this fear is rarely irrational and it is therefore imperative that the implementation manager deal with the resistance when it is first encountered (Leonard-Barton & Kraus, 1985).

It is also important for the implementation team to work with the design of hand-offs between departments. There is often a need for those who work with technological implementation to act as both implementer and developers. The general rule is that the development department will develop the technology and then hand it off to the department that will utilise it. However, the department, which will utilise the technology often tends to be unwilling or unable to take over responsibility for the innovation at the point in time during which development is ready to hand it over (Leonard-Barton & Kraus, 1985).

The point of hand-off is a very important stage of implementation that should be carefully designed, in order to make it as invisible as possible. This should be done by ensuring that departments are working in parallel long before the hand-off, in order to integrate the perspectives and needs of all departments involved. This can be done by thinking of implementation as an internal marketing task, where the work begins with a study on the users' needs and requirements and existing infrastructure is taken into consideration. An interdepartmental example of this could be for the R&D department of a company to view the production department as their customers. Thus, it becomes very important for R&D to be aware of production requirements, resources and needs in order to "sell" their innovations (Leonard-Barton & Kraus, 1985).

4.4.2.3 Cross-functional teams

Through the introduction of cross-functional teams, an organisation can ensure that aspects from all different departments involved are considered in projects from start to finish. This methodology can eliminate problems such as departments being involved too late and that there are no uniform plans for the development of projects between departments (Murthy, 2007).

Wong (2020) highlights the importance of being involved in other departments' processes. It is discussed how important it is to be aware of the work and goals of the remaining organisations in order to work towards the same common final goal. Through the implementation of cross-functional teams the authors Thomas & Prétat (2009) claim that this type of collaboration is achieved. The authors specifically highlight the importance of cross-functional communication between R&D and production, where the author expresses that with close collaboration between the departments, a better understanding for colleague's needs is achieved. Cross-functional teams can eliminate issues related to non-producibility of the component for example (Thomas & Prétat, 2009).

4.4.2.4 Dense teams

Dense team is where the importance of close collaborations is emphasized (Thomas & Prétat, 2009). By working in a team where employees are comfortable, it will automatically lead to employees sharing their understanding and skills. The challenges related to re-organising corporate departments could also be eliminated with the implementation of dense teams. This is because working closely with others facilitates the transfer of knowledge so that employees can quickly adjust to any re-organisation and focus on the new departments area of knowledge. The elimination of problems such as projects being handed over between different departments in the event of challenges are also eliminated with the implementation of dense teams (Thomas & Prétat, 2009).

According to the authors Thomas & Prétat (2009), collective actions are achieved through dense teams. This since scattered knowledge is achieved by jointly planning and scheduling the work to focus on the common goals at the company. The close collaboration also generates good relations between the departments and a stronger bond to achieve the company's common goals (Thomas & Prétat, 2009).

4.4.3 Internal Organisational Communication

The internal communication flow between company departments is crucial for successfully transferring knowledge, data, and experience from previous and ongoing projects (Thomas & Prétat, 2009). This is to succeed in advancing the implementation of new technology (Leonard-Barton & Kraus, 1985). Below are presented methodologies that can improve the internal communication flow in a company.

4.4.3.1 Common language

A common organisational language accomplishes a few different things: it creates a sense of alignment, it can alter the way employees think, it offers simple ways of communicating complex challenges and issues and it allows employees to communicate with a higher degree of efficiency about new innovations (Thakor, 2011).

One of the keys to success within an organisation is clear communication. It is therefore imperative that employees understand the terminology and concepts used in order to be able to communicate efficiently within the organisation and with customers (NBRI, 2021).

A common language can eliminate challenges created when technologies with different maturity levels are mixed. The approach helps develop internal definitions within the company that clearly define different categories of technology (Sinclair, 2020).The benefit of a common organisational language is that misunderstandings are minimised, there is a consistency in the language used, which benefits customers as well as employees in interdepartmental projects, the language provides a shorthand within the organisation and helps create a sense of culture for the employees (NBRI, 2021).

Creating a common language however, can be a challenge. The process is based on the concept of first identifying terminology, which is unique to the organisation and then creating new words and/or definitions that can be used in their stead. In order to identify the terms specific to the organisation, employees can be involved in the development process of a new language, this can also make transitioning towards these new phrases easier (NBRI, 2021).

4.4.3.2 Feedback loops

Feedback loops are a tool that can help an organisation create coordinated and committed goals. Implementing feedback loops is a method, which can be used in order to continuously identify improvement areas in an organisation, project, process or individual work for example. Once the improvement areas have been identified, potential improvements can be turned into goals and actions (Chervenkova, 2020).

The loop generally consists of three stages. During the first stage, the data generated by a decision is captured and stored. The data is then analysed in the second stage and in the third, a new adjusted decision is created based on the analysis. When the decision is put into action, new data is generated, and the loop starts again. Feedback loops should be an important part of any organisation as the tool can help improve both productivity and efficiency (Chervenkova, 2020). To see an example of a feedback loop, see figure 7 below.

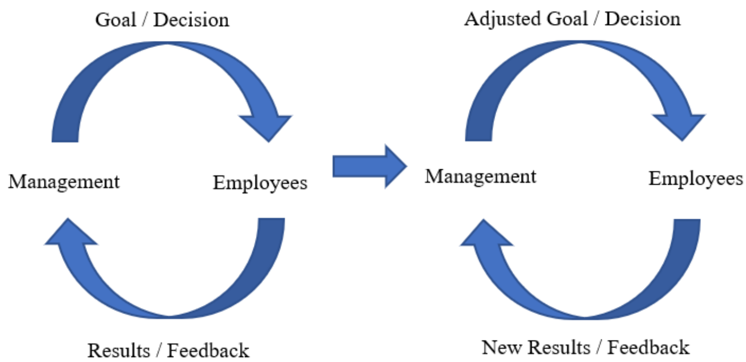

Figure 7: Example of a Feedback Loop in an organisation.

Feedback loops are also helpful in order to give the organisations employees context and help them see the impact of their contributions, which in turn can encourage and empower them (Wong, 2020).

The tool could potentially be used to improve cooperation between departments such as R&D and production for example or to improve the overall communication within an organisation between management and other employees as is suggested in the figure above.

4.4.3.3 Management communication

According to the authors Lee & Kim (2020) leadership communication is crucial for how the internal communication between company departments unfolds. Top-down communication is today a challenge within several organisations, the management message is not clearly communicated within the entire corporate hierarchy (Musquiz, 2021). In order for employees to feel that they have management support, it is required that the management communicates with its employees in a structured way that the employees can clearly understand (Lee & Kim, 2020). Management should be able to communicate within corporate departments in such a way that their message is clearly communicated to the entire hierarchy. Thus, a strategy for how to clearly communicate visions and goals and convey these through the entire corporate hierarchy should be developed (Lee & Kim, 2020).

Bottom-up communication is just as important as top-down communication but currently it is perceived to be more deficient than top-down. As communication should flow from management down into the corporate hierarchy, it should also flow back from the base towards management (Musquiz, 2021). Management is responsible for the flow of communication within the company and therefore communication from lower company levels should be taken equally seriously (Leonard-Barton & Kraus, 1985). This can only be achieved if management respects, listens, and considers employees' ability and capability. By doing this, employees will feel empowered and know that their challenges are taken seriously and will be discussed in upper levels of management (Lee & Kim, 2020).

4.4.4 Design Methodologies

Below different design methodologies are presented, which provide an insight into how challenges related to component, process and equipment can be overcome. These methodologies present how different design principles can facilitate qualification and verification while also enabling further implementation of AM repair.

4.4.4.1 Design for AM

According to Hensley, Sisco, Beauchamp, Godfrey, Rezayat, McFalls, Galicki, List, Carver, Stover, Gandy & Babu (2021) there have been efforts directed at developing qualification methods for AM but so far there is still no methodology, which can be followed for part- and process-based certification of AM.

In traditional manufacturing cases, the qualification procedure would entail qualification of the material batch, which will be used for manufacturing the products. In the case of AM however, there tends to be a variation in thermal energy during the AM operation, which means the qualification procedure has to be performed based on a part specific approach (Hensley et al., 2021).

Design for AM is an approach that is used in order to optimise the geometry of an AM component. This can be done by including internal voids or creating heat transfer pathways in the part geometry in order to reduce the heat impact of the AM operation for example. Thus, the concept of designing for AM is based on altering the design of components so as to avoid any undesired effects in later stages of processing (Hensley et al., 2021).

Thus, this approach ensures that the component is optimised for repair so that the material characteristics remain as unaffected as possible when/if the component is in need of repair at a later stage in the lifecycle.

4.4.4.2 Design for AM qualification

Qualification is a procedure, performed in order to determine whether a product or process meets or exceeds a set of specified requirements (Wang, Azarian & Pecht, 2008).

In order to remain competitive in the aerospace industry, reducing cost and lead time in product development and qualification has been described as a decisive factor. Implementing AM can become difficult with the current qualification methods used in the aerospace industry. Therefore, it is pointed out that qualification should be considered in the design phase of product development so that the AM components are designed for qualification. This should then reduce the total lead time and cost (Dordlofva, Borgue, Panarotto & Isaksson, 2019)

Design for crack propagation

One of the methods mentioned as essential for life sensitive part qualification is designing for crack propagation instead of focusing on crack initiation during the qualification process. An example could be to design components with certain margins, which would account for worst case scenarios in terms of defects. This could entail making the walls of the component thicker than what is necessary to create a safety margin in the design phase (Dordlofva et al., 2019).

It is important however to note that customers may be unwilling to forego current qualification requirements for metal components especially within the aerospace industry where customers are very conservative due to the high safety requirements. However, in order to build better process knowledge and a better understanding of the qualification procedures for AM components, a more expensive qualification process should be considered for early products (Dordlofva et al., 2019).

Topology optimisation

Topology Optimisation (TO) is another approach to design for qualification, which could be used for AM components. TO is a tool that can be used to create a holistic design framework where components can be qualified during the design phase. The tool makes it possible to create product designs, which meet requirements with margin to make up for any uncertainties and has the potential to reduce development time and cost (Dutta, Babu & Jared, 2019). The tool can be used to design AM parts with optimised properties in preparation for component use or post-processing for example (Dutta et al., 2019). Thus, the tool can be useful in order to design for qualification procedures early on in the design phase of product development.

It is however important to note according to Dordlofva et al. (2019) that TO for stress optimisation for example can entail a higher risk of failure due to rough surface conditions and defects in parts that have a limited life expectancy.

4.4.4.3 Design for AM equipment

When implementing AM, it is recommended that the company have a well-defined business case. The equipment and development costs are expensive investments, which must be estimated to ensure a profit margin. In situations where investments in AM equipment are made based on specific business cases, challenges can arise with the utilisation of the equipment for other components (Interviewee D). In addition, when the machine is adjusted for other components, it is necessary to take into consideration that it must still be able to perform operations for which it was specifically purchased (Interviewee J). Ensuring that components are designed for the available equipment minimises the number of times the equipment has to repeatedly be adjusted and reduces the risk of endpoint and access issues related to cell size limitations of the equipment. It can also help reduce the amount of time dedicated to programming for example since the equipment would be purchased with consideration to flexibility and general function (Interviewee B, D & J).

4.4.5 Inspection and Analysis

Below the potential inspection and analysis methods identified for use during qualification and evaluation of materials and components are presented.

4.4.5.1 Optical imaging

Optical imaging is a method used for large area imaging. The inspection utilises optical sensors or an optical imaging system and can be used as a Non-Destructive Evaluation (NDE) method for components/materials (Hensley et al., 2021).

The inspection method has good pixel resolution and entails a lower cost and smaller data size in comparison to IR inspection, which can be used in a similar manner. The method is also suitable if quick processing of data and immediate feedback is needed during the AM operation (Hensley et al., 2021).

Optical imaging is largely used in order to evaluate microstructural distributions in materials. It can be used to detect small defects due to porosity for example and other similar defects in components. It is important to note however that the inspection method tends to overestimate the porosity since the AM operation is likely to re-melt material during deposition, which should reduce the level of porosity in a component. According to Hensley et al. (2021) optical imaging-based detection of defects is still considered a suitable approach for model-based qualification. It is also suggested that the inspection method can be used in-situ to reconstruct the distribution of porosities as well as ex-situ to evaluate the component after heat treatment.

4.4.5.2 Infrared camera

According to Hensley et al. (2021) Infrared (IR) camera inspection is an in-situ monitoring method that can be used to evaluate the formation of defects in local regions of a component.

There are certain factors, which need to be considered before implementing IR inspection. For example, the resolution of the IR camera, operation complexities such as spatter, laser raster melting and sampling errors. These parameters can make small defect detection very difficult with IR. However, high frame rate IR can be useful for other purposes such as identifying characteristic peak decay and thermal backgrounds in order to facilitate thermal modelling for example. Unlike optical imaging however, it is important to note that the inspection method requires more data storage and longer data analysis. (Hensley et al., 2021).

4.4.5.3 Acoustic Emission Testing

Acoustic Emission Testing (AT) is a non-destructive inspection method where sensors are attached to a component. The sensors are used to capture stress waves when the component is subjected to an external force for example. The stress waves are then converted into electrical signals by the sensors, for processing. The signals monitor the intensity of acoustic emission, which help determine the structural integrity of the component (TWI, 2021b).

AT has the ability to detect and differentiate between a variety of different defects such as fibre breakage, cracking, delamination, and corrosion. The method is also useful in several different stages of testing such as operational testing, qualification testing and development testing (TWI, 2021b).

According to TWI (2021b) there are some limitations related to the inspection method as well. AT is limited to defects, which move or grow in the component tested. The method can be used to locate defects however, other inspection methods may be needed to diagnose the severity of the issues located.

4.4.5.4 Transmission Electron Microscopy

Transmission Electron Microscopy (TEM) is an inspection method where an electron beam is emitted from an electron gun. A variety of magnetic lenses focus the beam and transmit it through the material. Other lenses then use the transmitted electron to capture an image of the material microstructure (Chalmers, 2019).

It is important to note however that the method requires that the thickness of the material inspected be less than 100 nm, the material has to be dry due to that the TEM equipment operates in vacuum conditions and the material sample has to be able to withstand the electron beam exposure (Chalmers, 2019).

TEM is an inspection method that can be used for precise surface characterisation. The inspection method is used to assess properties such as grain size, grain shape, crystal texture, dislocation density, alloy segregation, cold work and porosity (Dutta et al., 2019).

4.4.5.5 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is an ex-situ inspection method that is considered optimal when inspecting the metallography after the deposition of AM material. The SEM inspection method is based on utilising an electron beam reading the component point by point. An image is then created by registering the scattering of the backward radiation from the component surface. In this method, the thickness of the part is not relevant, which is declared to be advantageous in the deposition of AM material as the material is deposited layer by layer (ZEIZZ, 2021).

SEM identifies information about the material's grain size, grain shape, dislocation density, alloy segregation, cold work, and porosity (Dutta et.al, 2019). This inspection method is also used in the analysis of surface roughness. These are all relevant parameters that facilitate the challenge of certifying the deposited material of an AM repair (Dutta et.al, 2019).

4.4.5.6 Computed Tomography

A typical internal inspection method considered to be of great advantage is Computed Tomography (CT). CT is a Non-Destructive Testing (NDT) method, which allows to inspect the component without actually destroying it in order to extract data. CT is a powerful tool, which takes the internal and external measurements and identifies the components defects and anomalies by analysing porosity, wall thickness and lack of fusion (Carlsson, 2016). A great advantage as well is the possibility of identifying the effectiveness of thermal post-processing methods utilised such as e.g., Hot Isostatic Pressing (HIP) (Portolés, O. Jordá, L. Jordá, Uriondo, Esperon-Miguez & Perinpanayagama, 2016).

The inspection method is based on imaging the component and gathering a specific number of Two-dimensional (2D) radiographs through 360 degree rotation. A software is then used to process these radiographs and a CT volume of the data is created. The data is then portrayed as 3D voxel data, and a 3D image is created based on this, which can be manipulated. The operator working with this inspection method can now rotate and flip the 3D image in multiple directions in order to find specific angles to cut through the sample for evaluation. The collected and identified data is stored in different point cloud data formats and is then used for measurements or CAD comparison (Carlsson, 2016).

4.4.5.7 Ultrasonic Testing

UT is considered as one of the most capable NDT methods for in-situ testing of AM manufactured parts. The inspection method is utilised for detecting surface, subsurface and internal defects in the component. UT can detect defects as deep as several meters, however, the detection of material thickness of the deposited AM material is a limitation in this inspection method (Honarvar & Varvani-Farahani, 2020).

The inspection method works using an ultrasound transducer connected to a diagnostic machine. This transducer is passed over the component and normally a couplant is being utilised such as oil or water in the case of immersion testing. The results of UT are presented in the form of 2D images and 3D images, which then can be utilised in a specific software in order to inspect the component in detail (TWI, 2021c).

4.4.5.8 Process Compensated Resonance Testing

Process Compensated Resonance Testing (PCRT) is an inspection method capable of measuring and inspecting components that have been repaired with AM. By assessing each component both internally and externally quantitatively, the structural integrity is identified. According to the author Weaver (2018), PCRT meets the partial validation required for components to confirm material conformity for areas of the component deposited with AM materials. The inspection method is also considered to be a fast process that does not require any chemicals and avoids the production of waste (Weaver, 2018).

PCRT is a whole-body inspection method that utilises partial resonances that can, via their sensitive accuracy, identify the dimensional state of the entire component. Statistical processing and pattern recognition tools are used to identify the components that do not match, and which can be separated away. In the case of a more complex component with specific areas of defects and changed material properties, these can also be identified specifically with the help of PCRT (Weaver, 2018).

The collected data of the method can be used to ensure that each component after the deposition of the AM material complies with the requirements and tolerances set. According to the author Weaver (2018), PCRT has shown discoveries at unacceptable levels of porosity, cracking, lack of fusion and even suboptimal heat treatment in AM components. These detected defects can be modeled and then programmed into a detectability algorithm. In other words, in the case of known structural problems, PCRT can help with quickly detecting these defects and work towards their elimination (Weaver, 2018).

4.4.5.9 Integrated Computational Materials Engineering

Integrated Computational Materials Engineering (ICME) is an approach for integrating information at multiple lengths. The purpose of the system is to link material behaviours such as fatigue and solidification for example, instead of isolating individual phenomena for material analysis. The system integrates materials information from all relevant areas of application to facilitate analysis and can then be used to analyse manufacturing, design, and material with a single extensive system (Allison, Backman & Christodoulou, 2006).

ICME is utilised by developing material models, which quantitatively describe the relationship between processing, structure, and properties. The approach facilitates the development process for new materials as well as durable and low-cost components. The benefit of an ICME system also lies in the concept of being able to perform simultaneous optimisation of the manufacturing process, the component design, and the materials selection with consideration to uncertainties (Allison et al., 2006).

4.4.5.10 Closed-loop feedback and control

Closed-loop control, which is also referred to as feedback control is a system where the output of the system is fed back into the system to some extent where it is compared to the desired output. The system uses this comparison to adjust the process in order to avoid deviations and achieve the desired output. Thus, the system can compensate for any errors that occur during the monitored process (Sharma, 2011).

In order to create a robust qualification and certification methodology it is imperative that a company develop more effective process control by implementing closed-loop in-processing methods. The system can help improve process analytics, which can be used to detect real-time material and process abnormalities (Russell, Wells, Waller, Poorganji, Ott, Nakagawa, Sandoval, Shamsaei & Seifi, 2019).

According to Russell et al. (2019), it's very important to understand the interaction between discontinuities and material microstructure before implementing this method. The article therefore emphasises the need to control the behaviour of AM materials, while also investing time in modelling and experimentation to produce AM components with the required properties.

An important challenge related to closed-loop in-process monitoring is that there is a lack of feedback sensors and measurement methods that can be used to acquire data needed for qualification. Closed-loop control systems are however described as necessary to ensure that a process fulfils requirements set on variability, repeatability, and performance (NIST, 2013).

The system can be quite complex and expensive but should be implemented in demanding applications where there is a need for higher automation (Sharma, 2011).

4.4.6 Application and Standards

According to the results of the AIM, there are a number of challenges within the company pertaining to the high requirements set on components and materials as well as a perceived lack of standards for AM. To overcome these challenges approaches to implementation and institutions working within standardisation have been suggested below.

4.4.6.1 Component application areas

One of the challenges related to qualification of AM processes is linked to the uncertainties and variations detected in materials and components during and after the AM operation has been completed. Process parameters such as energy levels, feedstock quality and deposition location can all fluctuate and affect the end quality of the component. For example, the variations can affect the material of the component and result in defects such as porosities, poor surface finish, residual stress, and deformations. These variations and uncertainties have resulted in a hesitancy to accept metal AM within industry. This is especially apparent within industries where the technology is implemented on high consequence applications. Thus, the importance of implementing AM on redundant applications with large design margins, conservative specifications and more benign operating environments should be emphasized and used as a strategic approach towards building AM knowledge (Dutta et al., 2019).

During the qualitative study of the thesis, interviewee G also emphasized that this might be a viable approach for the company to build more knowledge within the AM process and gain more experience. The interviewee claimed that perhaps the best strategic approach for the company would have been to introduce AM repair on components in stationary engines where the safety requirements and component criticality is not as high. Interviewee G believes that it would then have been easier for the company to perform repair operations on more critical components at a later stage, using the knowledge gained from the low-consequence component repairs.

Interviewee C also concurred with this approach and specified that it is important to not only identify less critical components for AM repair, but also to specifically identify less critical repair operations. The interviewee emphasised that component criticality classification could be broken down to become more specific so as to identify, which parts of a component are more critical, and which are less critical to the function. According to interviewee C, approaching criticality classification in this manner could make it easier to identify potential components suitable for AM repair.

According to Russell et al. (2019) another recommendation for companies within the aerospace industry is to develop a classification system, in order to facilitate criticality classification strategies. The classification system would be used to determine the criticality of a component or its parts and this could then be used in order to approximate what requirements should be set on a component and operation. Thus, the system could be used to determine, which components would be viable for an AM repair operation. NASA has created an AM part classification system, which has this function. The classification system allows the organisation to tailor requirements to their applications by adjusting the requirements to the risk associated with the AM component. The system is based on three key factors: consequence of failure, structural demand, and AM risk, where AM risk is assessed by evaluating five criteria related to the possibilities for inspection and qualification of the component (Russell et al., 2019).

4.4.6.2 AM standards

In the future, it is expected that more and more critical components within the aerospace industry will be considered for AM application as the AM technology matures, which makes the development of standards imperative to success. Currently the developed standards are not as comprehensive for AM as for other manufacturing technologies, but there are some institutes, which have created standards for the AM technology (Russell et al., 2019), (Mellor, 2013).

Because there is a significant lack of standards specifically for the process of qualification and certification of AM, the institutes and organisations mentioned in table

2 are working towards developing standards that pertain to the qualification of AM (Russell et al., 2019),(Dutta et al, 2019),(Portolés et al, 2016). The area of qualification and certification of AM is considered imperative to increase the maturity of the technology (Russell et al., 2019).

Table 2: A range of institutes and organisations, which develop standards within AM.

Standards Institutions and Organisations
American National Standards Institute
Additive Manufacturing Standardisation Collaborative
National Institute of Standards and Technology
National Aeronautic and Space Administration
United States Department of Defence
Federal Aviation Administration
European Aviation Safety Agency
American Society of Mechanical Engineers
American Society of Testing and Materials
American Welding Society
International Organisation for Standardisation
Metal Powder Industries Federation
Society of Automotive Engineers

According to Dutta et al. (2019), there are also organisations, which have generated internal specification for development, process and qualification procedures due to the lack of external standards within these areas. Dordlofva & Törlind (2017) also mention the development of internal standards as a common methodology, used by organisations when there is a lack of external standards due to the maturity of the technology being implemented for example. It is generally suggested that organisations develop internal standards based on their customers requirements or in collaboration with the customer to ensure that the standards developed are satisfactory to all parties involved.

4.5 Product cost management guideline for AM repairs

A challenge expressed during the qualitative study was the uncertainty linked to the cost of AM repair and what parameters need to be taken into consideration. In order to provide employees with a better insight into what parameters need to be taken into consideration for an accurate cost estimation for AM repair a product cost management guideline has been constructed. The purpose of the guideline is to help employees at the company gain a better understanding of the costs associated with AM repair.

The product cost management guideline presented below is loosely based on a cost guideline provided by GKN as well as literature by the authors: Cardeal, Höse, Ribeiro & Götze, (2020), Baumers, Beltrametti, Gasparre & Hauge, (2017), Oyesola, Mpofu, Mathe & Daniyan, (2019), Deppe, Lindemann & Koch,(2015), Previtali, Demir, Bucconi, Crosato & Penasa, (2017) & Fera, Fruggiero, Costabile, Lambiase & Pham, (2017). To view equations related to the parameters mentioned below, see appendix D.

In order to build a clear structure for the product cost management guideline, a cost model was created, which further visualises the costs linked to AM repair. The total cost of the phases presented below in figure 8 could be used in order to identify an estimated cost of the AM repair.

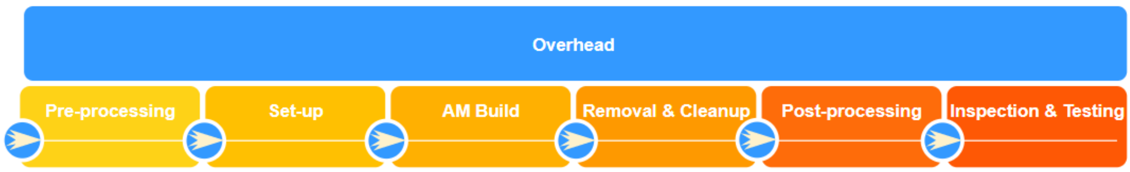

Figure 8: AM repair cost model.

4.5.1 Overhead

The overhead expenses included in the cost instruction are expenses, which are not necessarily linked to the creation of any service or product but still need to be taken into account for an accurate cost estimate.

4.5.1.1 Facility

The first cost variable included in the overhead cost is the facility cost, which is defined as the cost of renting time or space in the company's workshops where the necessary AM machinery is located. This cost can therefore vary depending on what workshop or machine is desired to perform the AM repair. When renting space in a workshop for a specific operation, it is assumed the costs of inventory, service and maintenance and software are included in the facility cost of that specific workshop.

The facility cost is largely dependent on the process time where the process time indicates the time it takes to complete a process such as cleaning, inspection or building for example.

Inventory
Inventory is a factor that is added during several steps in the cost model as the component moves through the process flow. The inventory cost needs to be taken into account as there could possibly be pauses in between process steps of the repair operation. Observe that the inventory price may vary depending on the size of the component.

Service and maintenance
Service and maintenance is an important cost factor, which is important to take into consideration in a cost calculation developed for the AM repair process. The tools and the machine that perform the AM process may need periodic maintenance to maintain the desired quality as they wear over time. Service and maintenance is an operation that depends mainly on the utilisation of the machine, the more a machine is utilised the more maintenance it will need to ensure that it maintains accuracy.

The operation may be performed by operators in-house or by the manufacturer of the machine depending on whether the manufacturers have patents on their machines that prevent company employees from opening them up and performing the operation themselves.

Software
Another Overhead cost, which can be considered in the cost estimate, is the cost of software licenses and programs. Some software is necessary in order to keep the AM machines functional as every repair process tends to be based on a program that can be adjusted.

4.5.1.2 Additional fixtures and tooling
During the build phase of the AM repair process there may also be a need for additional fixtures or tools. For example, fixtures that keep the component in place while the material is deposited in the AM machine may be necessary. Thus, expenses for any additional fixtures or tools need to be taken into account for the cost estimate as these may be specific to the component or other process needs and customised fixtures or tools can incur high expenses.

4.5.2 Pre-processing

The first phase of the AM repair process flow is the pre-processing phase, during which operations such as initial inspection, cleaning and coating are performed. These operations are defined below the pre-processing stage as they can be performed to prepare the component for AM repair before the process needs to be set-up or prepared in any way.

4.5.2.1 Inspection
The inspection stage of the pre-processing phase is the stage, at which the component is inspected upon arrival to make sure that it is in the condition that the

customer has specified. This step is very important as any large deviation in the expected deformation or material condition means a more customised repair process is necessary to repair the component in question.

Inspection of the received component can entail an inspection of the component with the naked eye or more thorough inspection methods such as penetrant testing in order to reveal any unexpected defects. It is therefore important to note that the cost of inspection may vary depending on the chosen methods for inspection.

4.5.2.2 Cleaning

The cleaning stage of the pre-processing phase is the stage, at which the component is cleaned in order to remove any foreign agents from the surface. This stage is necessary to make sure that the surface is free of any dirt or other material that may interfere with the next stages where the component is surface treated and AM repair is performed. Observe that cleaning may be needed before and after surface treatment of the component.

As in the case of inspection, there are many different methods that can be used in order to clean the component. It is therefore important to note that the cost of cleaning can vary depending on what cleaning agent and method is chosen.

4.5.2.3 Surface treatment

In the last stage of the pre-processing phase surface treatment is done. During this stage processes such as abrasive blasting or painting may be needed for example. This stage is important in order to create good surface conditions for the next stages in the AM repair.

In the case of surface treatment for future scanning, this is where the component is coated with a matte colour in order to ensure the scanning is done correctly and prevent any reflective properties of the material from interfering with the results of the scan. Thus, it is important to note that the cost of surface treatment may vary depending on the chosen material and method for the process.

4.5.2.4 Scanning

The scanning operation is when the operator scans the component that will be repaired. This can be done with the help of GOM (Geometric Optical Measurement) for example, which is a measurement method used for scanning a component in 3D. The data from the scanned component can later be utilised for programming of the machine. It is important to know whether this step needs to be repeated for every component or whether the deformation is similar enough that the same scan can be used for several components.

Scanning the component facilitates the work for the CAM (Computer Aided Manufacturing) engineer since the complete component can be transferred into the CAM software and in that way the engineer can easily start programming the machine.

4.5.3 Set-up

The second phase of the AM repair process flow is the Set-up phase, which includes the steps of programming, machine testing and material handling. These steps are further described below. The Set-up operations are performed in order to have the machine completely prepared to start the build operation and are normally performed by operators and engineers.

4.5.3.1 Programming

The programming phase is an important step to take into consideration because the cost can vary much depending on the deformation of the repair components. If the deformation of the repair components is similar the same program could potentially be used for all of the components but if not, a customised program could be needed for each component. This cost can also be affected by machine limitations since some machines can run bigger programs that could potentially adjust the AM weld path automatically.

This phase requires time and precision and can therefore be a costly step in the AM repair process. However, it is dependent on the components size, deformation and the skill of the CAM engineer.

4.5.3.2 Machine testing

In order to ascertain that the machine fulfills requirements on for example accuracy, it is important to perform regular testing. This can be done by running an AM weld on a test plate with the machine for example, where the height and width of the weld is measured. The test plate can also be weighed before and after the test, to determine what amount of material is deposited by the machine. This is done to guarantee that the accuracy requirements on the machine are met before the build operation on the component can be initiated.

4.5.3.3 Material handling

In the set-up phase material handling is relevant to include and a cost should be estimated. The time required for material handling of the component is very dependent on the component size, weight and the distance from inventory to workshop. In the aerospace industry normally the types of components that are planned for repair are massive and complex and therefore it is extra important to estimate this cost early on.

4.5.4 Build

After the set-up phase has been completed, the build phase can be initiated. The build phase is the phase during which the actual AM repair is performed. There are therefore a few different variables that can affect the cost of this phase. Included in these variables are facility-, operator-, hardware-, raw material-, gas-, scrap-, machine energy- and additional fixture/tool costs. The build phase differs greatly depending on the chosen AM technology and therefore it is important to identify the steps required during the process flow of the build to estimate the final cost of the build operation. However the steps described below are the general steps required to evaluate when estimating a cost for AM repair.

4.5.4.1 Operator

The operator cost included in the Build phase refers to the cost of ensuring an operator is present during the AM repair process in order to monitor the process and adjust any process parameters if necessary.

This is necessary as there may be variables such as deformation due to heat transfer or programming errors that can cause the AM nozzle to deviate from its intended path. This can cause defects in the component and it can lead to collisions with the machine itself. These errors can be costly to repair and delay the repair process. It is therefore important for an operator to monitor the process in order to avoid costly errors.

4.5.4.2 Hardware

During the Build phase there is also a cost for hardware. This variable includes any tools that may be required to perform the AM repair. For example if a new nozzle is required or an old nozzle needs to be replaced, this would be included in the hardware cost.

The hardware cost therefore depends on the expected lifetime of the chosen tool where the cost of purchasing the tool is distributed over the lifetime.

4.5.4.3 Raw material

The raw material cost variable is defined as the cost of all the raw material used during the build phase. This includes the cost of metal powder or wire used during the repair where a certain loss factor is included in order to account for the efficiency of the AM repair process.

In order to estimate the raw material cost it is therefore important to know the efficiency of the process chosen and how much material is required for a component repair.

4.5.4.4 Gas

During the AM repair there may also be a need for inert gas during the process. The inert gas is supplied directly to the application area or used to fill a chamber surrounding the component in order to prevent undesirable material reactions at high temperatures for example. Thus, the cost of the inert gas should also be included in the build cost estimate.

4.5.4.5 Scrap and rework

In order to account for any errors that may be made during the AM repair process of components it is also necessary to include a scrap and rework cost in the build phase. This is expressed through a scrap factor and a rework factor, which is an estimated percentage. The scrap factor describes how high the risk of failure is during AM repair where the failure entails that the component needs to be scrapped. Whereas the rework factor describes how high the risk of rework being needed for the component is.

This cost variable largely depends on the scrap and rework factor, which in turn may vary depending on variables that may make the process more complex such as size, geometry, material etc.

4.5.4.6 Machine energy

During the Build phase of the AM repair process, the energy consumption of the machine used for the repair process needs to be taken into account. The energy consumption may vary depending on the AM method and manufacturer so it is important to take this into consideration.

4.5.5 Removal and Cleanup

The fourth step of the AM repair process flow is removal and cleanup. This step covers three stages, which are material handling, machine cleaning and machine inspection. All these steps are further described below. The steps under removal and cleanup are all intended as steps that need to be executed after the build of a component. This is to ensure that the machine is fully capable and functional to run a new operation.

4.5.5.1 Material handling

After the component has been repaired, it needs to be removed from the machine and transported to the next phase of the process flow, which is post-processing. The time required for material handling of the component until it reaches the next phase of the process flow is very dependent on the component size, weight and the distance from the inventory to the post-processing area as well.

4.5.5.2 Machine cleaning

When the component has been sent to the next stage of the process flow, the machine needs to be cleaned. The cleaning method is dependent on what type of AM technology has been used in the repair operation and how much material that has been deposited. Every technology has a material loss factor, which determines how much waste needs to be removed from the AM cell. Moreover depending on the machine's requirements a specific cleaning agent may be required, which is also a factor that affects the final cost of the cleaning operation.

4.5.5.3 Machine inspection

After the cleaning has been completed an inspection of the machine is required to guarantee that the machine is fully capable and functional to run the next operation. The inspection method chosen should be dependent on the AM technology that the machine utilises under the build operation since that decides how the machine could have been affected by the previous operation.

4.5.6 Post-processing

Post-processing is the phase that follows after the component has been removed from the AM cell. During this phase it is important to determine what material and design characteristics need to be modified or altered, and in which condition the component needs to be delivered to the customer based on their requirements. Thus, the stages included in this phase are heat treatment, surface treatment and cleaning in preparation for the last phase of the AM repair process flow.

4.5.6.1 Heat treatment

Heat treatment may be necessary to perform once the component has been repaired in order to increase the durability, strength, age the material or relieve surface stress for example. The cost of the heat treatment may vary depending on which method is chosen to perform the treatment. Therefore, it is very important to determine which heat treatment method should be used in order to achieve the desired material characteristics in order to give an accurate estimate of the cost linked to heat treatment.

4.5.6.2 Surface treatment and material removal

Once the component has been repaired it may also be necessary to use some method for material removal in order to achieve a smoother surface where the AM repair has been performed. For example grinding could be necessary in order to increase the surface smoothness of the components.

4.5.6.3 Cleaning and removal of powder residue

Once the surface- and heat treatment have been performed, the component should once again be cleaned to remove surface residue in order to perform the last phase of the AM repair process where the component will be further inspected and tested to make sure it fulfills customer requirements and the company's quality standards.

Observe that the necessary cleaning agents may differ from those in the pre-processing phase as this depends on the prerequisites of the inspection methods used in the next phase.

4.5.7 Inspection and Testing

Inspection and testing is the final phase of the AM repair process. This phase is required to guarantee that the component meets all the requirements after the post-processing phase. The operations included under inspection and testing are inspection, quality control and final testing. These operations are described further below.

4.5.7.1 Inspection

The inspection stage is the stage, at which the component is inspected after all the post-processing to ensure that it is in the condition that the customer has specified. This step is very important in the final part of the process flow since processing of the component has been finished and this inspection will determine whether the component can be delivered to the customer or not.

The chosen inspection method is dependent on many different factors. Such as the components size, material, complexity and weight as well as the chosen AM repair technology.

4.5.7.2 Quality control

Quality control is a mandatory step in the process flow of AM repair. This, since as mentioned before, the aerospace industry has high safety requirements and therefore the quality control is very important to ensure that the component has met the expected quality and requirements. The calculated cost for quality control of a component is dependent on the requirements on the component. The higher the requirements are the more time will be required for the quality control procedure.

4.5.7.3 Final testing

Final testing is the final step in the AM repair process flow. In this operation if required a final test on the component will be performed. This testing method is dependent on what the repaired component is being utilised for, but also on the complexity of the component. If the repaired component is very expensive then an option for final testing could be NDT. Otherwise destructive testing could be an alternative as it can guarantee 100% that the repaired component fulfills the final requirements.

4.5.7.4 Marking

Once the component is ready to ship back to the customer, it is important to mark the component. This makes it easier to identify individual components in the future. This step is completed by an operator, where the component is marked and prepared for delivery.

4.5.8 Cost parameter uncertainties

The repeatability and robustness of a process shows the degree of maturity of the specific technology. The reliability in AM repair today is not high since the technology is still new on the market compared to other conventional methods. Thus, there are some uncertainties within AM repair, which affect the total product cost. Presented below are the uncertainties that may affect the final product cost of an AM repair process.

Pre-processing

- Inspection: Time may vary depending on the deformation severity of the component.
- Surface treatment: Method required may vary depending on the initial surface condition of the component and need for scanning.
- Scanning: Time required largely depends on how many components need to be scanned.

Set-up
- Programming: Depending on the capacity of the machine, several programs might be required for every component even though the deformation is similar.

AM Build
- Hardware: Replacement of tools and hardware depends on the utilisation frequency of the machine.
- Scrap & rework: The risk of failure, which leads to scrap or rework depends on the level of knowledge and experience obtained within the process and to some extent also the human factor.

Post-processing
- Heat treatment: The time required for heat treatment depends on the chosen AM technology and the complexity of the component.
- Surface treatment and material removal: The time required for surface treatment also depends on the chosen AM technology and the complexity of the component.

Inspection & Testing
- Inspection: The time required for this process depends on the component requirements.
- Quality control: The time required for this process depends on the component requirements.
- Final testing: The time required for this process depends on the component requirements.

4.5.9 GKN Cost Parameter Definitions

At GKN, the cost analysis is not necessarily performed as is described above and all of the parameters identified through case studies are not taken into account. Below the points on which the cost instruction above differs from the one that is currently used at GKN are presented.

- **Facility cost:** The facility cost at GKN is an hourly workshop cost where the operator cost is included in the hourly cost of the facility. This also means that when the operator is not needed to run or monitor a process, the hourly cost of that process is considered to be zero.

  The facility cost in the instruction above has not been structured to include the operator cost in the same manner because the operator cost is considered a direct labour cost while the facility cost is considered to be an overhead cost. Thus, the operator cost was not included in the facility cost since it would mean use of a workshop and equipment is free of charge while an operator is not needed. This is because costs such as rent or energy for example do not tend to be assumed to be zero, when an operator is not used but a process is still run in the facility.

- **Inventory cost:** The inventory cost of storing components in a warehouse is not considered at GKN. It is thus not included in the facility cost at the company in the same manner as described in the instruction above. The inventory cost seems to be considered negligible or it is a cost, which is shared among different workshops at the company.

- **Scrap and rework cost:** The scrap and rework cost assigned to the build phase in the instruction above is also not included in the same manner. The scrap and rework factor mentioned above is applied to the entire process at GKN as the risk of failure, which leads to scrap or rework is considered at every step in the process flow rather than just the build phase. During the creation of the instruction above however, this factor was considered to be most critical to take into consideration in the build phase of the repair.

5 Discussion

The chapter begins with a discussion on the interpretation of the results and extends to the research methodology, validity of research and recommendations for future research.

5.1 Interpretation of Results

During the thesis, there were many challenging areas, which were perceived as especially critical to the success of AM in repair purposes. Based on the results of the research, some solutions and opportunities were therefore considered to be particularly important to discuss and implement. Therefore below a road map of recommendations has been created which describes how the researches believe the company should proceed in order to overcome the challenges presented. The prioritisation is based on the strategic steps which the researchers believe will be profitable for the company or help increase knowledge within the organisation while also solving the challenges mentioned in the report. See figure 9 below, for the road map.

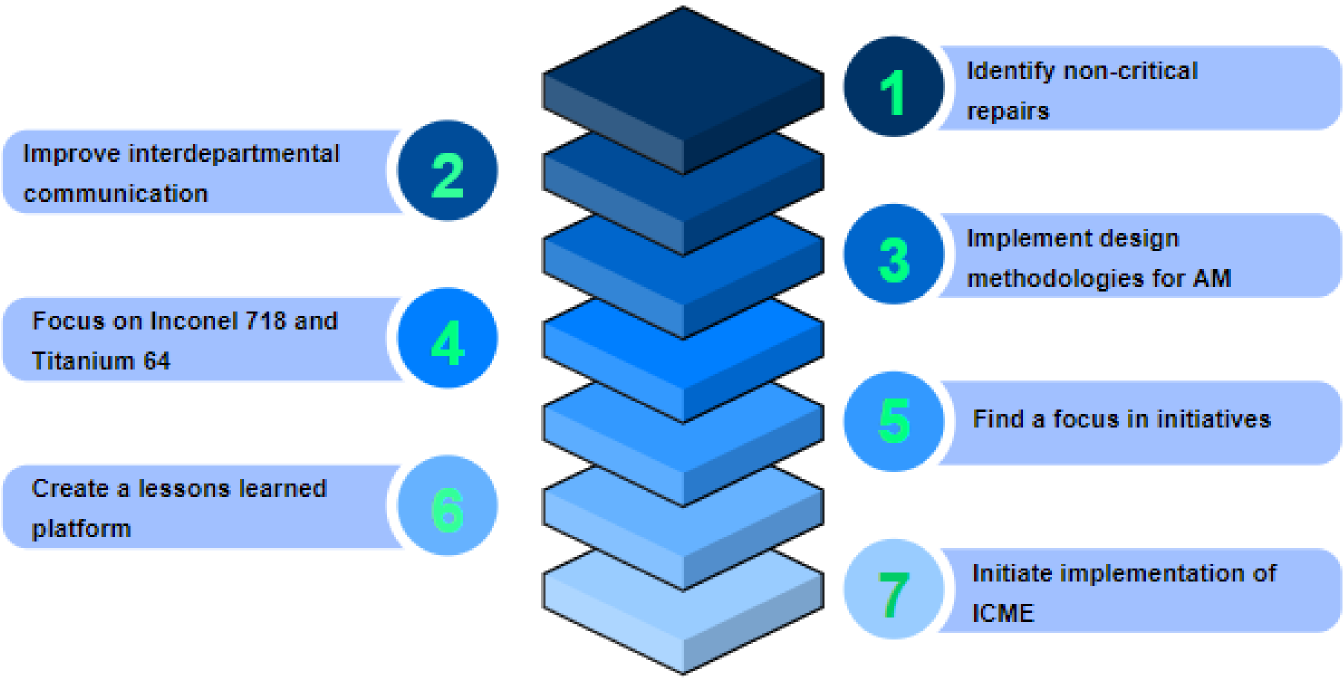

Figure 9: Road map of recommendations

Step 1
One of the major challenging areas that was mentioned in literature as well as at the company was qualification of AM components. Therefore, it is perceived as imperative for the company to consider implementing the technology on components, which are not critical or create a classification system, which identifies what parts of a component are more or less critical to the function so as to decrease the requirements on the AM repair operation and make qualification a less extensive process.

This measure is recommended while the technology is still in the development phase and it is necessary for the company to increase experience within AM.

Step 2
Another critical area of improvement is interdepartmental collaboration and communication within the company. The collaboration between R&D and production at the company was perceived as lacking and according to the literature this is a common result when there is a lack of communication between departments. Currently the departments work very independently from each other, which leads to mistakes, re-work and producibility issues. Thus, it is also recommended for the company to initiate more AM projects in teams such as cross-functional teams where employees from different departments collaborate. This should improve collaboration between departments and ensure that important aspects from all departments are taken into consideration.

Step 3
To reduce the complexity of qualification for AM repairs, it is also recommended that the company start considering qualification in the design phase of product development. This can be accomplished by implementing Design for AM and Design for Qualification methods that allow the company to determine how the qualification should be performed in the early stages of product development while also ensuring that the component in question is optimised for the AM repair operation.

Step 4
The analysis of the company's current state, showed that the company has initiatives active where the potential of Haynes 282 is evaluated. It is also noted that the only client, which is interested in Haynes 282, has doubts about the use of AM repair on aerospace components. Thus, it seems relevant to point out that the company may benefit from dropping these initiatives to focus more of their resources on projects where Inconel 718 and Titanium 64 are utilised.

Step 5
In terms of strategical approaches for the company, the results showed that the number of initiatives active at the company pose a problem since all of the initiatives compete for the same resources, which are dedicated to AM by the company. Thus, there is a clear need for the company to create a more focused approach towards what initiatives to finance, where the decisions need to be made with a goal in mind, which has been communicated throughout the company.

Step 6
In order to improve communication between departments and store valuable information, it was also perceived as important that the company consider updating their platform for information sharing and start sharing not only data but project assessments as well, where what has gone right and wrong during projects is described. This could benefit the company by ensuring that lessons learned from previous projects are preserved and mistakes are not repeated.

Step 7
From a more technical perspective, the results also showed that it is very difficult to estimate material characteristics and behaviours of components during and after the AM repair process. A relatively new approach, which aims to simplify this process is ICME. Therefore, it is recommended that the company start implementing ICME in their development process as soon as possible, considering a learning curve may have to be taken into consideration before the tool can become an efficient part of the product development process.

Something which is also important to point out, is that the challenges which have been mentioned during the report create a network. This means that by solving one issue you may have resolved the root cause of another challenge. It is therefore important to note that the process of overcoming the challenges mentioned in the report does not necessarily have to be very extensive because many of the challenges are interconnected.

The challenges mentioned are challenges, which the employees are aware of, but have not resolved. This may be because the root cause of an issue within one department has been located within another department for example. Therefore by providing a description of the challenges within AM repair for all departments, the intention is to provide employees and management the tools necessary to proceed with the development of AM repair.

5.2 Research Methodology

AM repair was a new subject for the researchers of this master's thesis and therefore it was decided that it would be beneficial to perform a pre-study on AM and AM repair at GKN. The pre-study was in the shape of a study visit to the company's workshops and study of the assigned GKN material within AM and AM repair. The studies provided a clearer understanding of where the company is today. In hindsight, it was clear that a more in-depth pre-study of assigned GKN material would have facilitated the design of the current state analysis, since some of the interview questions were formulated in a manner, which assumed the company had gained more AM experience than was actually the case.

For the identification of challenges at the company, an interview study was conducted with 11 employees at GKN who, with the help of the supervisor at the company for this master's thesis, were identified. Two benchmark studies were also conducted, one with Siemens and one with an AM expert. A challenge with conducting interview studies can be to get access to the right people in order to get answers to the interview questions. The majority of employees at the company were busy and much of the desired information was classified and difficult to obtain. However, this did not pose a large challenge during this research study as the employees were very accommodating and were perceived to answer the questions to the best of their ability.

The results of the interview study conducted at GKN were visualised in an AIM, where the challenges identified during the interviews are presented. The execution of the AIM turned out to take longer than expected. Transcribing the interviews was time consuming and since the interviews were conducted in Swedish, a translation of all transcriptions into English was also necessary. The interviews could alternatively have been conducted in English in order to save time. In addition, once the interviews had been completed, many of the challenges identified were similar but this was not apparent at first because the challenges were defined within varying contexts. Thus, the process of filtering the interview data became a time consuming procedure where the context, in which the challenges were described in transcriptions, also had to be investigated.

The literature study was an optimal approach for identifying alternative solutions or opportunities since many of the methodologies suggested help bridge the challenges previously defined during interviews, where some interviewees have also suggested similar solutions themselves. An alternative approach would have been to perform another interview study with employees at GKN, specifically oriented towards alternative solutions, instead of a literature study. In order to identify solutions, which the employees believe are suitable, since this could have generated solutions that would have been customised for the company or the aerospace industry.

Finally, to get a clearer view of the cost related to AM repairs, literature on AM and repairs were studied. The costs analysed in this material were all either specific to repairs by conventional methods or specific for AM without any consideration for repair. Therefore an alternative approach could have been to investigate whether Siemens or other companies for example, which perform AM repair would have been willing to participate in a benchmark to determine important parameters of a cost model for AM repair.

5.3 Validity of Research

During the thesis it was important that the validity of the research completed was evaluated at every stage. Thus, it is important to note that some stages of the thesis were performed with a strong approach in terms of validity, while others could have been improved or adjusted in order to increase the validity of the research.

During the thesis project, triangulation between literature and interviews with employees as well as external actors was very beneficial. The triangulation strengthened the validity of the results generated when challenging areas were identified and ensured that the solutions suggested to bridge the identified challenges were valid. However, there were other areas within the thesis project, which could have been performed in a manner that would have increased the validity of the research.

During the current state analysis, the assigned GKN material was perceived to be limited and difficult to rely on completely for the analysis. Due to Covid-19 some study visits could also not be performed due to the absence of employees in the workplace. This increased the need for information from interviewees to supplement missing data about the current state of the company. Therefore, the results of the current state analysis are based largely on the data collected during the interview study.

During the qualitative study, the Covid-19 pandemic meant most of the interviews had to be conducted online, and a clear difference was perceived between the interviews that were conducted virtually and those that were performed face to face. When the interviews were conducted face to face, the confidence of the interviewee in the researchers seemed to be stronger.

Another area where validity should be addressed is the AIM methodology. The AIM was constructed based on the challenges identified during the interview and thus the content in itself is considered valid. However, when the challenges were weighed in terms of, which areas are more critical, this was based on the concept of root cause identification by the researchers. An alternative approach would have been to involve employees from different departments in this process, in order to include their perspectives on the critically of the issues. It is likely this approach would have been difficult to implement however, due to the ongoing Covid-19 pandemic. Another option would have been to utilise analytical tools in order to identify, which challenging areas were mentioned by the largest number of interviewees and weight the AIM in this manner. This was not possible as the time frame of the thesis was not sufficient for the analysis however, this could have strengthened the AIM result.

A challenging area where the literature was limited was in the research of AM standards. During the project, a range of different standards institutions that provide or develop AM standards were identified; however due to the project budget, these standards could not be analysed in detail. Therefore, instead of recommending specific standards to follow, the report only proposes institutions that the company can turn to for standards within AM repair. If the budget of the thesis had been greater, specific standards from these institutions and organisations could have been chosen for the company to review. The validity of this results could therefore have been improved if the standards were purchased and examined in order to identify whether they provide information valuable to the company.

During the construction of a guideline for cost estimations of AM repairs, it is important to note that the literature within AM pertaining to repairs specifically, was very lacking. The guideline was therefore constructed based on literature, which pertained to AM or repairs through conventional methods. Thus, the validity of the result is debatable but as nothing could be found to compare the guideline with it is difficult to estimate how valid the guideline is.

5.4 Recommendations for Future Research

In order to build on the thesis research a few recommendations for such endeavours follow below.

- A new evaluation of the challenges identified within the company could be performed in order to re-evaluate the critical areas hindering the development of AM once the company has gained more knowledge and experience within the area and the maturity of the technology has increased.

- Further research could also be made within the area of standardisation for AM repair. It is recommended that research be initiated in collaboration with customers or other companies, working with AM for repair purposes. The research could help speed up the establishment of internal standards within the Aerospace industry and help the company standardise the AM repair development process.

- Future research within the implementation of LPBF technology for AM repair is also recommended. The technology has potential within the AM repair area according to the Siemens benchmark results. While the technology has not yet been tested for this purpose within the company, it may present opportunities for the company in the future. Thus, it is important that the company evaluate how the technology could be implemented on components for repair purposes.

6 Conclusion

The aim of this master thesis has been to investigate and evaluate the current state of AM at GKN with a focus on maintenance and repair operations within the company. The primary goal has been to identify challenges related to AM repair and suggest alternative solutions or opportunities, which can be employed in order for the company to overcome these challenges. Additionally, guidelines for a cost model of the repair process would be provided for the purpose of providing insight into important cost parameters.

By providing an answer to the research questions, upon which the thesis project was based, this aim has been fulfilled. The conclusions presented below have been drawn to clarify the result of the thesis and answer the research questions.

RQ1. What AM technologies does the company have today? What is the current state of knowledge pertaining to AM repair within the company? Where and how has AM repair been applied based on component size, material and geometry?

Through the results of the thesis it has been established that the technologies considered for AM repair/modification at the company currently are LMD-powder and LMD-wire technologies. AM repair has so far been implemented on component A and a modification of an engine component has been performed building an attachment in the shape of component C on the surface.

Component A is the largest component to be considered for AM repair at the company and currently larger components can not be repaired with the LMD-powder technology available due to cell size limitations. Exactly how small components for AM repair can become without affecting material characteristics during the AM process has not yet been determined by the company but it is known that certain sizes and geometries will inherently be affected by the high degree of heat transferred during the repair operation.

Currently, the materials that are used or considered for AM repair are Inconel 718, Titanium 64 and Haynes 282.

So far the company has focused on geometries where relatively flat surfaces are used to deposit the AM material and perform the repair operation.

The company has also gained experience within the implementation of AM in purposes other than repair, which are described in the current state analysis. The analysis provides a further description of what the current state of knowledge pertaining to AM repair is at the company.

RQ2. Where can challenges within the implementation of AM repair be identified and what are the alternative solutions for potentially overcoming these challenges?

This interview study resulted in the identification of several challenging areas within AM implementation, which are as follows: Strategy, Communication, Qualification and Verification, Experience, Competence, Equipment, Material aspects and Cost. The areas where most of the root causes were identified are Strategy, Communication and Qualification & Verification.

To overcome these challenges, it is recommended that the company follow the alternative solutions and opportunities presented in the results. Through the implementation of methods pertaining to Organisational structure, Interdepartmental collaboration, Internal organisational communication, Design Methodologies, Inspection and Analysis as well as Application and Standards, GKN could potentially overcome these challenges and further their work towards implementation of AM repair within their corporation.

In the discussion a road map is also presented with recommendations for the company to follow, in order to solve some of the most critical challenges, which may resolve other identified challenges as well.

RQ3. How could a cost model for AM repair be constructed and which parameters should be included in the guideline?

The thesis resulted in a Product Cost Management Guideline for AM repairs, which describes the costs related to the AM repair operation. The cost model has been devised in a manner where the costs are described in relation to the process steps, in which they are included and equations for these costs have been defined.

The cost parameters and the process steps are as follows:
Pre-processing: Inspection, Cleaning, Surface treatment and Scanning
Set-up: Programming, Machine testing and Material handling
AM Build: Operator, Hardware, Raw material, Gas, Scrap and rework and Machine energy
Removal and Cleanup: Material handling, Machine cleaning and Machine inspection
Post-processing: Heat treatment, Surface treatment and material removal, Cleaning and Removal of powder residue
Inspection and Testing: Inspection, Quality control, Final testing and Marking

The guideline also takes into consideration certain overhead costs such as: Inventory, Service and Maintenance, Software and Facility.

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A Interview Questions for Employees

Interview Questions

Introduction Questions:

1. What is your role at GKN?
2. How long have you been working within your current role?
3. What is your experience within repair at GKN?
   a. How long have you been working within that field?

AM Approach:

4. What reservations are there to implementing AM for repair?
5. What does the working process look like for the selection of a repairmethod?
6. How do you perceive the approach to AM repair at the company to be?
   a. Are employees motivated and willing to implement this type of service?

Konventionella Metoder:

7. What conventional methods are used for the purpose of repair at the company today at GKN? What conventional methods tend to be suggested for repairs?
8. What do you think are the greatest obstacles in the processdevelopment that GKN employs for AM today? How efficient is the process of verification and qualification for new processes such as AM?

AM Teknologin:

9. What AM technologies are available at the company today?
10. Which arguments have previously motivated the choice of AM repair? What made the technology more suitable than alternative conventioanl methods? What do you believe governs the choice of repair method the most?

AM Material:

11. What different material have been utilised for AM?
    a. For example: Titanium or Nickel alloys such as Inconel...etc.
    b. What component materials can be utilised for AM repair?
    c. How well does the AM powder attach to component materials
12. What changes in material properties have been observed as a result of AM repair?
    a. Are these changes good or bad? For example, does the strength, elasticity, toughness etc increase or decrease after the AM application?

AM Pre- and Post Processing:

13. What is the typical preparation process for AM and what are the typical pre- and post-processing steps?
    a. Are the pre- and post-processing steps required for AM similar for conventional methods?
    b. Do the processing steps increase or decrease in comparison?

AM kostnader:

14. What have previous AM repairs cost if you were to give an estimate?

15. What are the choices of processingmethods based on? Where it a trade-off usually considered between for example cost, quality, repair time etc.

Utmaningar:

16. Have you noticed any clear difficulties in implementing AM for repair?
    a. How do you believe these difficulties could be eliminated?

Erfarenhet:

17. Where do you believe GKN is today with consideration to the development of AM repair?
18. Why do you believe there is such a hesitance and carefulness with consideration to AM repair at the company?
19. Why are there such high requirements on the AM process in comparison to conventional welding for example or other methods which are more frequently used?
20. Where do you believe the lack of experience within AM is the greatest at GKN?
    a. What do you believe this lack of experience is due to?
21. What do you think about the current strategy which GKN employs to increase the experience within AM?
    a. Is it well thought out?
    b. What could be changed in order to implement the AM more efficiently?
22. Is there potential for increasing experience within AM at GKN by aquiring knowledge from other parts of the supply chain?
    a. What parts?

Kommunikation:

23. Do you believe that AM is prioritised to different extents at different departments in the company?
    a. Why do you believe that is?
24. Do you believe that the communication between departments is clear with regards to the development of AM?
    a. If not, why do you think this is?
25. There seems to be a clear gap between what operators in the workshops perceive as conceivable and what the company aims to accomplish with AM. Why do you believe this gap exists?
26. Do you perceive that there are clear goals and a clear plan for AM and the development of the technology at the company?
    a. If not, why is this? What is missing?

Processutveckling och kvalificering:

27. What does the verification/qualification procedure look like for a new repair technology if you were to describe it based on your own work?
28. What are the greatest obstacles in the processdevelopment which GKN employs today with consideration to AM? How efficient is this process?
29. Is it possible to perform testing, verification and qualification of AM at GKN? If not, why not?

30. As a closing question we would like to ask whether there are any employees at GKN which you believe might have valuable input to contribute with for this thesis?

B Interview Questions - Siemens Energy AB Finspång

Interview Questions

Introduction Questions:

- What is your name?
- What have you worked with when it comes to AM repair at Siemens?
- How long have you worked at the company?

Erfarenhet:

1. Is it clear to all departments such as R&T, Construction, Production and Maintenance, what limitations there are with regards to the AM technology available at the company?
2. Do you have higher requirements on AM processes in companrison to other more conventional manufacturing methods?

Kommunikation:

3. Is there a common language present for AM at the company? Are distinctions between repair, modification and new production made? Is it clear what is defined as AM at the company?
4. Is enough consideration given to productionparameters in the development phase?
5. How well-functioning is the communication between management at the company and other departments?
6. Do you perceive there to be any resistance towards the implementation of AM at the company?

Kvalificering och Verifiering

7. Is there sufficient experience within the procedures related to material certification?
8. Is there sufficient knowledge related to the effects of AM repair on material properties?
9. Is it clear which methods should be used for qualification and verification of a repair procedure?

Materialaspekter

10. What are the requirements set on material properties? Should the deposited material be identical to the original component material? How stringent are the requirements?
11. Do you have inspectionsmethods which are reliable for AM repair? Which are these?

Strategi:

12. Do you design components for AM repair?
13. Do you rely on external parts of you supply chain for the developmentphase?
14. Is there a uniform plan for the devlopment of AM repair at the company?
15. Are there any directives for how/when AM should be chosen at the company?
16. How do you presrve knowledge/data from previous projects?

Kostnad:

17. Are there any buffers created for unexpected costs in your business cases?

C Interview Questions - AM Expert

Interview Questions

Introduction Questions

- What is your name?
- Could you tell us a little bit about your background?
- How long have you worked within your current field?
- Have you worked with AM for repair purposes?

1. What opportunities do you see for AM repair in the aerospace industry? Where do you believe that the implementation of AM would be optimal? With consideration to the material, size or geometry?

2. Where do you believe the greatest challenge related to AM repair is, based on material, geometry and size? In what areas of implementation would it be easiest to motivate an investment in AM for the aerospace industry?

3. Why do you believe the technology has not been implemented to any greater extent for repair within the aerospace industry?

4. What do you believe would be required for AM to reach the same level of reliability as other conventional methods with consideration to repair in the aerospace industry?

5. What do you perceive the approach towards AM repair to be within the Aerospace industry? Are companies motivated towards implementing the technology?

6. Can you give an example of a conventional method within the aerospace industry which you believe could be replaced by AM? Why?

7. What cons do you perceive there to be with AM for repair purposes?

8. Why do you believe the requirements are so high for AM technology?

9. Do you believe there are more or less processing stages included in an AM operation in comparison to other manufacturing methods? Why?

10. Why do you believe the development cost of AM is so high in comparison with other methods? Is it due to the requirements placed on the manufacturing method, the component requirements, how new the technology is.. etc?

D Equations for Cost parameters

Overhead

Facility
*Facility cost = Rent (SEK / Hour) * Process time (Hours / Component) + Inventory cost (SEK / component) + Service and maintenance cost (SEK / component) + Software cost (SEK / component)*

Inventory
*Inventory cost = Inventory price (SEK / Hour) * Inventory occupation period (Hour / Component)*

Service and maintenance
Service and Maintenance Cost = Periodic maintenance price (SEK / Hours) / Total number of components produced during period (Components / Hours).

Software
Software cost = Periodic License cost (SEK / Period) / Total number of components produced during period (Components / Period).

Additional fixtures/tooling
Additional fixture / tooling cost = Fixture purchase cost (SEK) + Additional tooling cost (SEK).

Pre-processing

Inspection
*Inspection cost = Operator Hourly cost (SEK / Hours) * Inspection time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / component)*

Cleaning
*Cleaning cost = Cleaning agent price (SEK / kg) * Material usage (kg / Component) + Operator Hourly cost (SEK / Hour) * Cleaning time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / component)*

Surface treatment
*Surface treatment cost = Price of surface treatment material (SEK / kg) * Material usage (kg / Component) + Operator Hourly cost (SEK / Hours) * Processing time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / component)*

Scanning
*Scanning cost = Scanning time (Hours / Component) * Operator Hourly Cost (SEK / Hours) + Facility cost (SEK) + Additional fixture / tooling cost (SEK /Component)*

Set-up

Programming

*Programming cost = Operator Hourly Cost (SEK / Hours) * Programming time (Hours / Component) + Software cost (SEK)*

Machine testing

*Machine testing = Operator Hourly cost (SEK / Hours) * Testing time (Hours / Component) + Material cost (SEK / kg) + Gas cost (SEK / Component) + Machine Energy cost (SEK / Component) + Hardware cost (SEK / Component) + Facility cost (SEK)*

Material handling

*Material handling cost = Material handling time (Hours / Component) * Operator Hourly Cost (SEK / Hour)*

Build

Operator

*Operator cost = Build time (Hours / Component) * Operator Hourly Cost (SEK / Hour)*

Hardware

*Hardware cost = Price of tooling / Duration of tool (SEK / Hours) * Build time (Hours / Component)*

Raw material

*Raw material cost = (1 + Material loss factor (%)) * Material usage (kg / Component) * Price of raw material (SEK / kg)*

Gas

*Gas cost = (Price of gas cylinder (SEK) / Duration of cylinder (Hours)) * Build time (Hours / Component)*

Scrap and Rework

*Scrap and rework cost = Scrap factor (%) * Number of components repaired * Disposal cost (SEK / Hour) + Rework factor (%) * Number of components repaired * Rework cost (SEK / Component)*

Machine energy

*Machine energy cost = Machine energy consumption rate (kW / Hour) * Electricity Price (SEK / kW) * Build time (Hours / Component)*

Removal & Clean-up

Material handling

*Material handling cost = Material handling time (Hours / Component) * Operator Hourly Cost (SEK / Hours)*

Machine cleaning

*Cleaning cost = Cleaning agent price (SEK / kg) * Material usage (kg / Component) + Operator Hourly cost (SEK / Hour) * Cleaning time (Hours / Component) +Facility cost (SEK)*

Machine inspection
*Machine inspection = Operator Hourly cost (SEK / Hour) * Machine inspection time (Hours / Component) +Facility cost (SEK)*

Post-processing

Heat treatment
*Heat treatment cost = Operator Hourly Cost (SEK / Hour) * Heat treatment time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / Component)*

Surface treatment /Material removal
*Surface treatment cost = Operator Hourly Cost (SEK / Hour) * Processing time (Hours / Component) + Facility cost (SEK) + Surface treatment material cost (SEK / kg) * Surface treatment material usage (kg) + Additional fixture / tooling cost (SEK / Component)*

Cleaning / Removal of powder residue
*Cleaning cost = Cleaning agent price (SEK / kg) * Material usage (kg / Component) + Operator Hourly cost (SEK / Hour) * Cleaning time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / Component)*

Inspection & Testing

Inspection
*Inspection cost = Operator Hourly cost (SEK / Hour) * Inspection time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / Component)*

Quality control
*Quality control cost = Operator Hourly Cost (SEK / Hour) * Quality control time (Hours / Component) + Facility cost (SEK)*

Final testing
*Final testing = Operator Hourly cost (SEK / Hour) * Testing time (Hours / Component) + Facility cost (SEK) + Additional fixture / tooling cost (SEK / component)*

Marking
*Marking cost = Operator Hourly cost (SEK / Hour) * Marking time (Hours / Component) +Facility cost (SEK)*

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