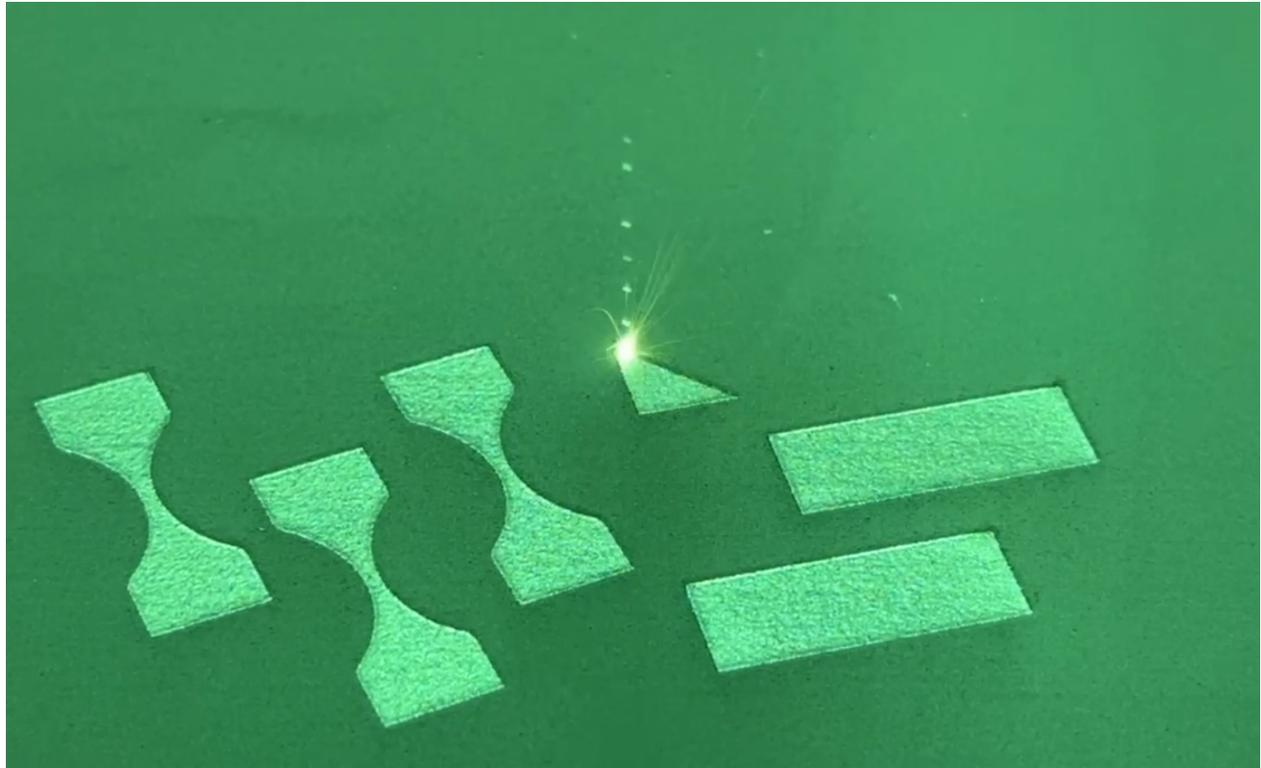
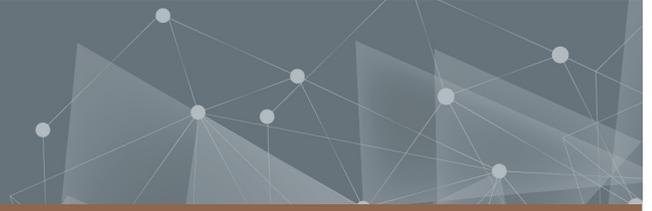




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Challenges and Opportunities within Design for Additive Manufacturing

Aiming for robust design of jet engine components

Master's thesis in Product Development

LUQMAAN SIDNEKOPPA  
VIJAYA KUMAR DASAPPA ASHOKA

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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CHALMERS UNIVERSITY OF TECHNOLOGY  
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MASTER'S THESIS 2024

# Challenges and Opportunities within Design for Additive Manufacturing

Aiming for robust design of jet engine components

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LUQMAAN SIDNEKOPPA AND VIJAYA KUMAR DASAPPA ASHOKA

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# Abstract

Additive manufacturing (AM) is transforming the design and manufacturing industries by allowing production of complex geometrical components that enhances efficiency and performance. However, despite its significant potential, AM poses several challenges, particularly in achieving cost-effective mass production.

This study focused on interviewing engineers within an aerospace product development organization to identify the challenges and opportunities related to AM powder bed development. The responses were analyzed, and the findings were visually represented using an (Design for additive manufacturing) DfAM AIM diagram. Additionally a benchmark was performed with the additional industrial partner that has experienced in this area.

The results from the interviews highlighted several key challenges in the AM design process and within the organization design practice. Design for additive manufacturing is a specialist area closely related to specific AM process. The study also identifies knowledge gaps and lack of communication between people and parts of organization. Process simulation software is not a standardized platform within the company, and difficult to use which means that front loading in design is still hard to perform.

A conclusion is that, the organization needs to undertake several strategic improvements such as bridging the knowledge gap and improve the communication. Implementing standardized design guidelines specific to AM will streamline the design process and reduce reliance on trial-and-error methods. Furthermore, by integrating advanced simulation tools early in the design phase support structures can be optimized, and material waste can be reduced, and manufacturing outcome can be more accurately predicted. This integration will not only improve efficiency but also reduce costs. Lastly, investing in research and development to refine post-processing techniques and explore alternative materials could further enhance the economic viability of AM.

Keywords: Design for Additive Manufacturing, Knowledge Gap, Additive Manufacturing, Simulation Software, Support structures.

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Name LUQMAAN SIDNEKOPPA AND VIJAYA KUMAR DASAPPA ASHOKA,  
Gothenburg, Month Year



# List of Abbreviations

Below is the list of abbreviations that have been used throughout this thesis listed in alphabetical order:

2D	Two-dimensional
3D	Three-dimensional
AM	Additive Manufacturing
ASTM	American Society of Testing and Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
DFA	Design for Assembly
DfAM	Design for Additive Manufacturing
DFMA	Design for Manufacturing and Assembly
DFSS	Design for Six Sigma
DMAIC	Define, Measure, Analyze, Improve, and Control
DFX	Design for X
GKN	Guest Keen and Nettlefolds
GOM	Geometric Optical Measurement
GTC	Global Technology Centre
HIP	Hot Isostatic Pressing
ICME	Integrated Computational Materials Engineering
IR	Infrared
LB	Laser Beam
LPBF	Laser Powder Bed Fusion
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
PBF-LB	Powder Bed Fusion – Laser Beam
PTC	Production Technical Centre
R&D	Research & Development
TO	Topology Optimisation
TRL	Technology Readiness Level



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# 1

## Introduction

### 1.1 Background

In this evolving world of the aerospace industry additive manufacturing (AM) stands out as a transformative technology, although considered relatively new and novel compared to traditional manufacturing methods like casting and forging. In contrast to casting or forging, AM presents a dynamic shift by offering an alternative approach that reduces dependence on existing suppliers, particularly major players in casting and forging. AM technology brings the promise of increase in flexibility and novel functionality like introduction to the potential of integrating complex geometrical functional components seamlessly into a single design [1].

GKN Aerospace with engineering tradition that dates back to 1930 have been depending on material suppliers for forging and casting to produce critical engine components. AM allows to avoid/minimize this traditional reliance by offering a way to produce parts internally, reducing dependence on external suppliers. This change in the manufacturing mindset corresponds with the industry's need for increased production process autonomy, control, and flexibility.

The Company have been manufacturing components through Direct Energy Deposition (DED) technology for the last 10 years and they are front runners in developing this technology. Now GKN Aerospace is adding Powder Bed Fusion – Laser Beam (PBF-LB) ), also often referred to as L-PBF or SLM technology to their existing manufacturing technologies. PBF-LB has potential to produce complex intricate geometries at higher resolution. one of the distinguishing features of this AM technology is in its ability to create Intricate geometries that were previously unfeasible or expensive to create using traditional methods. This capability opens new horizons for company in designing and allowing engineers to explore and implement complex geometries in ways that were previously constrained [2]. The aim is to fully utilize the unique capabilities of additive manufacturing by rethinking and optimizing designs rather than just replicating current components using an alternative production process.

Despite the transformative potential of AM, its application in the aerospace industry, particularly in the production of jet engine components, is still in its early stages. While there is a recognition of the technology's promise, there are relatively few examples of AM solutions for jet engine components in active production. This underscores the need for a concerted effort to refine and optimize the design process specifically for AM components.

The company has shifted their focus towards identifying areas in the design and production process where improvements can be made to enhance robustness and efficiency. This involves addressing challenges and gaps within (Design for additive manufacturing) DfAM, such as optimizing designs for PBF-LB process, ensuring material quality, and streamlining post-processing steps. Collaborative efforts between design engineers, materials engineers, manufacturing engineers, and AM engineers is essential in order to unlock the full potential of this revolutionary technology and integrate it seamlessly into the company's design practices to manufacture aerospace components. As the industry embarks on this transformative journey, GKN is conducting study on DfAM through this project to understand PBF-LB capabilities and the refinement of its application processes which guide the company undoubtedly to shape the future of additive manufacturing in the aerospace industry.

## 1.2 Aim

The key aim of this thesis project is to understand and review the existing design processes in AM, identify challenges, knowledge gaps and opportunities, and propose improvements to enhance robustness and efficiency in production with a comparison study on finding available simulation software.

## 1.3 Research Questions

1. **RQ-1:** What are the current industrial challenges in the design process for AM?
2. **RQ-2:** How can GKN improve their current process?

## 1.4 Limitations

- This report's scope will be focused on Design for Additive Manufacturing and its current applications within GKN Aerospace focusing on how its performed for PBF-LB .
- The examination will center on the methods and strategies employed by GKN Aerospace in their present utilization of DfAM techniques.
- Identification of suitable simulation software for support structure generation for AM components will be explored, with a particular emphasis on how GKN can effectively implement its capabilities.

# 2

## Theoretical Framework

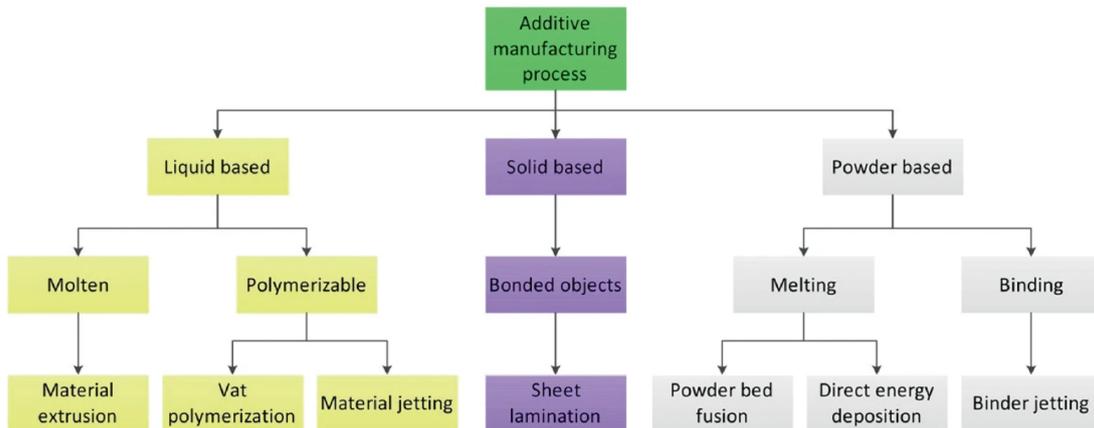
### 2.1 Introduction

AM is the process of joining materials to make parts from 3D CAD model , usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [3] .

The AM technology uses data from models created in software such as Computer Aided Design (CAD) or with 3-D scanners to create the component defined in the models through the deposition of material. The material is deposited in layer upon layer until the object is complete .

According to [3] ISO/ASTM 52900 (2021), additive manufacturing (AM) processes can be categorized in a way that allows for the discussion of a broad category of machines see Figure 2.1, rather than requiring a detailed explanation of the numerous commercial variations within a particular process methodology.

These processes are divided into 7 categories see Figure 2.1[4]:



**Figure 2.1:** Classification of additive manufacturing according to ISO/ASTM 52,900 (ISO/ASTM)

#### 1. Material extrusion (MEX)

- An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

2. Vat photopolymerization (VPP)
  - An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.
3. Material jetting (MJT)
  - An additive manufacturing process in which droplets of build material are selectively deposited (example materials include photopolymer and wax)
4. Sheet lamination (SHL)
  - An additive manufacturing process in which sheets of material are bonded to form an object.
5. Powder bed fusion (PBF)
  - An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
6. Directed energy deposition (DED)
  - An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. Focused thermal energy means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.
7. Binder jetting (BJT)
  - An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

These AM processes have certain differences, but for this thesis we are focusing on Powder Bed Fusion – Laser Beam (PBF-LB ) and will be presented further below.

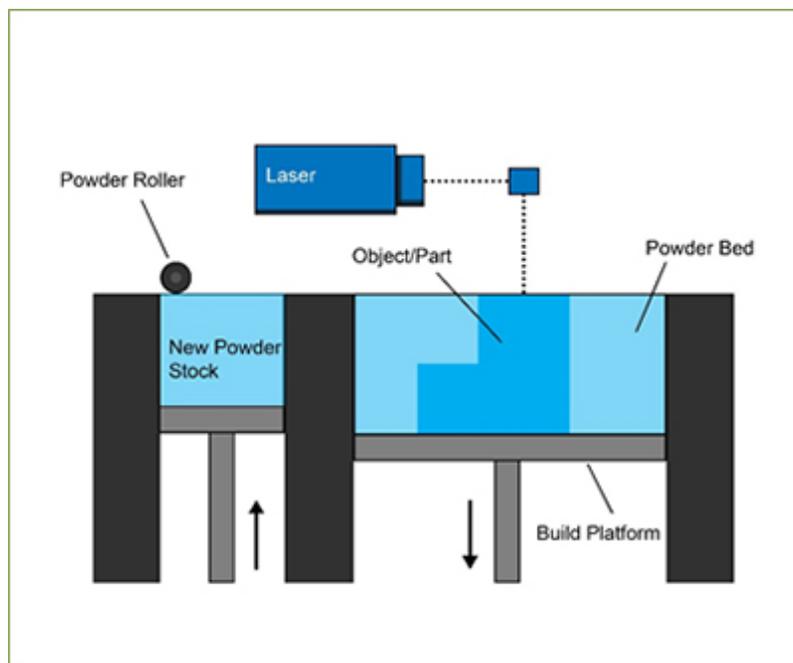
## 2.2 Powder Bed Fusion – Laser Beam

In essence, Powder Bed Fusion – Laser Beam (PBF-LB ) operates by selectively melting metal powder layer by layer, enabling the creation of intricate and complex parts with high precision see Figure 2.2[5]. This process provides a high level of accuracy and efficiency, offering remarkable flexibility in both design and production. PBF-LB is particularly well-suited for manufacturing components with complex geometries that would be difficult or impossible to produce using traditional methods, making it a versatile solution in modern manufacturing.

This category contains the laser-based powder bed fusion process (PBF-LB), and according to the ISO/ASTM standard ISO/ASTM 52900, the process should be described as using a laser beam (LB) with the acronym PBF-LB in technical documentation. However, the terminology PBF-LB as well as LPBF and even SLM is widely in use and is acceptable. [5].

In the Powder Bed Fusion – Laser Beam (PBF-LB ) process, a 3D CAD model of the part is crucial. This model is divided into thin layers using specialized software called a slicer. The layers are then built one at a time by melting metal powder particles together. The process begins by purging the machine's chamber, with inert gas to reach necessary level of oxygen content and build plate can be further heated to a specific temperature for printing. Further on, fine layer of metal powder is spread over the build platform. Powder Bed Fusion – Laser Beam (PBF-LB )

operates by selectively melting metal powder layer by layer, enabling the creation of intricate and complex parts with high precision. This process provides a high level of accuracy and efficiency, offering remarkable flexibility in both design and production. PBF-LB is particularly well-suited for manufacturing components with complex geometries that would be difficult or impossible to produce using traditional methods, making it a versatile solution in modern manufacturing. Laser scans each layer's cross-section, melting the metal particles together. Once melted, the particles solidify, forming the first layer of the component. This layer adheres to the build platform with the help of support structures. After each layer is completed, the build platform lowers slightly, allowing another layer of powder to be spread and melted. This process repeats layer by layer until the entire part is created. Once printing is finished, the machine cools, and any leftover powder is collected for reuse in future prints.



**Figure 2.2:** Powder Bed Fusion – Laser Beam diagram

## 2.3 Design for Additive Manufacturing

Design for Additive Manufacturing (DfAM) is a type of design method and manufacturing method where by functional performance and other key product life-cycle considerations such as manufacturability, reliability and cost can be optimized subjected to the capabilities of AM technologies.[6]

Design for Additive Manufacturing (DfAM) brings a new perspective to the design process by harnessing the unique possibilities of additive manufacturing technology. This approach has been successfully applied across various industries, showcasing its creativity and effectiveness. Unlike traditional methods such as design for man-

ufacturing (DFM), design for maintenance, or design for cost (DFC), which focus on reducing production challenges and minimizing costs, DfAM allows designers to explore the specific capabilities and advantages of additive manufacturing.

In DfAM, various design perspectives come together, blending elements from traditional methodologies like DFM, DFC, and others. The core idea is to combine AM technology into the design process to enhance efficiency, functionality, and performance without compromising manufacturing feasibility and increasing costs.[6]

In the aerospace industry, design for additive manufacturing (DfAM) techniques have been applied to topology optimization, a method used to reduce component mass and material usage while maintaining stiffness. This process is particularly suited for complex geometries that can only be effectively produced using additive manufacturing technologies (Diegel, 2019). DfAM encourages a shift in mindset, prompting designers to consider manufacturing constraints and opportunities from the beginning of the design process. This approach allows for the creation of designs that not only meet functional requirements but also leverage the unique advantages of additive manufacturing. Furthermore, DfAM fosters collaboration between design engineers and manufacturing experts to ensure that designs are optimized for additive manufacturing processes. By involving manufacturing expertise early in the design phase, potential challenges can be identified and addressed, leading to more efficient production processes and higher-quality final products.

One of the primary advantages of DfAM is its emphasis on embracing the capabilities of AM rather than adapting designs to fit existing manufacturing processes. Traditional design methods often involve tailoring designs to minimize manufacturing complexities and costs. However, DfAM encourages design engineers to explore the full potential of AM, by providing opportunities for innovation and optimization. By integrating Design for Additive Manufacturing (DfAM) principles into the design process, engineers can overcome traditional manufacturing limitations and fully exploit the capabilities of additive manufacturing (AM). DfAM allows designers to account for AM-specific challenges such as overhangs, optimal angles for layer printing, recoating direction, and the need for support structures. These considerations are critical for minimizing post-processing, improving print reliability, and ensuring the quality of the final part. Additionally, DfAM helps in the strategic placement of parts on the build platform to reduce material waste and ensure better heat distribution. This approach also enables engineers to create complex geometries, lightweight components, and robust design structures while facilitating rapid prototyping and iteration, streamlining both the design and manufacturing process.[6]

## 2.4 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 measure 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 2.3 [7].

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. These stages are mainly the focus for universities and government funded sources as there is a greater focus on the research phase.
- 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 analyzed to determine the parameter operating range. In the fifth stage, the technology is validated through a simulated environment. The sixth stage is focused on demonstrating the technology performance in the simulated environment.
- Level 4-6 are often referred 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.
- Level 7-9: The last stages of the TRL that focuses on the implementation of the developed technology. At the seventh stage a prototype of the system is implemented in a functional environment. In the eighth stage, the technology is 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 [7].



**Figure 2.3:** Technology-Readiness-Level

## 2.5 Zero Defects

Zero defect is a concept commonly used in the aerospace industry, aimed at minimizing errors and defects through preventive measures. It's a management tool designed to ensure that the entire team works together toward the goal of achieving flawless production, both in terms of manufacturing processes and the quality of the final parts. The key objective is not only to avoid defects in the manufactured components but also to ensure that the entire manufacturing process operates without errors, leading to consistent high-quality results [8].

In AM the quality standard is aimed at achieving flawless production of 3D printed parts. Achieving zero defects requires precise calibration of printing parameters, thorough monitoring of material properties, and quality assurance measures throughout the manufacturing process. This ensures the enhancement of control and optimization of the printing process to every manufactured component to meet the required specifications without any defects.

## 2.6 Robust Design

Robust design for AM primarily focuses on enhancing functionality and minimizing geometric defects see Figure 2.4. AM offers manufacturing advantages, enabling the creation of robust products while reducing costs. The aim is to design products and components that can withstand variations and uncertainties inherent in the AM process. The main goal is to ensure that manufactured parts consistently meet specific requirements and standards, despite variations in materials, equipment, operating conditions, and other factors. However, designers often face challenges due to the lack of design guidelines and standardization in AM processes, leading to difficulties in implementing best practices [9].

### 2.6.1 Design for Six Sigma

Six sigma is a method which is set for improving processes and reducing defects. Six sigma mainly focuses on fulfilling customer needs in systemic approach and enhancing quality of products or services. It is a disciplined data driven approach [10].

The term six sigma comes from statistical model of manufacturing processes. The strategy comes from DMAIC: Define, Measure, Analyze, Improve, and Control (DMAIC).

In the initial define phase the issues are identified and objectives are set . Then in measure phase, data is gathered on quality and exciting performances is evaluated. Later in analyze phase , the causes behind defects are unearthed and examined. Afterwards, the improve phase concentrates on executing remedies to tackle identified problems. In last control phase , it is decided to ensure the enhancement are

maintained over time.

Six Sigma utilizes statistical tools and techniques to analyze data and make informed decisions. By emphasizing data-driven problem-solving, Six Sigma helps organizations achieve measurable improvements in quality, customer satisfaction, and efficiency.

While the Six Sigma methodology follows the DMAIC approach (Design, Measure, Analyse, Improve and Control), Design for Six Sigma (DfSS) often uses the IDOV approach (Identify, Design, Optimise and Verify) instead [11]. In other words, Six Sigma is used for existing processes and DfSS is used when designing new processes and products. Mader writes in that DfSS is applied during product design or redesign process. He defines DfSS as a mix of qualitative and quantitative tools and key performance measures that help companies to apply strategies and tactics in order to achieve more efficient design process management, and to optimise the key drivers, for instance the cost and quality.

### **2.6.2 Design for Assembly**

The Design for Assembly (DFA) method was created to reduce assembly time and cost of product life cycle by reducing number of parts and operations. DFA mainly focuses on minimizing parts and standardization of parts. The goal is to reduce time and cost of assembly by considering single part function into multi-functional design and considering non-critical parts into critical parts, which results in improving assembly [12]. DFA also helps teams streamline assemblies and complex models by simplifying the attachment directions, hence reducing attachment time.

### **2.6.3 Design for Manufacturing**

The DFA method was developed in order to support Design for manufacturing (DFM), to optimize the design and manufacture of assembly. DFM main objective is to simplify product design by reducing number of parts, and simulation process (Otto & Wood, 2000). The focus is to optimize each part to reduce or eliminate the need for expensive, complex and unnecessary features which could be difficult to manufacture. It allows and helps in selection of cost effective materials and processes during the manufacturing stages, by reducing overall product cost and achieving reduced time to market efficiency.

### **2.6.4 Design for Manufacturing and Assembly**

DfMA is useful for improving piece-functional designs by inspiring system functional designs. As a qualitative approach, it can be viewed as a knowledge based technique that invokes a series of guidelines, principles, recommendations, or rules of thumb for designing a product to ease manufacturing and assembly tasks while lowering the manufacturing costs [13].

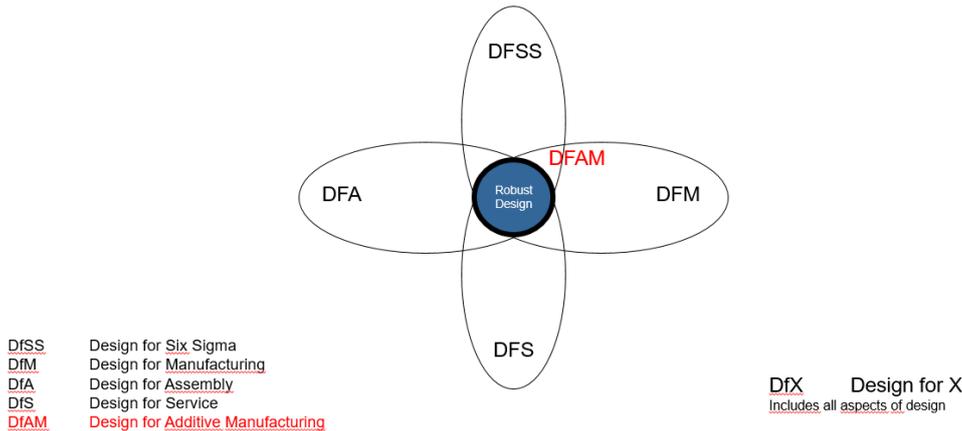
DfMA was developed for minimization, standardization, and modularization of components in an assembly which are the key characteristics associated with the DFMA. These lead to benefits of an improved design with simplified assemblies (in terms of unambiguous part orientation, less handling, fewer adjustments, etc.), fewer manufacturing operations, lower costs from eliminating complex tooling and dedicated fixtures, greater modularity, and easier repair and maintenance.

**2.6.5 Design for X (DFX)**

Design for X is a extensive approach to product design which mainly aims to develop various advantageous characteristic throughout the lifecycle of a product. It bounds a range of design methodologies focused on achieving greater customer satisfaction by increasing positive attributes and reducing cost over products lifetime [13].

The "X" in DFX symbolizes the various set of characteristics or qualities that designers strive to develop, modified to specific project needs and objectives [14]. DFX includes well-known methodologies such as Design for Assembly (DFA), Design for Manufacturing (DFM), and Design for Manufacturing and Assembly (DfMA), among others. These methodologies are now seen as integral parts of the broader DFX framework see Figure 2.4.

The importance of DFX lies in its ability to enhance product quality, accelerate time-to-market, streamline decision-making processes, and boost the overall productivity of design engineering teams [14]. As products become increasingly complex, DFX becomes even more valuable, serving as a foundational approach for designers to address multiple objectives and constraints effectively.



**Figure 2.4:** Relation of DfAM with other Design Processes

## 2.7 Simulation's capabilities on PBF-LB Process

Simulation software's helps in understanding and predicting various critical aspects of the AM process, particularly for Powder Bed Fusion – Laser Beam (PBF-LB ) processes. the process identified while performing simulation are explained below,

**Residual Stresses and Distortions** Simulation software can predict the residual stresses and distortions that may occur in the final part due to the thermal cycles and rapid cooling involved in the PBF-LB process . This helps identifying potential areas of warping, cracking, or deformation, allowing for preventive measures or design modifications.

**Support Structure Design** Proper support structure design is crucial for successful print in PBF-LB machine, especially for parts with overhanging features or complex geometries. Simulation software can analyze the part geometry and identify areas requiring support structures, as well as optimize the support design to minimize material usage and facilitate heat dissipation.

**Build Orientation** The build orientation of a part on the build plate can significantly impact the amount of support material required, residual stresses, and surface finish. Simulation software can evaluate different build orientations and suggest the optimal orientation to minimize defects and improve part quality.

**Process Parameter Optimization** Simulation software can help optimize process parameters such as laser power, scan speed, hatch spacing, and layer thickness, by predicting their impact on factors like melt pool dynamics, residual stresses, and porosity . This optimization can improve part quality and process efficiency.

**Defect Prediction and Failure Analysis** By simulating the PBF-LB process, software can identify potential defects or failure zones, such as lack of fusion, key-hole porosity, or excessive deformation . This information can be used for failure analysis and process improvement.

**Support Generation and Latticing** Some simulation software, like Autodesk Netfabb, offers the ability to generate unique support structures and lightweight lattice structures , which can improve the accuracy of predictions on build quality and potential failures.

# 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 study

The research study for this thesis is conducted based on 5 steps see Figure A.1: a qualitative study, literature study, action research, benchmark study and performing simulation. The thesis work is an investigation to find the challenges within GKN on DfAM. It is determined to be a good approach since the research is still to be made and finding out the gaps and challenges, is an important contribution from this thesis work accordingly with the time plan see Appendix A.1 [15].

The research strategy for this thesis is based on data collection, which is done for several steps of the work. The data collection helps and supports for understanding the research area and helps to develop the solutions accordingly which is necessary for the thesis work. The methodology of this project is also chosen as the exploration of different data sources which helps in strengthening of the research [15].

The research began with an initial study of the company's current work within DfAM as well as a literature study on DfAM in order to understand and gain knowledge before initiating the qualitative study.

The qualitative study was initiated with a study of company information on AM and DfAM 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 DfAM in general. This was also necessary in order to ensure that the results of the qualitative study were valid.

## 3.2 Action Research

In this research study action research was considered has an methodological approach. Action research is a practical, problem-solving methodology often used in educational, organizational, or community settings. It aims to generate actionable solutions to real-world issues while simultaneously developing knowledge. According to "**The Good Research Guide**"[15], action research involves a cyclical process of planning, acting, observing, and reflecting, where researchers actively collaborate with participants to identify a problem, implement interventions, and evaluate outcomes. This method is particularly valuable because it not only helps to solve specific problems but also fosters professional development and engagement.

This approach helped to understand the issues within the context, thereby producing results that are relevant and directly applicable to practice. The iterative nature of action research allows for continuous refinement of interventions, making it highly adaptive to changing circumstances.

## 3.3 Qualitative Study

To begin our thesis research, we conducted a qualitative study to evaluate the company's current state of design for additive manufacturing (DfAM). With this project, we aimed to learn more about the state of DfAM implementation as it stands today and pinpoint the primary difficulties particular to this field [15].

## 3.4 Initial study of DfAM at GKN

As the first step of our research at GKN, we conducted a thorough analysis to create the thesis structure. Obtaining a variety of papers, records, and study materials from our GKN supervisors was an essential stage in this process. Our investigation into the fields of additive manufacturing and design optimization was anchored by these resources.

We sought to acquire a thorough grasp of the complexities and difficulties related to the field of design for additive manufacturing (DfAM) by researching the literature and material that had already been produced. The concepts of additive manufacturing, material characteristics, process optimization strategies, support structure design, post-processing, and case studies showcasing effective DfAM implementations across a range of sectors were just a few of the many subjects covered in our study. By carefully going over scholarly articles, business reports, and technical documentation, we sought to pinpoint important trends, industry best practices, and topics that needed further study.

This first research phase was crucial in giving us the background information and understanding that needed to develop thoughtful research questions and project

approaches. We were able to find gaps and chances for innovation by carefully examining the corpus of previous work, which eventually helped to determine the course of our future research projects.

The start of our exploration for DfAM with a thorough literature review to better understand the nuances of this developing subject. This first exploratory stage gave us the fundamental information and understanding that formed the basis of our study. We set out to obtain a thorough grasp of the complexities, challenges and difficulties related to DfAM by researching the literature and material that were already in existence.

In simultaneously we carried out qualitative research to learn more about particular facets of DfAM, like support generation and post-processing techniques. We were able to find important insights and viewpoints by searching through a large number of academic articles, research papers, and industry reports using keywords like "design for additive manufacturing, Post-processing, quality inspections, support design" in our search parameters.

Conducted in parallel with our qualitative inquiry, the literature study proved to be an evolving and iterative process. As we read more carefully through the literature, we carefully noted important topics and ideas related to DfAM, such as process difficulties and optimization techniques. We were able to obtain a thorough grasp of the complex world of additive manufacturing by combining data from multiple sources. This information provided direction for developing our study questions and methods, providing a strong basis for our next work.

#### **3.4.1 Interviews at GKN**

A number of personnel interviews were undertaken in order to obtain insight into the company's existing design for additive manufacturing (DfAM) procedure. These interviews were conducted with the intention of gathering viewpoints on DfAM, including employee impressions, difficulties encountered, and areas for development. By conducting these interviews, we aimed to close the knowledge gap between theory and practice and develop a comprehensive grasp of DfAM in the context of organizations.

Our supervisors, who are actively involved in the project and have DfAM knowledge, carefully selected the interview applicants. The selection of candidates was based on their participation in several facets of DfAM inside the organization and their relevance to the DfAM thesis project. We sought to gather a wide range of viewpoints and experiences pertaining to DfAM by including staff members from several departments, including R & D, design, production, project management, material engineering, and AM engineering.

The interviews provided significant understanding into the obstacles, deficiencies,

and opportunities related to the implementation of DfAM inside the organization. By utilizing the combined knowledge and experience of staff members from several departments, we were able to identify important areas that needed strategic intervention and development. Our study objectives, techniques, and suggestions for improving DfAM processes inside the company were shaped by these findings.

Interviewees	Roles
A	Material AM GTC
B	Design GTC
C	Design GTC
D	Design GTC
E	Design Space turbine
F	Material specialist AM
G	Manufacturing GTC
H	Manufacturing simulations, PD
I	Design PD
J	Permanova Manufacturing
K	Project manager

#### 3.4.2 Interview structure

The semi-structured interview technique allowed for flexibility and adaptation to the knowledge acquired from each subsequent session. After every interview, the questions were revised and reexamined in light of the knowledge and understanding gained from earlier interviews (Appendix-1). Through the use of an iterative method, it was possible to delve further into important DfAM-related themes by ensuring that successive interviews were guided by the subject’s increasing understanding.

After conducting the literature study and GKN OMS analysis, the interview questions were prepared to align with the three main themes identified in Design for Additive Manufacturing (DfAM). It was found that these three themes—product development, Additive Manufacturing, and Design for AM—were essential subjects for further research in order to understand the strategies and operations of the company. In order to obtain a thorough understanding of GKN’s approach to additive manufacturing and to enable a detailed analysis of significant opportunity and challenges in the industry, the interview questions were based on these theme topics.

The interview questions were carefully prepared ahead of time and sent to the interviewees over email. This proactive measure was used to guarantee that the interviewees were adequately prepared and knowledgeable about the subjects that would be covered in the interview. We wanted to create a more meaningful and informed conversation by giving the interviewers the questions ahead of time, so they could more effectively express their ideas and observations on the subject of DfAM.

Open-ended questions were used in the interviews to allow the participants to openly discuss their opinions, experiences, and thoughts. We were able to compile a wide range of viewpoints and experiences pertaining to DfAM thanks to this method, which promoted a robust interchange of knowledge. We wanted to get detailed insights and important viewpoints from the interviews that would not have come through using a more planned or closed-ended questioning style, so we asked them directly for their opinions.

## 3.5 Benchmarking

Benchmarking is a method used to assess and compare products and work processes, aiding in improvement efforts and strategic decision-making. By leveraging external knowledge, benchmarking enhances internal safety measures and guides improvement processes effectively [16].

In this project, benchmarking was selected to enhance reliability and validity. By comparing GKN's challenges with those of an external company working with AM, it was possible to discern whether these challenges were specific to GKN or common across similar companies. Additionally, benchmarking with an AM expert provided valuable insights into DfAM challenges and gaps.

Following [16], the first step involved gathering public data and conducting benchmarking through surveys or interviews. An online search was conducted to understand the company's current AM experience and research status. This research informed the development of interview questions, aimed at filling in any data gaps. Interview questions for both company benchmarking and AM expert benchmarking were formulated in collaboration with the thesis supervisor at Chalmers and GKN. Interviews were conducted either virtually or face-to-face, depending on the interviewees' availability.

Semi-structured interviews were employed, allowing to capture interviewees' personal insights and reflections on the topics [15]. This approach facilitated a deeper understanding of the challenges and gaps in DfAM, contributing to the overall research objectives.

### 3.5.1 Benchmarking Interviews

Interviewees	Roles
L	AM Material specialist
M	Design team lead
N	AM engineer

The bench-marking interview was conducted with Siemens engineers. The structure for benchmarking interviews was decided in meetings. They were semi-structured with open questions to allow employees to add their input. This ensured relevant information to be captured even if not explicitly asked [15].

During benchmarking interviews, further explanations were provided for questions without responses by adding context. Open-ended questions were limited to focus answers on the subject. Interview lengths varied based on interviewee knowledge and commitment.

Due to confidentiality, not all interviews could be recorded, but consent was sought to maintain detail. Audio recordings were preferred over field notes for detailed answers and increased validity .

Interviewees were assured of anonymity, and recordings would be deleted after the project deadline for honesty and transparency [17]. If consent was not given, information would be collected via field notes.

Some interviews were conducted online via platforms like Microsoft Teams due to interviewee availability and different company locations, while others were in person.

## 3.6 Data Analysis

This section outlines the steps involved in doing the data analysis and the results obtained for each mode of data collection. Chapter 4, Results, contains the data analysis method results.

### 3.6.1 Qualitative Study

The qualitative study involved conducting interviews to gather necessary information for data preparation and analysis. This analysis was done by transcribing the interviews and highlighting key information provided by the interviewees [15].

Following transcription, a feedback form was created and sent to all interviewees to gather their feedback on the answers or important points highlighted in the transcriptions. This step aimed to identify challenges within DfAM that GKN employees were facing in AM.

Once data was collected from the transcriptions, it was summarized. The AIM ( Affinity and Interrelationship Method ) was then utilized to further analyze the data.

### 3.6.1.1 Affinity and Interrelationship Method

The AIM method, similar to Shoji Shiba's 19-step approach, is a problem-solving tool for analyzing qualitative data [18].

We chose the AIM method to sort, structure, organize, and analyze the data gathered from interviews. This method helped in identifying the relationships between different challenges mentioned during the interviews.

The process involved summarizing the challenges from the qualitative study into concise statements and grouping them based on similarities. These grouped statements were then categorized to define challenging areas in DfAM.

Once challenges were grouped and categorized, interrelationships between them were identified to understand their origins and root causes. Categories were then weighted based on the number of interrelationships, prioritizing areas with the most outward directed arrows as critical to address first.

Literature analysis was conducted using various approaches described in literature [3]. Identified literature was sorted into folders based on search keywords for better organization. Each folder represented similar categorical areas, aiding in clearer data management.

Careful re-reading of literature helped mark relevant data for inclusion in the results. Results from literature were then organized according to AIM headings. This helped in using appropriate literature for analyzing different areas defined in AIM.

Once interviews were conducted and recorded, data analysis for benchmark studies began. The first step involved transcribing the interviews to aid analysis and locate important data for later use [15].

After transcription, interview answers were carefully reviewed, and a deeper analysis of the transcriptions was conducted. Once interview analysis was completed, a summary of extracted data from transcriptions could be generated.



# 4

## Results & Discussions

### 4.1 DfAM Analysis

It is important for the company to understand DfAM process and PBF-LB AM technology ( Interviewee B ). GKN strives towards increasing their knowledge within DfAM process. Main focus of this thesis is was to understand the gaps and challenges within the organization and suggest methods for improvements.

- **AM Experience**

The AM technology considered for this study is PBF-LB and there are other AM technologies available at the company like DED. From the date of interviews which were conducted, we found that the company has very experienced employees who are working on AM (Design , manufacturing, materials.). The challenge is that the process for DfAM has to be set which can help the organization to improve and to explore (Interviewee E).

- **DfAM Process and strategy**

In a recent interview study at GKN, it was discovered that the company faced some gaps with the DfAM process, particularly in the Designing of components or DfAM Product development (PD) process. Many interviewees expressed that these challenges were due to shortage of AM engineers and deficiency of AM knowledge.

Various issues were highlighted, indicating that the DfAM process is still in its infancy and undergoing development. This lack of expertise and established methodologies impacts the smooth implementation of DfAM within the company. GKN is currently, working on the development of DfAM process and encountering challenges in integrating AM into their design processes for PBF-LB technology. Addressing these challenges will require investments in talent development and the refinement of design strategies

#### 4.1.1 Data gathering

The qualitative study was completed, with a total of 70 challenges from the interview study. Subsequently, a data gathering matrix was employed, dividing these challenges into three categories: product development see Figure 4.1, additive manufacturing see Figure 4.2, and DfAM see Figure 4.3. Within these categories, sub-

categories were created to provide a clearer and comprehensive understanding of the challenges. Only the important ones are mentioned based on the criticality of their expressions. This methodical approach allowed for a structured analysis of the challenges faced by GKN, enabling the prioritization of key areas for improvement in product development, additive manufacturing, and DfAM processes.

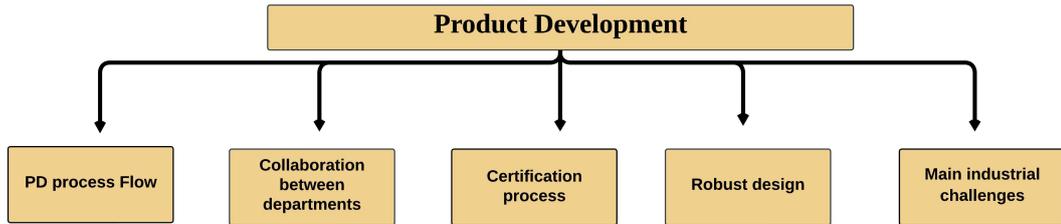


Figure 4.1: Product Development

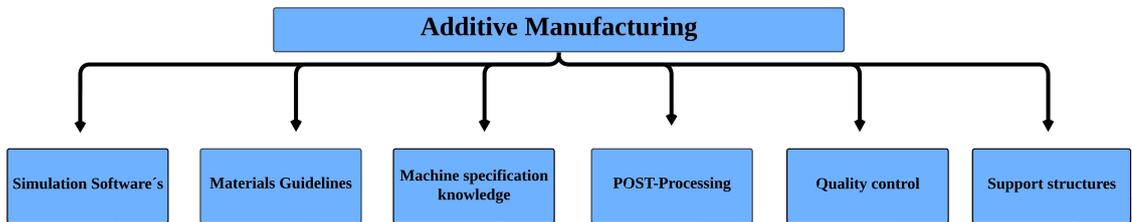


Figure 4.2: Additive Manufacturing

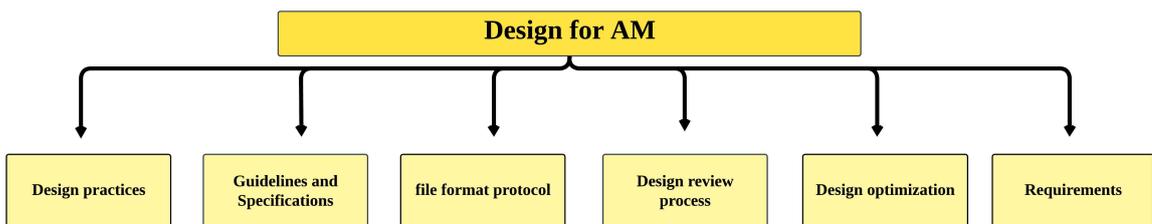


Figure 4.3: Design for AM

### 4.1.2 Challenges in Design for Additive Manufacturing

The challenges related to DfAM were extracted from the transcriptions of each participant in the interviews. All participants contributed with valuable information, highlighting numerous challenges concerning to AM. After completing the interviews, transcriptions were made for each, and a comprehensive list of challenges was compiled.

These challenges were then categorized into three main groups: Product development, additive manufacturing, and DfAM. Subsequently, an elimination matrix see Appendix Figure A.2 was constructed to refine the list, merging similar challenges and eliminating redundant ones. Following the completion of the initial elimination matrix, a group discussion was conducted to identify and emphasize the significant challenges.

This collaborative effort aimed to prioritize key areas for further analysis and action. The next step was creating an AIM diagram, which will be elaborated upon in the subsequent section. This systematic approach ensured a thorough examination of the challenges encountered in DfAM, facilitating the development of targeted strategies to address them effectively.

#### 4.1.2.1 DfAM AIM Diagram

The DfAM AIM diagram was collaboratively plotted during a group discussion involving GKN supervisors see Figure B.1. This diagram provides a clear visualization of how different groups are divided and how challenges are presented within the organization. The primary objective was to identify important challenges highlighted in the interview study. Further down in this section, each challenge will be explained in detail. This detailed examination aims to provide a comprehensive understanding of the specific hurdles encountered in the context of AM at GKN.

By addressing these challenges, the organization can devise strategies to overcome them and enhance its DfAM processes. The DfAM AIM diagram serves as a valuable tool for organizing and prioritizing these challenges, enabling the development of focused interventions to address them effectively. Through this structured approach, GKN can streamline its additive manufacturing efforts and maximize the benefits derived from incorporating DfAM principles into its operations.

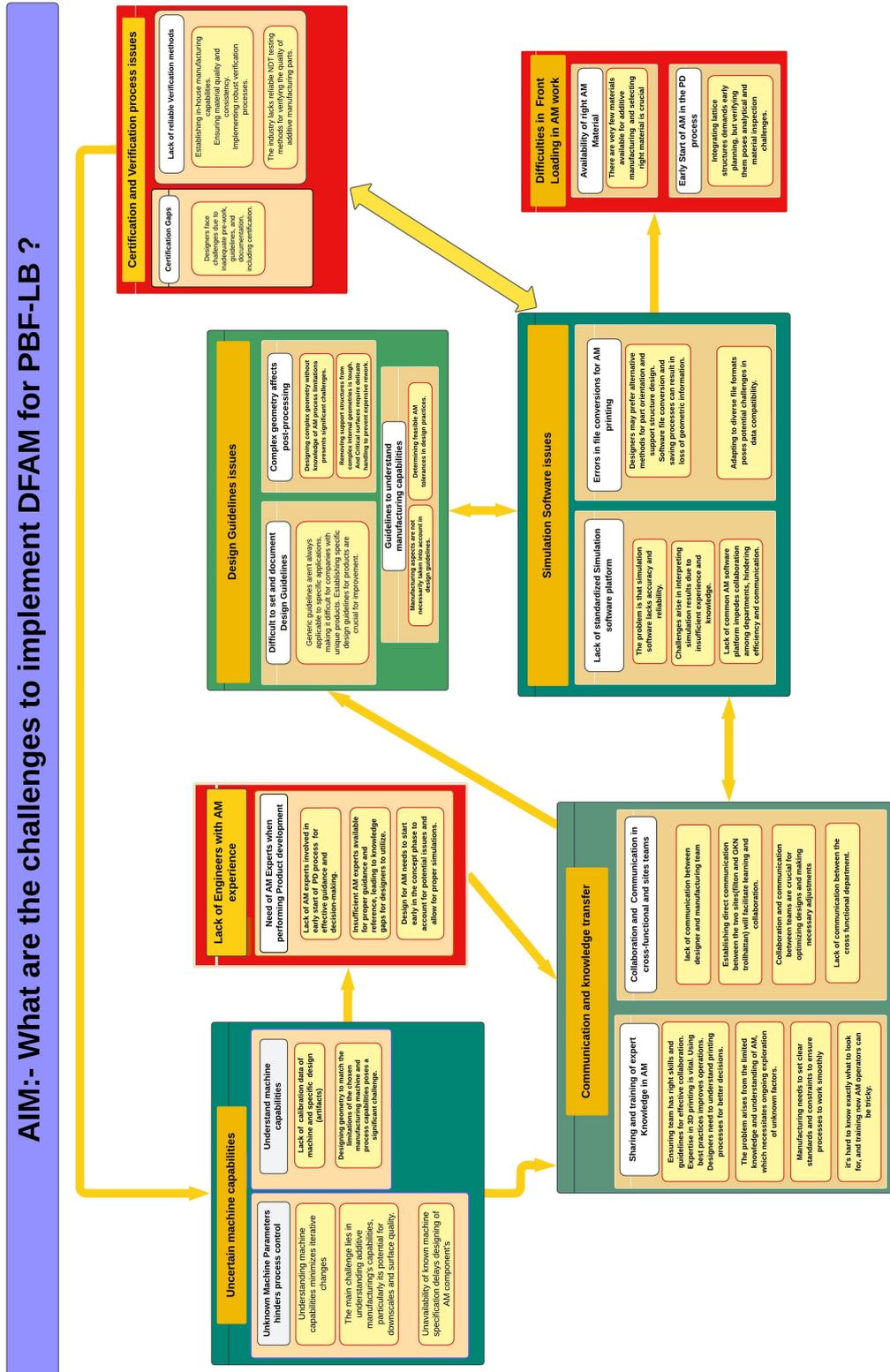


Figure 4.4: DfAM AIM diagram process flow

### 4.1.3 DfAM AIM Process diagram

The challenges in implementing (DfAM) for (PBF-LB ) are interconnected across multiple areas. Below is a detailed explanation of each challenge and how they are related. Figure B.1 can be simplified and can be translated and simplified to figure 4.5 .

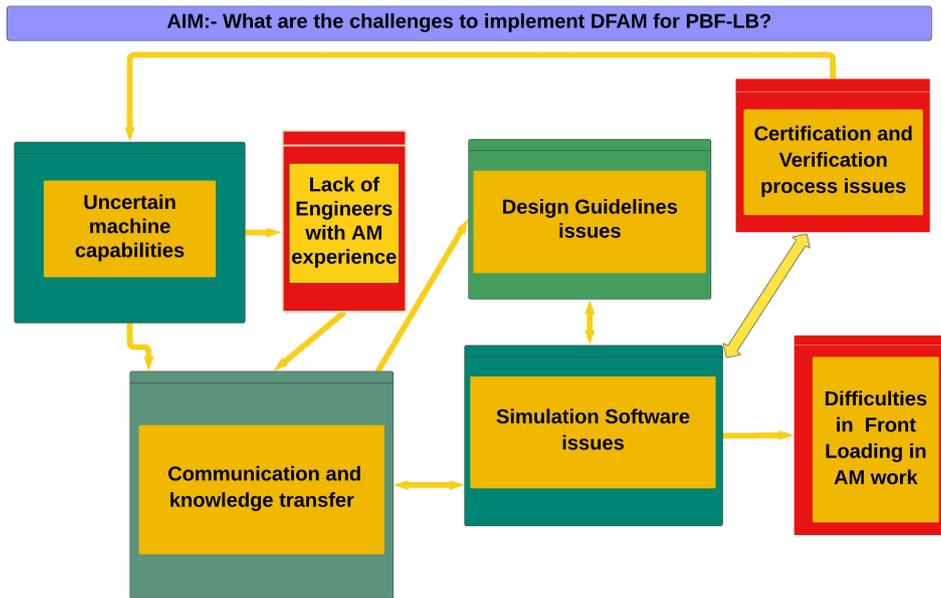


Figure 4.5: Simplified DfAM AIM diagram process flow

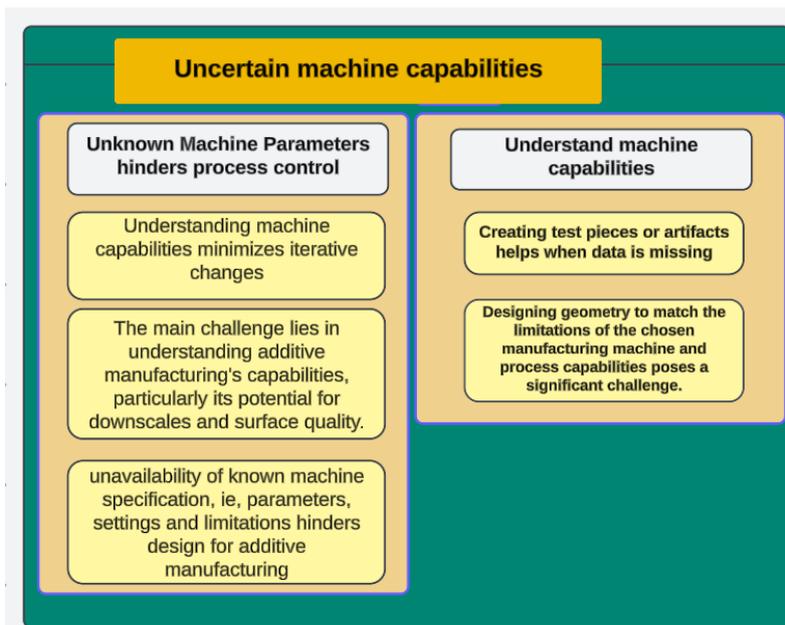


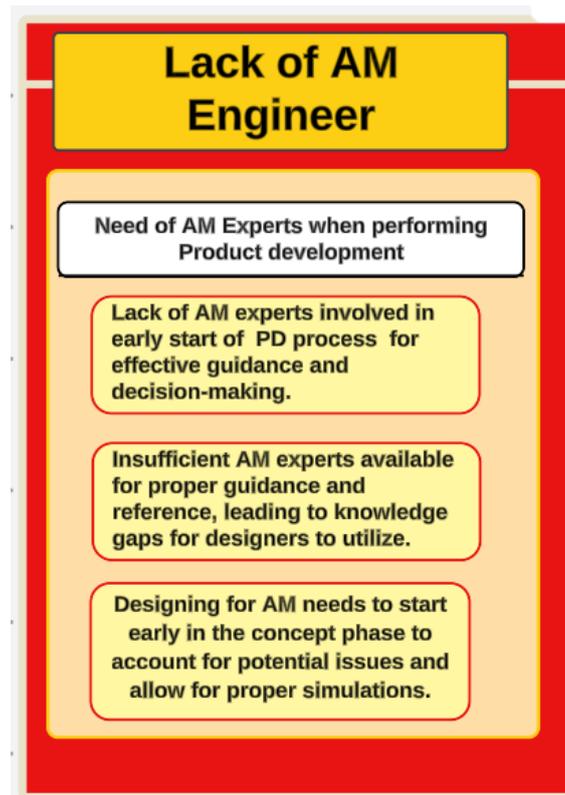
Figure 4.6: Uncertain machine capabilities

In Figure 4.6 the difficulties in understanding and controlling the capabilities of machines used in PBF-LB. This challenge is foundational because all further design and production steps depend on the knowledge of machine parameters and capabilities

**Unknown Machine Parameters:** Without clearly defined machine parameters settings (e.g., layer thickness, laser power, speed etc.), it becomes difficult to optimize and control the process. This leads to unpredictable surface quality or part dimensions, which hinders the refinement of component designs in iterative cycles.

**Understanding Machine Capabilities:** If the machine's capabilities are not fully understood, design engineers struggle to develop part geometry with the machine's potential, leading to poor-quality parts.

Uncertainty about machine capabilities creates a ripple effect, influencing all other aspects of the design process. For example, without knowing machine constraints, it's difficult to create effective Design Guidelines or properly simulate the process in the simulation software.



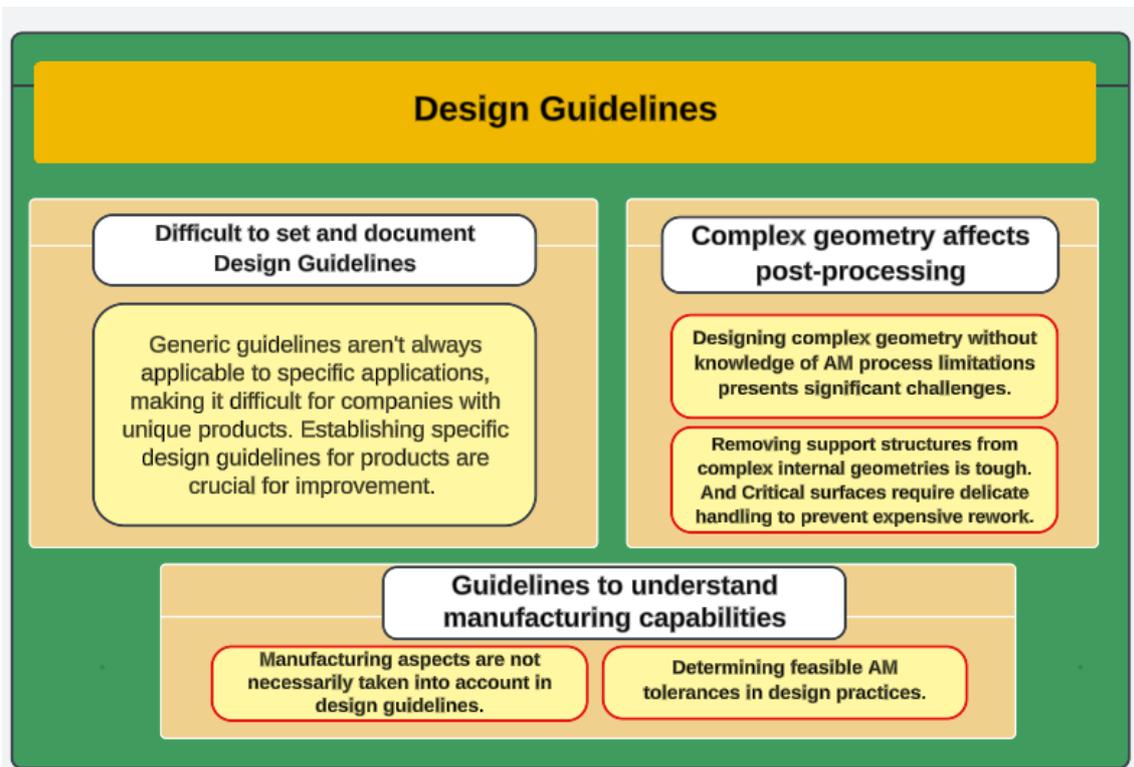
**Figure 4.7:** Lack of AM engineer

In Figure 4.7 the importance of skilled personnel for AM product development. This is critical for navigating the complexities in AM technologies. This challenge highlights the shortage of expertise in AM, which can slow development and could lead to inferior decisions.

**Need for AM Experts:** Experienced engineers are essential for guiding the product development process, during the early stages. Lack of AM experts results in delays and inefficiencies when making decisions in design, materials, and process optimizations.

**Expert Guidance:** Without experts, the feedback loop between design and manufacturing is weakened, limiting the ability to efficiently troubleshoot issues and innovate.

Lack of AM experience leads the issues with machine capabilities and design guidelines, as engineers without specific AM knowledge might not be able to assess machine potential and develop suitable designs. Also impacting utilization simulation software which can save the lead time, buy-to-fly ratio and manufacturing cost



**Figure 4.8:** Design Guidelines

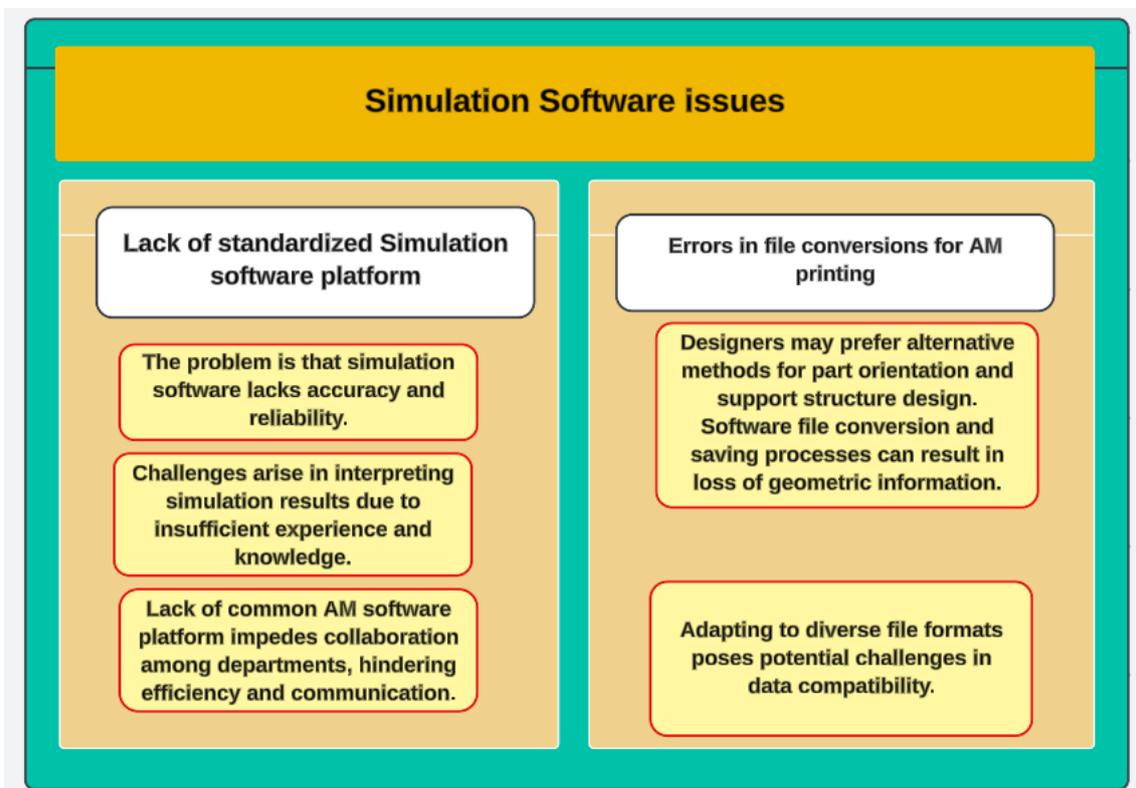
The figure 4.8 shows design guidelines for AM are either non-existent or too generic, making it challenging to design parts.

**Difficult to Set and Document Guidelines:** AM lacks clear guidelines tailored for specific applications. This results in engineers struggling to apply best practices for different part geometries or materials.

**Complex Geometry Affects Post-Processing:** AM enables complex designs, but those geometries often require more post-processing (e.g., removing support structures), which adds cost and time.

**Guidelines to Understand Manufacturing Capabilities:** Without proper guidelines, engineers can't adequately design for specific AM capabilities, such as machine tolerances or material limitations.

**Inadequate Design Guidelines** often result from a lack of knowledge about Machine Capabilities and AM Expertise. The absence of guidelines also impacts Simulation Software tools because clear design standards are necessary for accurate simulations.



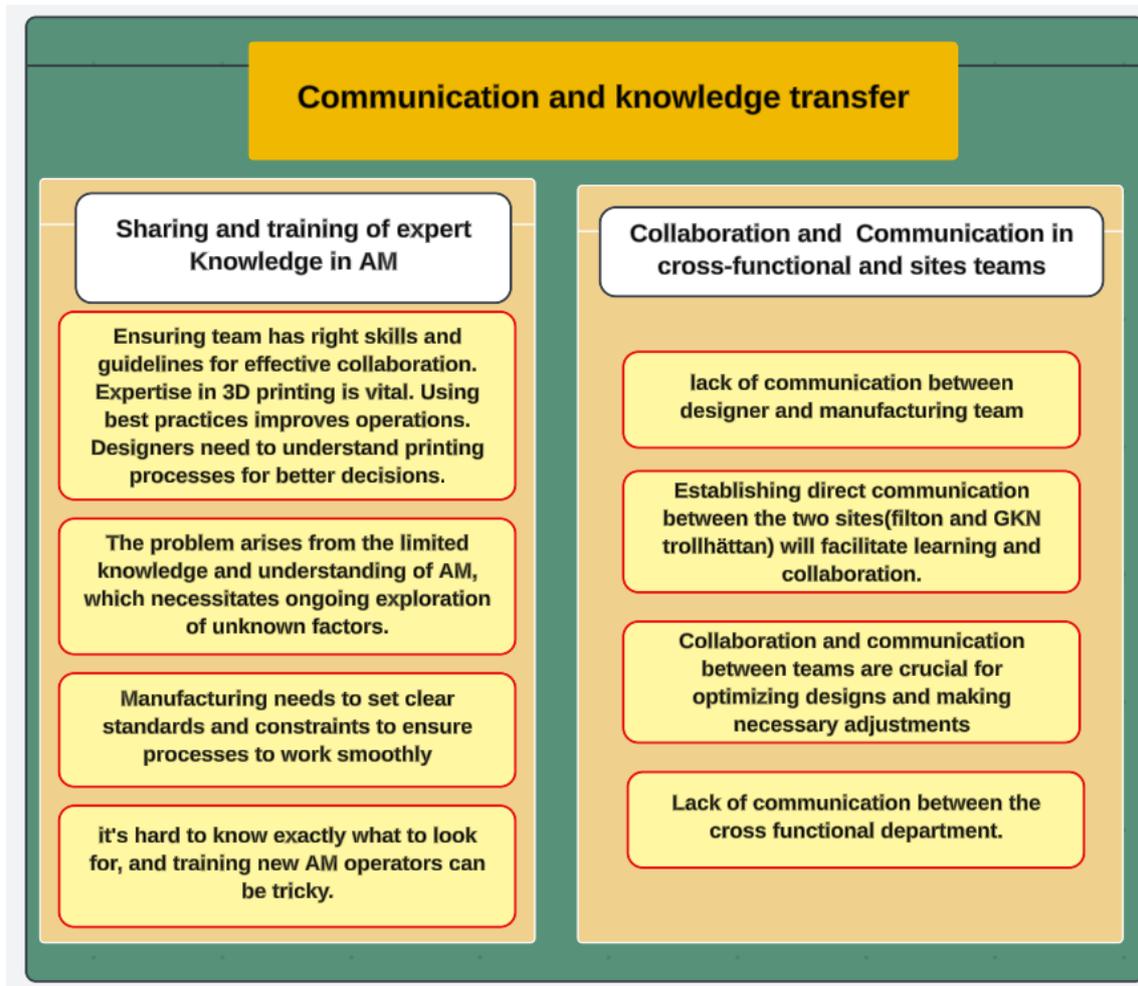
**Figure 4.9:** Simulation software issues

The simulation software figure 4.9 for AM faces challenges in accuracy, reliability, and ease of use, which can hinder product development.

**Lack of Standardized Simulation Platforms:** The current simulation tools are not standardized, and their interpretations often vary. This inconsistency leads to problems in predicting AM behavior, making it harder to optimize processes.

**Errors in File Conversions:** When converting digital files into formats suitable for AM printing, there can be errors or inconsistencies that further complicate the design process.

Without accurate simulations, designers are less capable of adjusting to Machine Capabilities or implementing Design Guidelines effectively. Poor simulations increase the reliance on human expertise, exacerbating the Lack of Engineers with AM Experience.



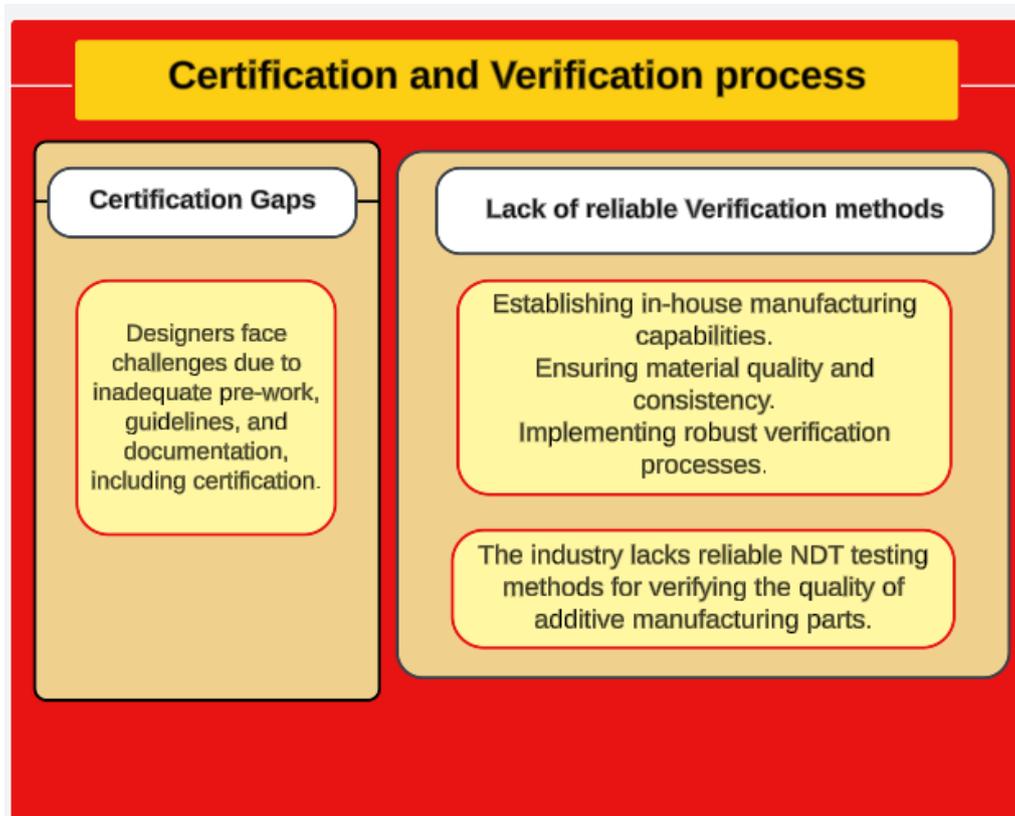
**Figure 4.10:** Communication and knowledge transfer

The figure 4.10 shows communication between cross-functional teams (design, manufacturing, and testing) is often fragmented, resulting in inefficiencies.

**Sharing and Training of AM Knowledge:** There's often a lack of structured knowledge sharing, both within engineering teams and between the manufacturing floor and design engineers. As AM is a specialized field, continuous training and collaboration are essential.

**Collaboration and Communication:** Miscommunication between the design and manufacturing teams can lead to misunderstandings, delays, and suboptimal designs.

The success of AM processes hinges on effective communication. Poor communication makes it more difficult to address Design Guidelines Issues, properly utilize Simulation Software, or adapt to Machine Capabilities. It also slows the dissemination of critical AM Expertise.



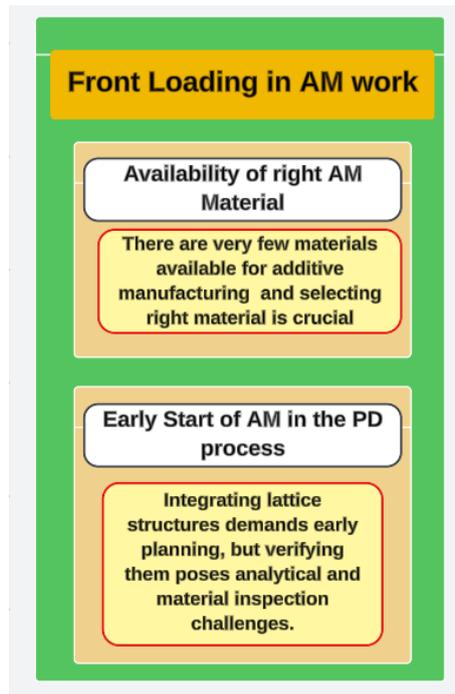
**Figure 4.11:** Certification and Verification process

The certification and verification Figure 4.11 shows of parts manufactured using AM are challenging due to the lack of standard, reliable testing methods.

**Certification Gaps:** Certifying AM parts is difficult because many certification bodies have not yet fully adapted to AM technologies. As a result, companies struggle to meet certification standards.

**Lack of Reliable Verification Methods:** Traditional Non-Destructive Testing (NDT) methods don't always work for AM parts, making it hard to verify their structural integrity.

Without reliable certification methods, AM parts may face delays in regulatory approval, particularly in industries like aerospace and healthcare. This issue directly connects to the Design Guidelines and Machine Capabilities, as these need to be aligned with certification requirements.



**Figure 4.12:** Front Loading in AM work

Starting AM integration early in the product development cycle is crucial but also challenging figure 4.12.

**Availability of Right AM Material:** There's a limited selection of materials for AM, making it difficult to integrate the right material early in the design process.

**Early Start of AM in Product Development:** Incorporating AM elements like lattice structures early in the design phase is vital for optimization. However, doing so requires a deep understanding of both material properties and machine capabilities, which can pose a significant analytical and process challenge.

The early integration of AM elements is crucial for aligning Design Guidelines, Machine Capabilities, and Simulation Software with project goals. Delaying AM considerations increases the complexity of the design process and makes it more difficult to adapt later.

These challenges are deeply connected. For example, Uncertain Machine Capabilities affect the ability to create proper Design Guidelines and to run accurate Simulations, which in turn complicates the Certification and Verification Process. Additionally, the Lack of Engineers with AM Experience impacts almost every stage of the AM process, from understanding machine capabilities to communicating across teams.

A detailed explanation of each challenge shown in the DfAM AIM diagram can be found in Appendix 2.

### 4.1.4 Benchmarking from Siemens

In the benchmarking study, it was observed that while the challenges faced were similar across organizations, a few of these challenges had already been overcome by other company. One significant challenge was the certification process. The company in interview, relied on both its internal standards and ISO guidelines. However, maintaining consistency and understanding the limitations, particularly when dealing with rough printed surfaces and varying machine tolerances, was difficult. To tackle this, the company developed an internal certification process that effectively resolved their certification issues. By establishing internal standards and aligning them with ISO requirements, they ensured their products met regulatory expectations despite the inconsistencies in surface quality and machine tolerances.

Another key challenge they addressed was the communication gap among different departments. This was resolved by fostering better coordination and collaboration among AM engineers, project leaders, designers, material experts, and even machine operators. This cross-functional approach ensured that everyone involved in the production process was aligned, minimizing miscommunication and improving overall project efficiency.

The company also took proactive steps in participating in standardization initiatives. By doing so, they contributed to the creation of uniform certification procedures and quality standards, which helped them ensure reliable and compliant manufacturing practices across their production lines.

To address the challenge of setting design guidelines and implementing quality control, the company focused on comprehensive calibration and process control measures. These controls helped them manage the variations between different printers, ensuring consistent product quality across multiple machines.

One of the issues they resolved was front-loading the AM process. By engaging experienced DfAM (Design for Additive Manufacturing) designers and AM engineers early in the design phase, they were able to identify and address potential issues, leading to more optimized designs. This early involvement of specialists allowed for better problem-solving and more efficient use of AM technology, ultimately improving the overall development process.

Through these strategies, the company successfully overcame some of the critical challenges that are common in the additive manufacturing industry.

## 4.2 Pilot Case study: Simulation software issues

### 4.2.1 Types of simulation software's

To perform the simulation for AM parts, Simufact software was utilized at GKN and Chalmers university. Initially parts were designed in Siemens NX CAD software. For simulating the additive manufacturing process, Simufact was utilized. This has been provided both by GKN Aerospace and through Chalmers University of Technology. Initial design of the part was based on Siemens NX, while support structures have been designed in two primary tools, Magics and NX Additive. Magics was chosen for the advanced support generation capabilities and its user-friendly interface, allowing complex support geometries to be generated with ease. NX Additive provided an integrated range of tools within the Siemens NX environment, which made the transition from part design to support structure design nearly seamless. This allowed the attainment of optimal support structures relating to the printing process.

Process simulation of the AM build was done with Simufact. This simulation became imperative in order to predict and avoid some expected potential issues, like distortions or residual stresses, which the printing process could give way to. The reasons for selecting Simufact were its detailed mechanical simulation capabilities, together with its already existing use at GKN Aerospace. The simulations only addressed mechanical aspects; the main results of the simulations thus yielded information concerning stress distributions, deformations, and possible failure points.

### 4.2.2 Types of Support structures

There are different types of support structures available in AM. This section aims to focus on support structures used in the simulation process for PBF-LB which are Block support, Tree-like support, Line support and Lattice support.

In PBF-LB, support structures are essential to ensure the printed parts have better integrity and quality. To avoid necessary overhang in parts it is required to provide necessary support, which can reduce heat dissipation, and prevent warping or distortion during the build process.

The types of Support structure:

1. Block Support
2. Tree-like
3. Line Support
4. Lattice Support
5. Self-supporting structures
6. Hybrid Supports
7. Cone Support
8. Contour supports

- **Block Support**

This is the simplest type of support structure, consisting of solid blocks or pillars that connect the part to the build plate.

Block supports are essentially solid cubes or rectangular like structure which provide a large contact area between the support and the part. They are relatively simple to design and generate, and offer robust support for overhanging features. However, they require a significant amount of support material, leading to increased material waste and post-processing time for removal. Additionally, the large contact area can create substantial thermal gradients and residual stresses in the part.

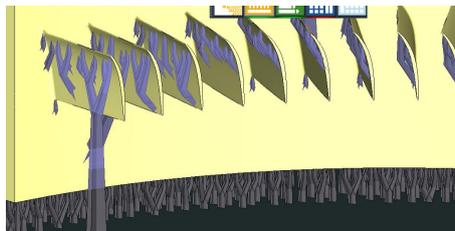
[19]

- **Tree-like Support**

Tree-like support structure also known as Gating support structure which resembles a tree-like structure with a trunk and branches. The branches connect to the part at specific points, minimizing the contact area see figure 4.13.

Tree-like supports consist of a main trunk and branches are to connected to the part at multiple points. This design reduces the amount of support's and material usage when compared to block supports. The minimized contact area allows for better heat dissipation, reducing thermal gradients and residual stresses in the part. However, these supports are more complex to design and generate, and may not provide sufficient support for large overhanging features.

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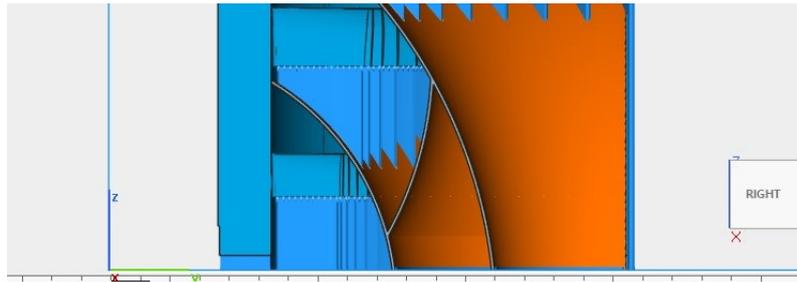


**Figure 4.13:** Tree Support

- **Line Support**

Line Support also known as Polyline support structure which consists of a series of thin lines or polylines that connects the part to the build plate see figure 4.14.

Line supports are network of thin lines that connect the part to the build plate. This design minimizes the amount of support material required and allows for good heat dissipation, reducing residual stresses. However this Line support are not like tree-like supports, they may not provide sufficient support for large overhanging features, and their design and placement require careful consideration to ensure sufficient support.

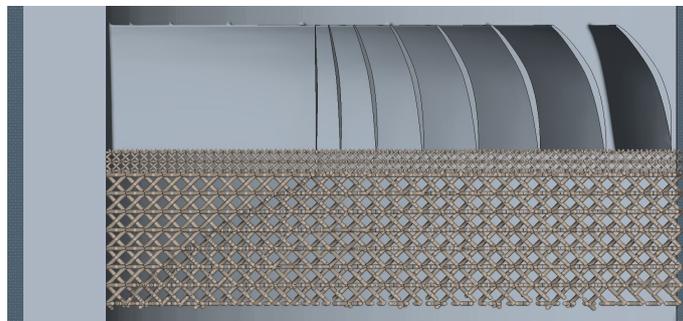


**Figure 4.14:** Line support

- **Lattice Support**

Lattice supports are a type of support structures used in AM processes like PBF-LB. They consist of interconnected bars or struts that create a scaffolding-like or lattice structures see figure 4.15.

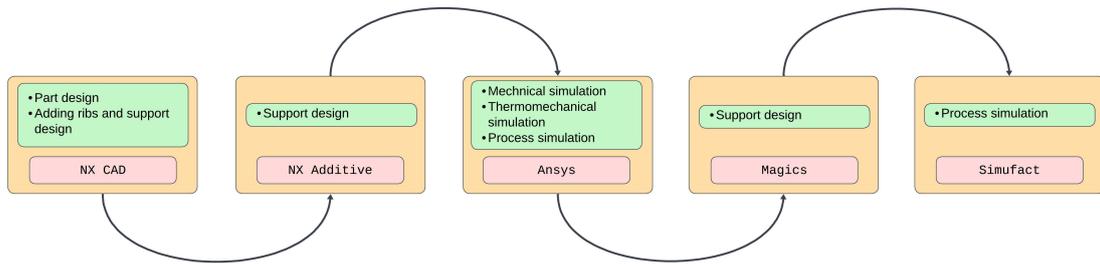
Lattice supports provide rigidity and support for parts with overhangs, undercuts, or complex geometries. They are designed to minimize the amount of support material required while still offering sufficient structural integrity. The lattice structure allows for better heat dissipation and reduced residual stresses compared to block supports. Additionally, the open design facilitates easier removal of the support material during post-processing.



**Figure 4.15:** Lattice support

### 4.2.3 Software design workflows

In the design for additive manufacturing (DfAM) process, especially for critical components like the stator part of a jet engine, the process begins with evaluating the part for overhangs in various orientations. These orientations are determined by understanding the critical features of the part—those areas where supports should not be generated to avoid damage. The goal is to orient the part in a way that supports are generated in non-critical areas, ensuring that the critical features remain unaffected during the printing and post-processing stages figure 4.16 describes the design process with different simulation tools involved.



**Figure 4.16:** Support design and simulation process flow

**Evaluation of Overhangs** The first step involves checking the part for overhangs in different orientations. Overhangs are areas that extend out from the main body of the part and are prone to sagging or warping during the printing process if not properly supported.

**Determining Critical Features** Identify the critical features of the part that should remain free from supports. For a jet engine stator, these could include the vane stages, intricate internal geometries, and mating surfaces. Understanding these critical features helps in deciding the optimal orientation for printing.

**Optimal Part Orientation** The part is oriented in such a way that minimizes the need for supports on critical features. This orientation should balance the need for structural integrity during printing with ease of post-processing. The goal is to ensure that supports are generated in non-critical areas, facilitating their removal without affecting the part's functionality.

**Initial Layer and Base Supports** Once the orientation is finalized, the next step is to define the base support structures. The initial layer of the part is usually printed at a certain height above the build plate. This separation makes it easier to remove the part from the build plate after printing.

The base supports are typically block supports, chosen for their strength and stability. Block supports provide a solid foundation for the part and help in maintaining its position during the printing process.

**Additional Support Structures** With the base supports defined, other support structures are then added as needed, based on the part's orientation and specific requirements. These supports can include lattice supports, tree supports, or other types depending on the complexity and geometry of the part.

Each type of support structure is selected based on its ability to provide stability during printing while being easy to remove during post-processing. For instance, lattice supports are useful for complex geometries, whereas tree supports can be beneficial for minimizing material usage.

**Simulation and Adjustment** Before actual printing, the support structures and part orientation are simulated using software tools to predict potential issues and optimize the design further. This step ensures that the supports will function as intended and that the critical features of the part are preserved.

**Post-Processing Considerations** Finally, the design of the support structures also considers the ease of post-processing. Supports should be easy to remove without causing damage to the part. This involves strategic placement and type selection to ensure that post-processing steps like support removal and surface finishing do not compromise the integrity of the critical features.

#### 4.2.4 File formatting

In the file formatting process for our project, we had three different approaches to ensure compatibility and optimize the workflow for simulation and support design. Each approach involved converting the part file into different formats and utilizing various software tools to achieve the desired results.

- **Approach 1: Part File to STL and Importing to Simufact**

**Initial Part File Conversion** The original part file, created in a CAD software, was converted into an STL (Stereolithography) file. The STL format is widely used for 3D printing and simulation purposes due to its simplicity and ability to represent complex geometries accurately.

**Importing into Simufact** The converted STL file was then imported into Simufact, a simulation software used for additive manufacturing. In Simufact, the part had various simulations to predict potential issues, such as deformation, thermal stresses, and other mechanical properties during the printing process.

- **Approach 2: Part File to STEP, Support Design in Magics, and Importing to Simufact**

**Part File Conversion to STEP** The original part file was converted into a STEP (Standard for the Exchange of Product Data) file. STEP files are a neutral format that facilitates the exchange of information between different CAD systems, ensuring the preservation of precise geometry and design details.

**Support Design in Magics** The STEP file was imported into Magics, a software used for support design for 3D printing. In Magics, we designed the necessary support structures tailored to the specific requirements of the part. After completing the support design, the file was exported from Magics in the 3DMF (3D Manufacturing Format), which includes both the part geometry and the designed supports.

**Importing into Simufact** The 3DMF file was then imported into Simufact. This approach allowed us to simulate the part with the designed supports in place, providing a comprehensive analysis of the printing process and potential issues.

- **Approach 3: Direct Export from NX to Simufact**

**Exporting from NX** In the third approach, the part file was handled directly within NX, a comprehensive CAD/CAM/CAE software suite. NX offers advanced tools for design, simulation, and manufacturing processes.

**Direct Import into Simufact** The part file was exported from NX and imported directly into Simufact. This streamlined approach eliminated intermediate steps, ensuring a seamless transition from design to simulation. It allowed for direct application of the support structures and facilitated efficient simulation of the part's behavior during the additive manufacturing process.

- **Each of these approaches had its own set of advantages**

**Approach 1** allowed for a straightforward conversion and quick import into Simufact, making it ideal for initial simulations and preliminary analysis.

**Approach 2** provided the flexibility to design customized support structures in Magics, which were then accurately simulated in Simufact, ensuring a detailed and optimized support strategy.

**Approach 3** leveraged the advanced capabilities of NX for direct export, reducing the need for multiple conversions and ensuring a seamless workflow.

### 4.2.5 Post-processing

In this project, the design of support structures was planned, keeping in mind the post-processing methods required for their removal. The choice of support structures was influenced by the need to balance ease of removal, the integrity of the final part, and the post-processing techniques available.

- **Manual Removal Supports**

**Lattice Supports** Lattice supports were designed for areas where manual removal was feasible. These supports, characterized by their lightweight and mesh-like structure, could be removed manually using hand tools. The ease of removal minimized the risk of damaging the part during post-processing, making them ideal for delicate or complex geometries.

- **Conventional Post-Processing Supports**

**Block Supports** Block supports were used in areas requiring robust and

sturdy support during the printing process. These solid structures provided excellent stability but necessitated more rigorous post-processing methods for removal. The techniques employed included.

**CNC Milling** CNC milling was utilized to precisely machine away the block supports, ensuring the part's surfaces remained intact and met the required tolerances.

**Line Supports** Line supports, which are simpler and more straightforward than block supports, were designed for areas where a moderate amount of support was needed. The removal of line supports also required conventional methods such as CNC milling, ensuring the clean separation of the support from the part without damaging it.

**Tree Supports** Tree supports, characterized by their branching structure, were used in specific areas where minimal contact with the part was desired. These supports, while providing adequate stability during printing, required conventional post-processing methods for removal.

#### 4.2.6 Support design considerations

**Part Geometry and Overhang Size:** Larger overhangs generally require more robust support structures.

**Material Properties:** Different materials have varying thermal properties and susceptibility to residual stresses, influencing support design.

**Build Orientation:** Optimizing the part orientation on the build plate can minimize the need for supports.

**Heat Transfer and Residual Stress Management:** Support designs should facilitate heat dissipation and minimize residual stresses to prevent deformation or cracking. Lattice and tree-like supports are often preferred.

**Post-Processing Considerations:** The ease of support removal during post-processing impacts part quality and production time. Lattice or hybrid supports may be easier to remove than solid blocks.

**Support Optimization:** Computational methods like topology optimization, genetic algorithms, and finite element analysis are used to optimize support designs, minimizing material usage and residual stresses while meeting design constraints.

### 4.2.7 Discussion of model

The model under consideration is a stator, a component of a jet engine. This stator is designed as a sectioned part, divided into two semicircular halves, each featuring three stages of vanes. The initial plan for manufacturing this model involves using PBF-LB .

**Orientation for Printing:** Proper orientation of the stator parts during the PBF-LB process is crucial. The orientation can significantly affect the quality, mechanical properties, and dimensional accuracy of the final product. By understanding the critical features of the stator, such as the vane stages and their alignment, we can determine the best orientation to minimize defects, warping, and residual stresses.

**Support Structures:** The PBF-LB process requires the use of support structures to stabilize the part during printing, particularly for overhanging features and complex geometries. Identifying the critical features of the stator helps in determining where these support structures need to be added.

**Removal of Supports:** Equally important is knowing where support structures can be strategically removed during post-processing. Effective support removal ensures that the final product meets the required tolerances and surface finish without damaging the part. This requires a thorough understanding of the part's design and its critical features, ensuring that supports are placed in accessible areas and do not interfere with the functionality of the stator.

**Post-Processing Considerations:** The placement and removal of support structures also impact the post-processing steps. Knowing the critical features helps in planning these steps efficiently, reducing the time and effort required for post-processing

### 4.2.8 Analysis of model

The model we are working with is a stator, a component of a jet engine. It is a semi-circular part with three stages of vanes. The goal is to print this stator in one go using PBF-LB .

During our discussions about the model, we realized the importance of identifying critical features that should not have supports, as these areas would require additional post-processing. One key area we identified was the leading edges of the blades. It was crucial that no supports were generated on these surfaces to avoid any post-processing that could damage them.

Understanding these requirements allowed us to start designing the model with support generation and simulation in mind. We focused on ensuring that the critical features were protected while optimizing the design for successful printing and minimal post-processing.

### 4.2.9 Comparison of support structures

Initially, we started by determining the best orientation for the stator part to avoid generating supports on the leading edges of the blades. We aimed to optimize the part's orientation to minimize the need for supports in these critical areas.

Our first simulation was conducted in Simufact, focusing on support generation and part orientation. We decided to use tree supports for this initial setup due to their effectiveness in supporting complex geometries. We used a mesh size of 3mm for the simulation.

In this simulation, we concentrated solely on mechanical aspects, aiming to evaluate total displacement and deformation under different voxel sizes. This helped us understand how the part would behave during the printing process and allowed us to make necessary adjustments to ensure successful printing and minimal post-processing.

### 4.2.10 Results of model

In our initial tests using the tree support structure, we gained valuable insights into how the part deformed during the printing process. The results showed us exactly where the deformations were occurring and how effectively the tree supports were providing the necessary support for the overhanging regions. In areas prone to sagging or warping. By analyzing these results, we were able to understand the strengths and weaknesses of the tree support structures and make informed decisions on how to refine our support strategy for better performance. This understanding was key in ensuring the final print would meet our high-quality standards with minimal post-processing required.

### 4.2.11 Case study of model

One of the objectives of this thesis was to provide solutions for the current process, which was achieved through interviews, gathering challenges, and plotting the Design for Additive Manufacturing (DfAM) diagram. Given the wide range of challenges identified, we focused on one specific issue: the file format process. To address this, we were provided with a model of a jet engine component, which served as a case study for implementing and verifying a standardized file format process.

The model was used to design the support structures in multiple software programs, with the aim of creating a standardized file format that could be seamlessly opened and utilized across different platforms. This standardization enabled consistent process simulation, demonstrating the effectiveness of the approach.

### 4.2.11.1 Explanation of CAD model

The jet engine part used in the study was a stator component, which included a three-stage stator vane with varying lengths and different numbers of vanes in each stage. To make assembly and manufacturing easier, the model was divided into a 180-degree section.

- **Simulation of model**

For the simulation, Simufact was chosen due to its use at both Chalmers University of Technology and GKN Aerospace. This software's capability to simulate the PBF-LB process made it ideal for the study. The focus was on mechanical simulations to assess deformations during the printing process.

The workflow began with importing the part file from the design software, followed by the generation of initial support structures in Simufact. As the study progressed, support design iterations were carried out using Magics and NX Additive, tools known for their advanced support generation capabilities.

The primary objective of the simulation phase was to monitor deformations in the model during the printing process and to determine the optimal mesh size for accurate results. The study aimed to gather detailed deformation data, evaluate different mesh sizes, and identify the most suitable support design for the part, ensuring minimal deformation and optimal print quality. This comprehensive approach was essential to achieving high-quality results with the least amount of post-processing required.

- **Orientation of model**

The model under consideration was a semicircular part, specifically a stator with blades. To optimize the printing process, the initial orientation of the model involved tilting it 20 degrees in both the x and y directions. This orientation was chosen to minimize the overhang angles of the blades within the stator, thereby reducing the need for extensive support structures.

This specific orientation also accounted for the recoater movement during the powder refill stage of the printing process. By ensuring a minimal cross-sectional area in the blade region, the risk of the recoater scraping against the melted part was minimized. This precaution was crucial to prevent any potential displacement or misalignment of the part during the printing process, which could compromise the integrity and accuracy of the final product.

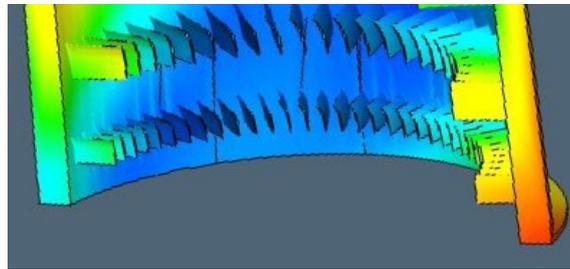
- **Support structure generation**

The initial support design for the chosen orientation incorporated tree supports, given the minimal overhang of the vanes. This choice was driven by the central part of the vanes having the least overhang compared to other sections. Tree supports were auto-generated to ensure that no supports intruded on the leading edge of the vanes, as the primary objective was to avoid any supports in this critical area. This strategy aimed to maintain the integrity and quality

of the leading edge of the blades, which are crucial for the performance of the stator.

- **Outcome of the simulation**

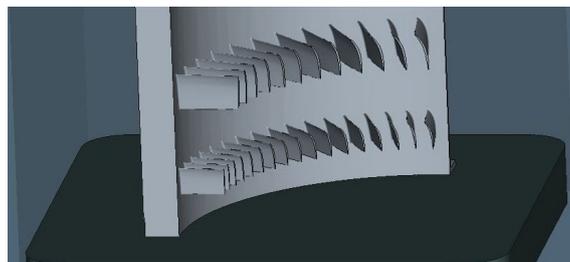
The initial analysis used a mesh size of 2mm (see Figure 4.17) to study how the part deforms. The results showed that using a smaller mesh size gave a clearer picture of the deformations happening in the part. The colors in the image represent the levels of displacement, with warmer colors showing areas of higher deformation. This finer mesh size provided a more detailed view of how the part reacted during the printing process, helping to identify problem areas and allowing for better adjustments to the support structures and overall design.



**Figure 4.17:** Simulation of tree support of 2mm voxel mesh size showcasing total displacement

#### 4.2.12 Sectioned CAD model

The 1.5mm mesh size provided better results in the simulations, but attempts to use a 1mm mesh size often led to errors. The smaller mesh size proved too large for the system to handle. To overcome this issue and continue the studies, the model was sectioned into 90-degree segments see figure 4.18. This approach allowed for more manageable simulations and provided a deeper understanding of the deformations that might occur during the actual manufacturing process. By focusing on smaller sections, the simulations could run more efficiently, offering detailed insights without overwhelming the system.



**Figure 4.18:** Sectioned 90deg model

- **Simulation of model**

Using a 1.5mm mesh size gave a clearer and more detailed view of the part's possible deformations, helping us understand the stresses better. Although the 2mm mesh size was helpful, it didn't show the finer details as well. Comparing the two mesh sizes helped us choose the best one for more accurate simulations, leading to better predictions of how the part would behave during the actual manufacturing process.

- **Orientation of model**

For the sectioned 90-degree model, the initial orientation involved tilting the model 20 degrees in both the x and y directions. This orientation minimized the overhang angle of the stator blades, ensuring that they remained as stable as possible during the printing process. The orientation was chosen to ensure that the recoater, which travels to refill the powder during printing, encountered minimal cross-sectional area. This approach was crucial in preventing the recoater from scraping through the melted part and potentially altering the part's orientation during the printing process. The careful consideration of these factors aimed to maintain the integrity and accuracy of the final printed part.

- **Support structure generation**

The support structures designed for the model included line and block supports. Given the orientation, the overhang from the blades was minimal, with the trailing edge being the primary area of concern. Line supports were suitable for these minimal overhang areas, ensuring adequate support without compromising the blades' structure. For the base part, where the model connects to the build plate, block supports were employed. These supports provided the necessary stability and strength to maintain the integrity of the part throughout the printing process, ensuring it remained securely anchored to the build plate.

- **Outcome of the sectioned CAD model simulation**

The sectioned 90-degree model provided clearer insights into deformation patterns and identified specific regions requiring pre-deformation adjustments before printing. This detailed analysis allowed for a more precise understanding of where structural changes were necessary to ensure optimal results during the actual printing process. By focusing on these critical areas, the overall quality and accuracy of the printed part were significantly improved.

### 4.2.13 Sectioned CAD model (90deg)

In the previous sectioned 90-degree model, the supports were automatically generated using Simufact, which posed a challenge due to minimal overhang on the blades' orientation. However, this orientation cannot be directly applied to the 180-degree model. The outer blades in the 180-degree model have different overhang

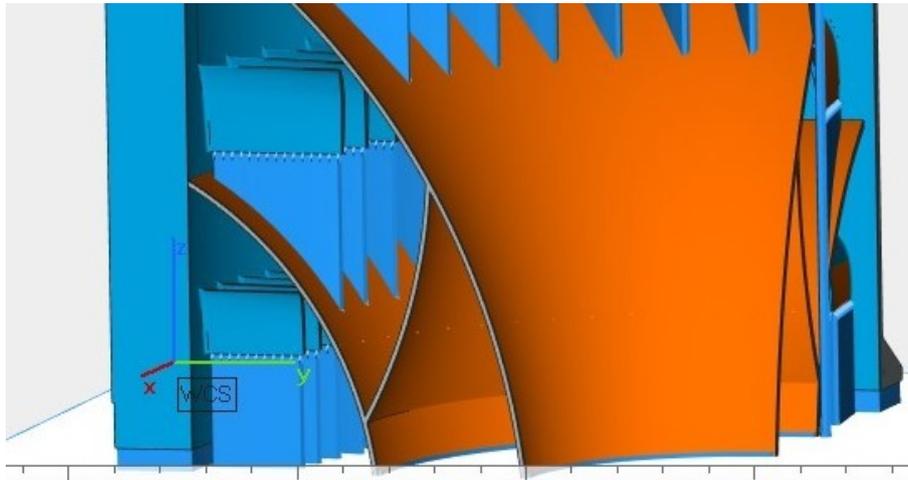
requirements compared to the sectioned 90-degree model. Despite maintaining the same orientation for both models, designing support structures for the 180-degree model required careful consideration. The goal was to avoid generating supports in areas where they could potentially cause damage or compromise critical parts of the component during printing and post-processing.

- **Designing of support structure using NX**

To design the support structure, the initial approach included an arch that extended from the base plate to the trailing edge of the blades. This design ensured that no supports were generated on the leading edge of the blade, thereby keeping them clear of any support interference.

- **Selective line support generation using Magics**

Initially, no support zone was specified for the blades in the model to prevent automatic generation or interference with the part. To address this, supports were generated from the trailing edge up to the arch designed in NX. Using of line support was appropriate because the overhang from the leading edge had a cross-sectional area of 1mm, making line support suitable for the design see figure 4.19.



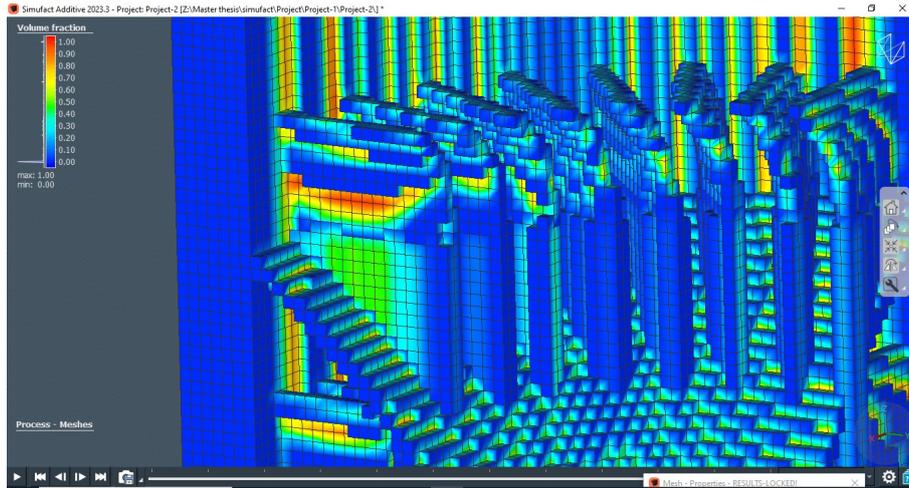
**Figure 4.19:** Line support generation using Magics

- **Selective block support generation using Magics**

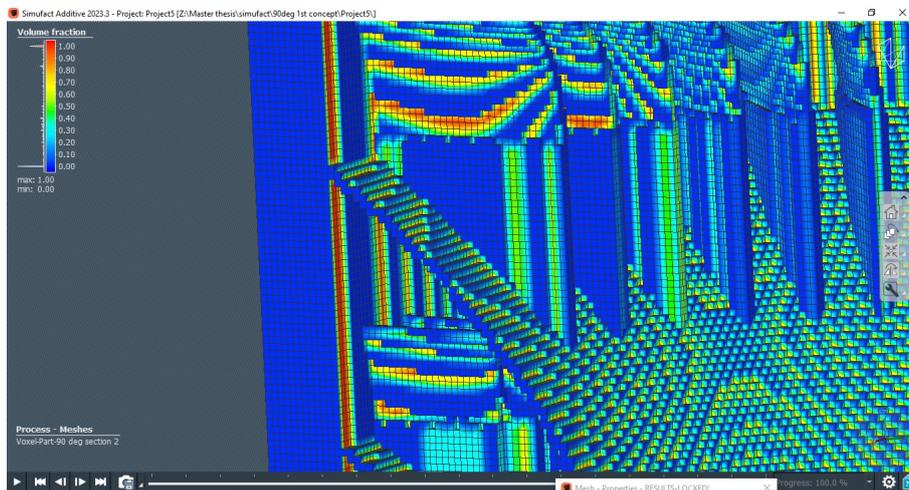
Initially, the leading edge of the vanes was isolated as an area where support did not need to be generated. This was done by defining the specific zones where line supports should not be applied. By doing so, unnecessary supports on the leading edge were avoided, ensuring a clean and efficient design. Once the line supports were appropriately positioned, block supports were used for the base of the part attached to the build plate. This approach was chosen to strengthen the part and prevent any potential warping during the printing process.

- **Simulation of model**

The simulation of the model was conducted in Simufact with an orientation of 90 degrees in both the X and Y axes, using mesh sizes of 2 mm see figure 4.20 and 1.5 mm see figure 4.21. This setup resulted in the following simulation outcomes showcasing the total displacement of mesh size 2mm see figure 4.22 and 1.5mm see figure 4.23 and total displacement in normal direction of mesh size 2 mm see figure 4.24 and 1.5mm see figure 4.25.

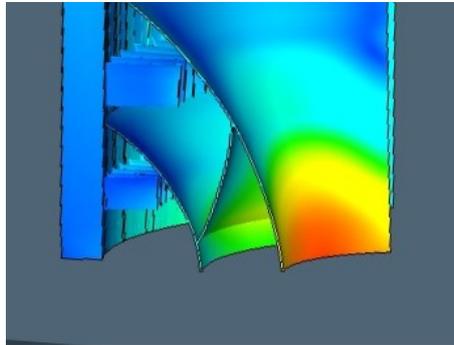


**Figure 4.20:** Voxel fraction distribution at 2 mm mesh size

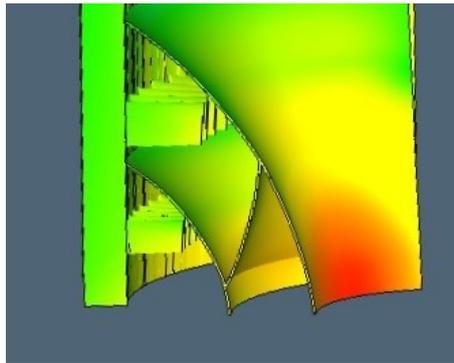


**Figure 4.21:** Voxel fraction distribution at 1.5 mm mesh size

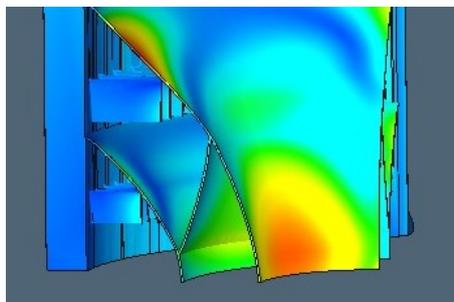
- **Outcome of the sectioned CAD model simulation**



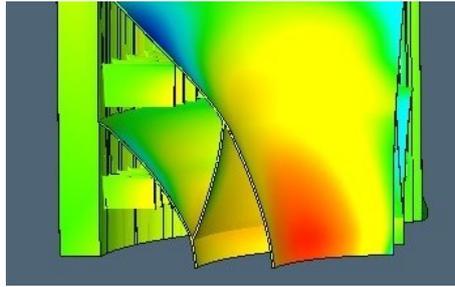
**Figure 4.22:** Simulation of sectioned model at 2 mm voxel mesh size showcasing total displacement



**Figure 4.23:** Simulation of sectioned model at 1.5 mm voxel mesh size showcasing total displacement



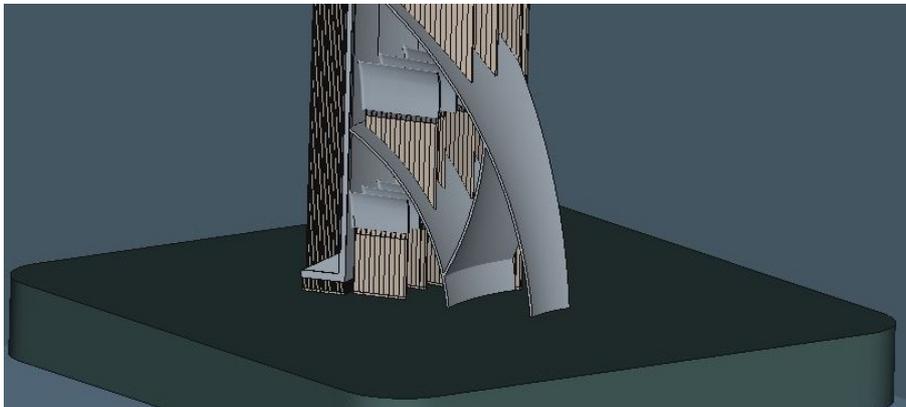
**Figure 4.24:** Simulation of sectioned model at 2 mm voxel mesh size showcasing total displacement in normal direction



**Figure 4.25:** Simulation of sectioned model at 1.5 mm voxel mesh size showcasing total displacement in normal direction

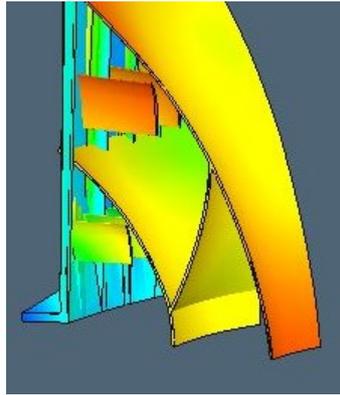
#### 4.2.14 Sectioned CAD model (30deg)

To speed up the simulation for the 90-degree section, the model was divided into 30-degree sections see figure 4.26. This approach allows for faster simulations while maintaining an effective support structure. The goal for this sectioned model was to achieve rapid simulation and efficient support design.

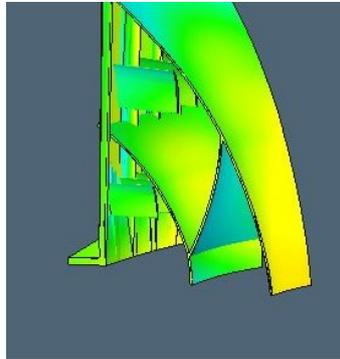


**Figure 4.26:** Sectioned 30 deg support structure

The simulation results from the 30 deg sectioned model of 1.5 mm mesh size of the total displacement shown in the figure 4.27 and the total displacement normal direction shown in the figure 4.28.



**Figure 4.27:** Sectioned 30 deg Simulation of sectioned model at 1.5 mm voxel mesh size showcasing total displacement



**Figure 4.28:** Sectioned 30 deg Simulation of sectioned model at 1.5 mm voxel mesh size showcasing total displacement in normal direction

#### 4.2.15 Sectioned CAD model (90 deg) lattice

To speed up the simulation for the 90-degree section, the model was divided into 30-degree sections. This approach allows for faster simulations while maintaining an effective support structure. The goal for this sectioned model was to achieve rapid simulation and efficient support design.

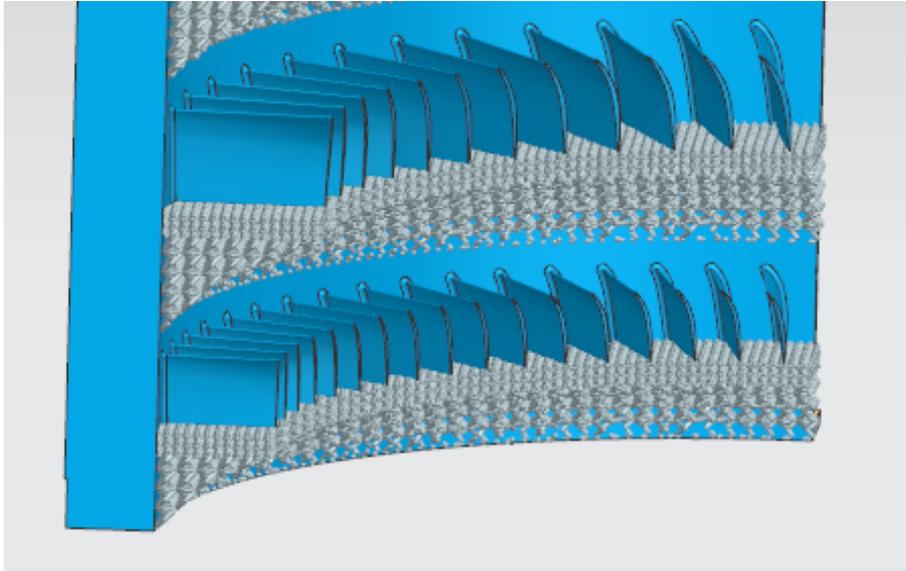
- **Designing of lattice support structure using NX**

To design a lattice support structure see figure 4.29, the initial consideration is to define the part's orientation for building. Once the orientation is set, the overhangs and areas needing support (and those that don't) are identified.

With this know parameters, a solid support structure is created from the imaginary base plate up to the overhangs. At the overhangs, the support is designed to have breakaway sections, which are split into a 5mm solid support and the rest as lattice support.

Using the NX DfAM (Design for Additive Manufacturing) feature, the solid part is then converted into a lattice support by specifying the cell size and the

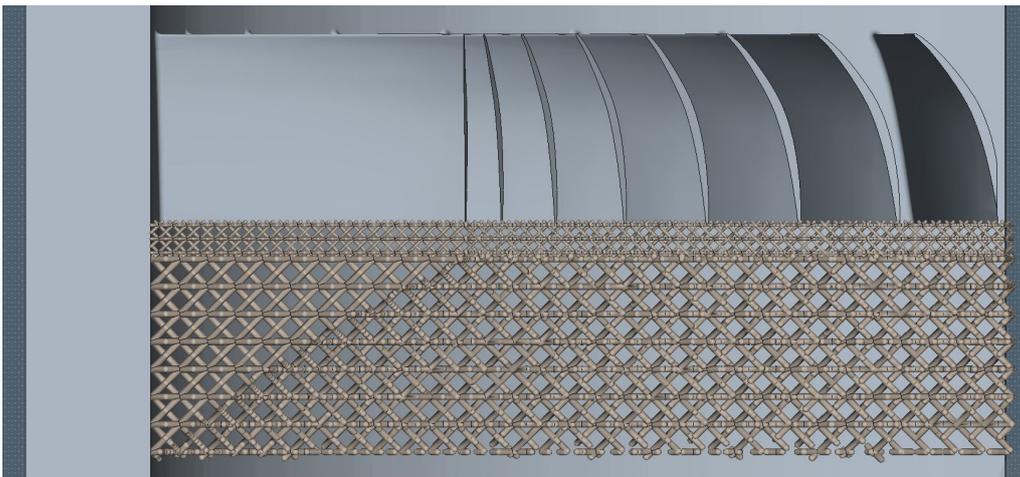
diameter of the lattice rods. If needed, a finer lattice structure or additional breakaway support can be added to the split part.



**Figure 4.29:** Lattice support structure

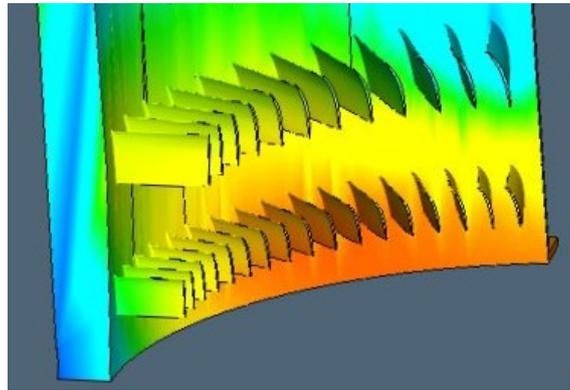
- **Simulation of model**

The simulation was performed in Simufact, as shown in Figure 4.30, with the model oriented at 90 degrees along both the X and Y axes. Mesh sizes of 2 mm and 1.5 mm were used. The results for the 1.5 mm mesh are displayed in Figure 4.31 for total displacement and in Figure 4.32 for displacement in the normal direction. The areas with more deformation are shown in darker warm colors, while lighter warm colors indicate less deformation.

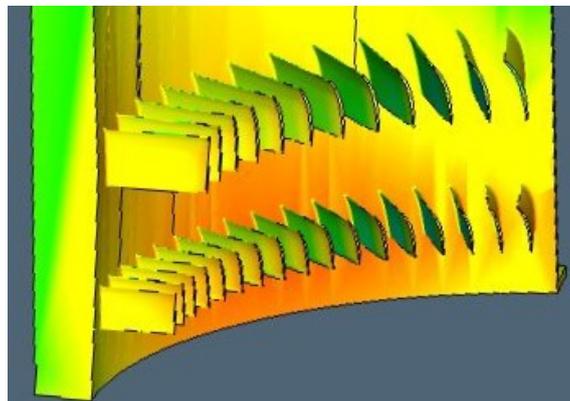


**Figure 4.30:** Lattice support structure

- Outcome of the sectioned CAD model simulation



**Figure 4.31:** Simulation of sectioned model using lattice support structure at 1.5 mm voxel mesh size showcasing total displacement



**Figure 4.32:** Simulation of sectioned model using lattice support structure at 1.5 mm voxel mesh size showcasing total displacement in normal direction

### 4.3 Comparison study of simulation results

When compared to the simulation results, the findings from the sectioned model's deformations varied notably. These differences indicate that directly comparing the deformation results of the sectioned models to those of other models may be inaccurate. Inconsistencies are caused by adjustments to the model. As a result, directly comparing deformation findings from different models may lead to incorrect results.

Where as focusing on various support structures was effective. It saved a lot of computational time because the models were symmetric. The evaluation of multiple support structures to determine which is most suitable without simulating the complete model. This streamlined the process and provided helpful insight on how to set up support for the entire model.

Further a study on mesh convergence, is required to obtain more simulation findings. This refining the mesh and seeing how the results vary as the mesh is finer. The process of sectioning the model to study deformations isn't just about the mesh size; it also accurately shows how the model behaves. A mesh convergence study will help the sectioned model's deformation findings, allowing for simpler comparison of models and improved design decisions.

# 5

## Conclusion

The aim of this thesis has been to identify and suggest improvements within DfAM at **GKN** with specific focus on working with PBF-LB technology. The primary objective was to understand the existing AM design processes, identify the challenges faced and opportunities. Additionally to perform a comprehensive comparison study on simulation software to generate support structure.

By addressing the research questions that served as the foundation of this thesis project, the primary aim has been successfully achieved. The following conclusions have been drawn to clarify the results of the study and provide comprehensive answers to the research questions.

### **RQ-1. What are the current industrial challenges in the design process for AM?**

As the design process for (AM) is still relatively new and evolving, it brings both challenges and opportunities. To identify the specific challenges within the organization, it was crucial to gather insights from those directly involved in the design for additive manufacturing (DfAM) process. This was achieved by interviewing engineers within an aerospace product development organization to identify the challenges and opportunities related to AM laser powder bed fusion development, which provided a clearer picture of the gaps and workflow issues across different department.

The results from the interviews were then transcribed and several key challenges were highlighted in the AM design process within the organization. To determine whether these challenges were unique or common across other organizations, an internal bench marking study was conducted. The study revealed that many of the challenges were indeed similar in other organizations, reinforcing the relevance and usefulness to this study.

Addressing these challenges DfAM AIM diagram was plotted figure 4.4 , and 7 main groups were identified. Out of these groups 2 were considered most critical, lack of AM engineer see figure 4.7 and certification and verification process see figure 4.11.

### **RQ-2. How can GKN improve their current process?**

There were many improvement areas that GKN can deep dive into. But given the wide scope of the DfAM AIM diagram, it was important to focus on one specific challenge within the available time frame. The chosen issue was the simulation process, where a case study was done by doing simulation on support structure generation, also considering the file formatting process.

There were some issues highlighted during the interview study about a standardized file format often resulted in losing of geometrical shapes of parts or corrupting the file, with no clear way to trace these errors back to their source. To fix this, a standardized file format was created and intended to be used during both the support structure design and simulation stages, ensuring consistency throughout the study.

Various approaches were explored to optimize the support structure design for better simulation outcomes. Due to the large size of the model, obtaining simulation results was challenging. To overcome this, the model was divided into sections, and simulations were conducted on these smaller parts. This method reduced the time required to obtain results and allowed for finer mesh resolution, leading to more accurate predictions in the process simulation.

It was not a good approach to section the model as the results can vary from the full size model. The analysis compares different types of support structures in order to save computational time. However, more analysis is needed to confirm this study. However, setting a standardized simulation platform can improve collaboration between departments and its can help organization to improve in future.

## **5.1 Future Study**

For future studies, there are several areas to explore. The DfAM AIM diagram identified seven challenge groups, and one of these groups was explored for the case study. Therefore, future research could focus on addressing the remaining six challenge groups.

Additionally, another area for future study is the use of lattice support structures. These structures can help optimize support designs for complex overhangs and reduce the time needed for post-processing.

Finally, a Cause and Effects diagram was created as can be found in figure A.4. This diagram can be a good help when working through the robustness of a design. This work was not finalized, and should therefore be concluded by another work.

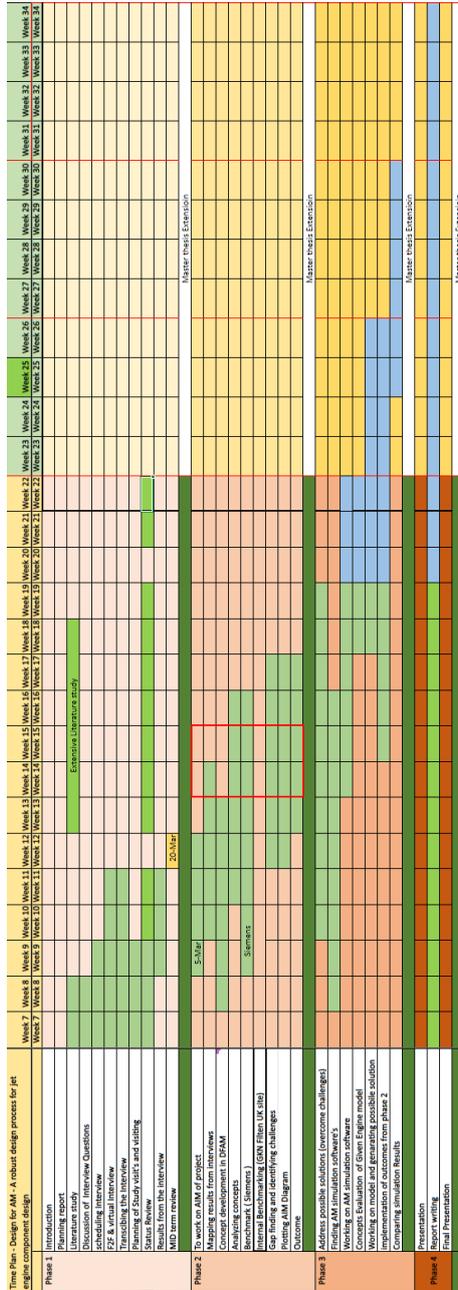
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# A

## Appendix 1



SL-NO	Position at GKN	Product Development					Additive Manufacturing					Design for AM							
		PD process	collaboration	certification	Robust design	Main industrial	Suggestions	Simulation	Materials Guideline	Machine specification	POST-Processing	Quality control	Support structures	Design practices	Guidelines and	Design review	file format	Design optimization	Requirements
1	Design GTC																		
2	Design GTC																		
3	Design Space turbine, lot of experience																		
4	Material specialist AM (Quality Analysis)																		
6	Manufacturing simulations, PD																		
7	Design PD, RISE																		
8	Permanova Manufacturing Lead																		
9	Project manager FLPP																		

Figure A.2: Data Gathering

SLNO	Position at GM	Challenges from Interview								
		CHALLENGE 1	CHALLENGE 2	CHALLENGE 3	CHALLENGE 4	CHALLENGE 5	CHALLENGE 6	CHALLENGE 7	CHALLENGE 8	CHALLENGE 9
1	Design GTC	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Nothing close collaboration between design and manufacturing teams, including conceptual design, to understand and address manufacturing limitations.	Transitioning from manufacturing to AM requires a benchmarking study.	Difficult departments use varied methods for material surface finish.	Challenges include managing support structures, evaluating material strength, and ensuring parts remain manufacturable after printing.	Downside opportunity for AM is the automation of the manual manufacturing machine and process capabilities.	Enables optimizing part orientation, nesting, and tooling to reduce material waste and ensure seamless transitions.	Increasing the volume of additive manufacturing (AM) experts is essential. Adjusting to different file formats, which can present challenges.	How to use AM to create parts, assemble, and create a unified platform to streamline iterations within a single software.
2	Design GTC	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	Correct part positioning is essential to ensure proper orientation and self-supporting features.	Flow charts and additive manufacturing (AM) design principles contribute to improved outcomes.	Engaging in discussions with AM operators is essential.	Adjusting to different file formats, which can present challenges.	How to use AM to create parts, assemble, and create a unified platform to streamline iterations within a single software.
3	Design Space turbine, lot of experience	Identify critical features and account for potential deformations. Choose collaboration experts aligned on project goals.	A shortage of manufacturing engineers restricts their participation in product development.	Manufacturing influences surface quality yet designers must prioritize robust design.	Difficult departments use varied methods for material surface finish.	By collaborating with simulation specialists, designers can identify and address areas of concern.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.
4	Material specialist AM (Quality Analyst)	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	It's crucial to select the right AM for additive manufacturing to ensure optimal results.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.
5	Manufacturing simulations, PD	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	Design engineers must understand tolerance and printing tradeoffs to address manufacturing requirements.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.
6	Design PD, BSE	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	Design engineers must understand tolerance and printing tradeoffs to address manufacturing requirements.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.
7	Design PD, BSE	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	Design engineers must understand tolerance and printing tradeoffs to address manufacturing requirements.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.
8	Performance Manufacturing Lead	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	Design engineers must understand tolerance and printing tradeoffs to address manufacturing requirements.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.
9	Project manager FLP	Designers must grasp AM increase for potential deformations. Choose collaboration experts aligned on project goals.	Challenge emerge from inconsistent AM capabilities and the need to compare the validation process.	Manufacturing influences surface quality yet designers must prioritize robust design.	Different departments use varied methods for material surface finish.	Design engineers must understand tolerance and printing tradeoffs to address manufacturing requirements.	Iterations are crucial for improvement gains in the machine aid in identifying the optimal design space.	Checking test piece helps when data is missing.	In additive manufacturing (AM), modifying parts for manufacturing can impact the surface quality required for requirements.	Part orientation is critical, and effective communication with the manufacturer is essential.

Figure A.3: Elimination matrix

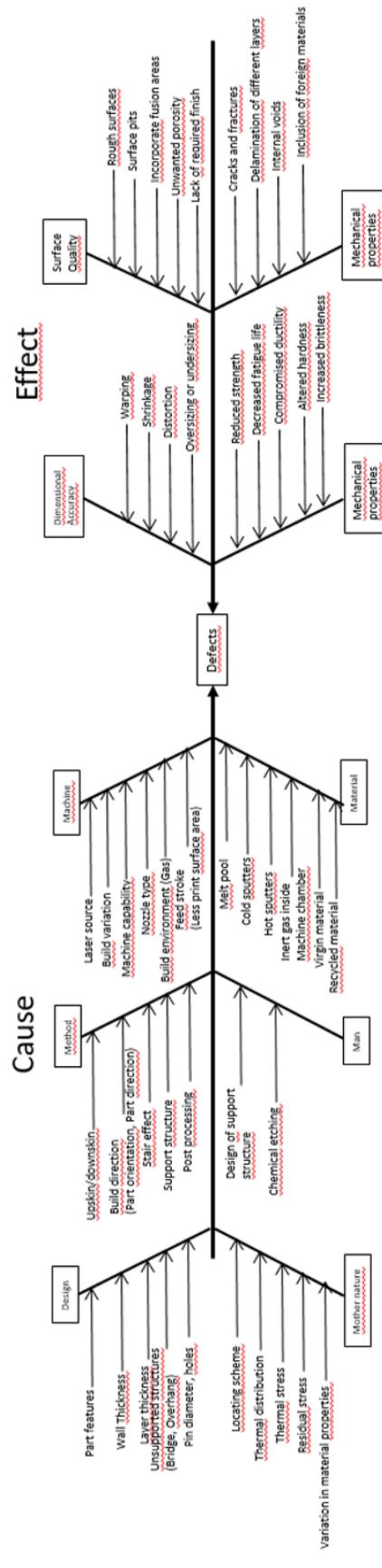


Figure A.4: Cause and effect Diagram

## A.1 Interview Questions

- **Product Development**

1. How is manufacturing influencing PD?
2. How is Zero Defect and Robustness influencing PD?
3. How can topology optimization and lattice structure methods be integrated with AM to create novel and optimal solutions for aerospace problems?
4. How can the multi-material and multi-functional capabilities of AM be utilized for aerospace components?
5. What are the opportunities and limitations for the creation of optimal designs?
6. How do you conclude the development of a topology optimized design model?
7. How does the collaboration between inter-departments function in the context of Design for Additive Manufacturing (DfAM)?
8. How does the integration of manufacturing, zero defects, optimization, multi-material functionalities, and inter-departmental collaboration influence optimal aerospace designs in additive manufacturing?

- **Design for AM**

1. Do designers verify the orientation of the build surface of the part before initiating the design process?
2. Is generative design consistently applied in Additive Manufacturing, or does it vary based on the part characteristics?
3. Do designers face limitations imposed by the build volume of the Additive Manufacturing machine when creating part designs, and if yes, what consequences may arise?
4. How the initial development of part is design compared to casting and additive manufacturing?
5. How do designers handle orientation, generative design variation, AM machine volume constraints, and initial design differences between casting and AM?

- **Additive Manufacturing**

1. What challenges do you see by applying AM to Aero-engine products?
2. Do you have experience of AM?
3. How can the post-processing of AM parts be minimized or eliminated to reduce the cost and time of production?
4. How can the certification and standardization of AM parts be achieved for aerospace applications?
5. How can the AM process parameters be optimized and monitored to ensure the repeatability and reliability of the printed parts?

6. What challenges arise in applying AM to aero-engine products, and how can strategies address post-processing, certification, standardization, and process parameter optimization for repeatability and reliability?
7. What is the current slicing software used?
8. What are the current AM simulation software's used?
9. How are designers specifying the resolution of the printed part?
10. What is the connection between slicing software and machine software in the context of Additive Manufacturing?
11. Are you obligated to utilize proprietary software provided by the Additive Manufacturing machine manufacturer?
12. Do the design engineers check the part after the printing of part? What methodology do keep while inspecting the part?
13. What software and methodologies are used in additive manufacturing, covering slicing, simulation, resolution setting, machine software integration, and post-print inspection?

## A.2 Benchmarking Interview Questions

- **General Questions**

1. What process or methodology does Siemens follow for DfAM?
2. Is DfAM done in a single platform software or multiple?
3. How do you adhere to file format changes?
4. Does Siemens have concurrent engineering methodology?
5. How do you achieve repeatability in DfAM?
6. What are the reliable NDT testing methods for AM parts?
7. What are the simulations conducted before the part is printed?
8. Who are your competitors in this field?
9. What are the industrial challenges associated with DfAM?
10. How do artifacts contribute to the benefits of DfAM?

- **Product Development**

1. How is Zero Defect and Robustness influencing PD?
2. How can topology optimization and lattice structure methods be integrated with AM to create novel and optimal solutions for aerospace problems?
3. What are the opportunities and limitations for the creation of optimal designs?
4. How does the collaboration between inter-departments function in the context of Design for Additive Manufacturing (DfAM)?

- **Additive Manufacturing**

1. What challenges do you see by applying AM to your products?

2. How can the post-processing of AM parts be minimized or eliminated to reduce the cost and time of production?
3. How can the certification and standardization of AM parts be achieved for your applications?
4. How can the AM process parameters be optimized and monitored to ensure the repeatability and reliability of the printed parts?
5. What are the current AM simulation software's used?

- **Design for AM**

1. How can AM be properly considered and worked during Design of a component?
2. Do you know of certain software or methods that can be used?
3. How should designers adapt or change their way of working to a process where additive manufacturing is an integrated part?
4. Do designers verify the orientation of the build surface of the part before initiating the design process?
5. Is generative design consistently applied in Additive Manufacturing, or does it vary based on the part characteristics?





# B

## Appendix 2

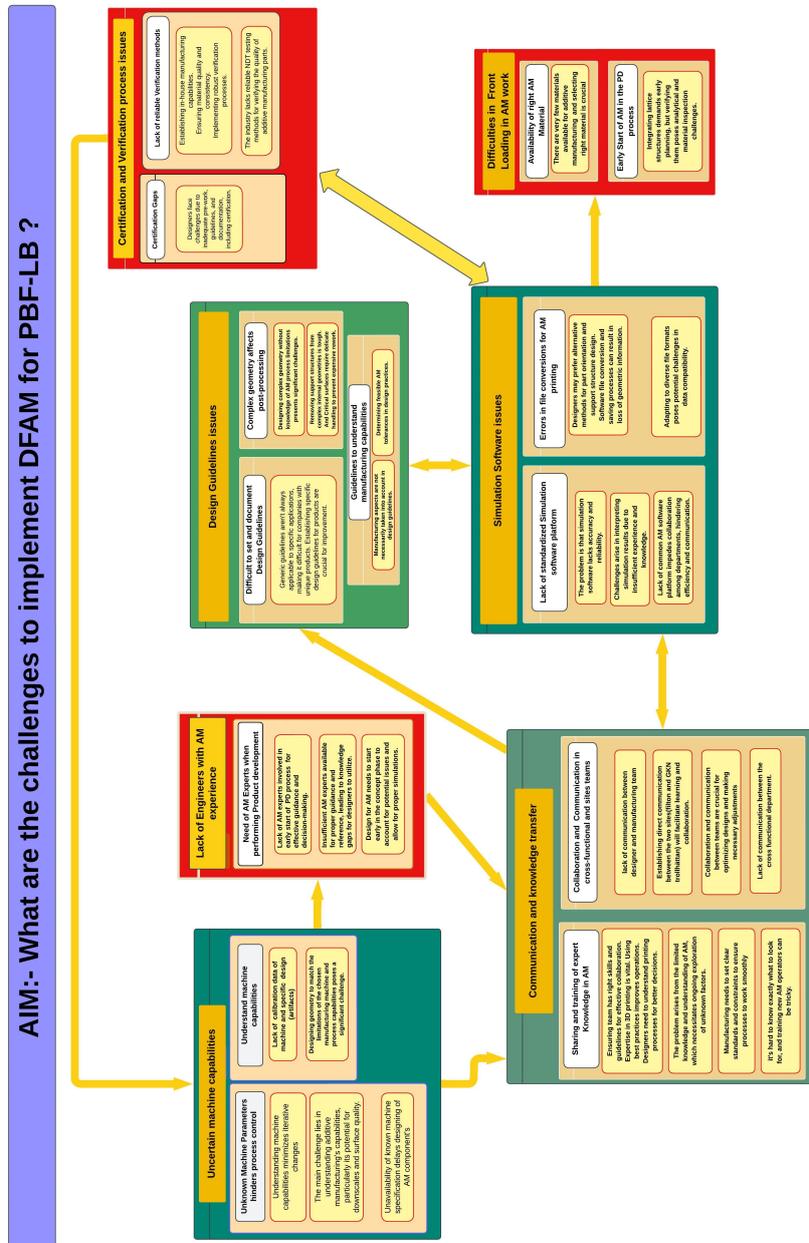


Figure B.1: DfAM AIM diagram process flow

## B.1 Uncertain machine capabilities

In this group figure 4.6 , there are two sub groups , defining the challenges occurred which were highlighted by most of the interviewees . Uncertain machine capabilities concerning the parameters, artifacts, build angle , over-hang angle, etc. These challenges are faced when test samples are being printed or artifacts are being developed to test the machine capability.(Interviewee E & Interviewee B )

### B.1.1 Unknown Machine Parameters hinders process control

In the Interview study, we came across many challenges related to AM, but specifically few challenges were related to AM machines.

- **Challenge-1** Understanding machine capabilities minimizes iterative changes.

AM is a manufacturing process which is still immature and is a growing industry. According to Interviewee E & K understanding the capabilities of the PBF-LB machine is crucial for efficient design. Exploring processes enabling lower build angles could unlock more design possibilities.

- **Challenge-2** The main challenge lies in understanding additive manufacturing's capabilities, particularly its potential for down skin and surface quality.

The focus is to develop a design process which is process-centric, rather than machine-specific. Knowledge gained from one type of machine, like powder bed fusion (PBF), can often be applied to others machines provided by different hardware manufacturers. While each process may have its nuances, the fundamentals remain similar. For instance, designing for Powder Bed Fusion – Laser Beam can be translated powder bed fusion with electron beam, but processes are very different and hence different limitations needs to be considered.

- **Challenge-3** Unavailability of known machine specification delays designing of AM component's.

According to interview study, most of the employees were unaware of machine specification. These parameters are very important in order to print, but in DfAM, it is important to know machine specification to design the Component. Interviewee C, B, D and J suggested Design practices should be tailored to specific machines to understand their constraints.

### B.1.2 Understand machine capabilities

- **Challenge-4** Lack of calibration data of machine and specific design (artifacts).

According to interview study, there is need of machine specification data to develop test pieces or artefacts. In the company, manufacturing engineers, develop test pieces to analyze the machine with different angles over angles and to create a new set of data according to Interviewee H .

- **Challenge-5** Designing geometry to match the limitations of the chosen manufacturing machine and process capabilities poses a significant challenge.

Interviewee B expressed the concern on designing the component and print the component on different machines of different manufacturers. Since there is a significance, challenge and limitations to print the component with the same accuracy level. Its reproducibility problem – since different manufacturers use different more hardware and process parameters.

## B.2 Lack of Engineers with AM experience

### B.2.1 Need of AM Experts when performing Product development

- **Challenge-6** Lack of AM experts involved in early start of PD process for effective guidance and decision-making Figure 4.7.

Several employees agreed that the availability of AM engineers in product development phase is necessary.

According to interviewee H and K , the company has to bring AM engineers to support the product development. Interviewee B , D, and I, expressed that AM engineers often guides in decision making for printing. However, there is a shift as Design engineers, learn more about the process, allowing them to take responsibility of both process and functionality.

- **Challenge-7** :Insufficient AM experts available for proper guidance and reference, leading to knowledge gaps for designers to utilize.

A challenge identified by Interviewee I is that there is a lack of sufficient expertise developing a component for DfAM. Lack of Communication between design team and AM engineering and manufacturing . As AM requirement are unclear whether all designers need AM knowledge of specific AM engineers should be hired.

- **Challenge-8** Design for AM needs to start early in the concept phase to account for potential issues and allow for proper simulations.

The issue of lacking components designed for AM is something that was clearly identified when analyzing the interviews. The identified challenge from the interview study is that the components available at the company are not designed

for AM. Interviewee A, B, C, and K express this challenge about developing new components specific for DfAM. By following all the stages of product development. Interview H also explains that the simulation of component should be done in concept development stage to have a good analysis and view on the concept development which helps to mitigate further issues.

## B.3 Design Guidelines issues

During the interview study Figure 4.8, it became evident that many of the employee at the company expressed their view on design guidelines and that they can be very specific for different products due to their complexity. Below further explanation of these challenges is given.

### B.3.1 Difficult to set and document Design Guidelines

- **Challenge-9** Generic guidelines aren't always applicable to specific applications, making it difficult for companies with unique products. Establishing specific design guidelines for products are crucial for improvement.

Interviewee K expressed that the main challenges in AM design are the lack of industry experience and established guidelines. Engineers often face "first-time" situations, leading to repeated mistakes. Generic guidelines aren't always applicable to specific applications, making it difficult for companies with unique products. Establishing specific design guidelines for products is crucial for improvement. Starting with best practices and gradually incorporating design practices into operations is essential for progress.

### B.3.2 Complex geometry affects post-processing

- **Challenge-10** Designing complex geometry without knowledge of AM process limitations presents significant challenges.

While designing parts for AM, having knowledge of DfAM process is important. Currently, the designed parts are made for traditional process rather than for AM specific (Interviewee G and B). The current knowledge gap leads a significant challenge in understanding the product development process for AM and by considering major parameters while designing.

- **Challenge-11** Removing support structures from complex internal geometries is tough and Critical surfaces require delicate handling to prevent expensive rework.

The support structure removal remains a challenging task for AM parts. The design of components should be AM specific requirements and decisions about the manufacturing process & post processing are made along-side in initial phase of design considerations. Orientation of parts is iterated many times to

accommodate support structures while minimizing surface quality degradation and porosity ( Interviewee B ).

Interviewee B also expressed that the challenge lies in predicting and mitigating potential defects which may occur beneath support structures, requiring careful planning and consideration throughout the design and manufacturing process.

### B.3.3 Guidelines to understand manufacturing capabilities

- **Challenge-12** Manufacturing aspects are not necessarily taken into account in design guidelines.

Current design guidelines seem to prioritize mechanical verification over manufacturing considerations. This results in designs that may be mechanically sound but not optimized for manufacturing processes. Incorporating manufacturing aspects in design guidelines is crucial for ensuring that parts can be efficiently and cost-effectively produced. Without this integration, there is a risk of creating designs that are difficult or expensive to manufacture, leading to inefficiencies and increased production costs(Interviewee E).

- **Challenge-13** Determining feasible AM tolerances in design practices.

Interviewee K and B expressed that, AM introduces specific challenges in determining feasible tolerances due to its unique processes and material behaviors. Traditional design practices may not fully address these AM-specific tolerances, leading to parts that do not meet desired specifications or performance standards. To enhance the effectiveness of design for AM, it is essential to establish guidelines that accurately reflect feasible tolerances, ensuring that parts are both manufacturable and functional within the required precision.

## B.4 Certification and Verification process issues

### B.4.1 Certification Gaps

- **Challenge-14** Designers face challenges due to inadequate pre-work, guidelines, and documentation, including certification Figure 4.11.

Interviewee C emphasized that, Designers often struggle due to insufficient pre-work, unclear guidelines, and lack of comprehensive documentation, which includes certification processes. Close collaboration between design and manufacturing teams is essential to address these gaps. Forming cross-functional teams comprising design experts, AM specialists, process engineers, and post-processing professionals can help bridge these knowledge gaps. This collabo-

rative approach ensures that designers are aware of manufacturing limitations and requirements, leading to more efficient and feasible designs.

Interviewee I & J, Designers also need to meet not only initial design requirements but also consider aspects such as NDT, post-processing, and quality assurance. Expanding the pool of AM experts and ensuring that designers have access to detailed guidelines and documentation can help in aligning design outcomes with product requirements, as seen during critical design reviews. Understanding machine parameters and limitations through close collaboration with manufacturers can mitigate risks like build failure or component deformation, ensuring robust designs that can withstand manufacturing processes without compromising quality.

#### **B.4.2 Lack of reliable Verification methods**

- **Challenge-15** Establishing in-house manufacturing capabilities. Ensuring material quality and consistency. Implementing robust verification processes.

Interviewee G & F indicate importance of, developing in-house AM capabilities involves understanding machine parameters and limitations, which influence design and production efficiency. Key considerations include build plate size and the interaction of multiple parts during printing, as overloading can lead to build failures or deformations. Interviewee K said that, ensuring material quality and consistency is vital, as different manufacturing processes can affect surface quality and structural integrity. Implementing robust verification processes, such as NDT, is essential to maintain high-quality standards. Designers must work closely with manufacturers to adapt designs for manufacturability, ensuring they can withstand manufacturing processes without defects.

- **Challenge-16** The industry lacks reliable NDT testing methods for verifying the quality of additive manufacturing parts.

Interviewee K, Most of the AM industry faces a significant amount of challenge in verifying the quality of parts due to insufficient reliable NDT methods. Mainly techniques like X-ray and CT scans are used more often, but have some limitations in resolution and cost, making them less effective for AM parts. Additionally, the unique micro-structure of AM parts differs from traditional manufacturing, rendering existing defect charts unreliable. This gap in reliable NDT methods hampers the ability to detect issues such as cracks, which often form after multiple layers during printing. Addressing this challenge requires developing validated NDT techniques that can accurately assess the quality of AM parts, ensuring their integrity and performance.

## B.5 Communication and knowledge transfer

### B.5.1 Sharing and training of expert Knowledge in AM

- **Challenge-17** Ensuring team has right skills and guidelines for effective collaboration. Expertise in 3D printing is vital. Using best practices improves operations. Designers need to understand printing processes for better decisions Figure 4.10.

Effective collaboration between design and manufacturing teams requires a solid understanding of 3D printing. Forming cross-functional teams with design experts, AM specialists, process engineers, and post-processing professionals ensures designers are aware of manufacturing limitations and best practices. This collaborative approach supports informed decision-making and enhances operational efficiency. Expanding the pool of AM experts and providing clear guidelines helps bridge knowledge gaps, ensuring that outcomes presented during design reviews align closely with product requirements.

- **Challenge-18** The problem arises from the limited knowledge and understanding of AM, which necessitates ongoing exploration of unknown factors.

AM is a relatively new field, and its continuous evolution means there are still many unknown factors (Interviewee H). Limited knowledge and understanding of AM processes and materials can lead to design and manufacturing challenges. Ongoing exploration and research are necessary to address these gaps. Collaboration between different teams and consistent support from dedicated AM specialists can help navigate these unknowns, leading to better-informed decisions and innovative solutions.

- **Challenge-19** Manufacturing needs to set clear standards and constraints to ensure processes to work smoothly

Interviewee E emphasized importance, to ensure smooth manufacturing processes, it's crucial to establish clear standards and constraints. Understanding machine parameters and limitations, such as build plate size and part orientation, helps avoid issues like build failures or deformations. Clear guidelines and communication between designers and AM operators ensure that critical surfaces are correctly identified and managed. Setting these standards helps streamline operations and maintain quality across different AM projects.

- **Challenge-20** It's hard to know exactly what to look for, and training new AM operators can be tricky.

Training new AM operators is challenging due to the complexity and novelty of AM processes. Knowing what to look for in terms of potential issues like cracks or deformations requires a deep understanding of AM. The development of

reliable inspection techniques and clear guidelines can aid in training operators effectively (Interviewees K, B, & D). Close communication with experienced AM specialists and iterative learning from simulations and real builds can help new operators gain the necessary skills and confidence to manage AM processes successfully.

### **B.5.2 Collaboration and Communication in cross-functional and sites teams**

- **Challenge-21** Lack of communication between designer and manufacturing team.

Effective communication between designers and the manufacturing team is crucial for ensuring that designs are manufacturable and meet quality standards. Currently, there is a significant gap, with manufacturing engineers often unable to fully engage in the product development process due to limited time and resources. This communication gap results in delays and potential misalignments in design and manufacturing requirements, leading to inefficiencies and rework. Improving communication channels and collaboration between these teams is essential for timely and effective design adjustments and optimizations.

- **Challenge-22** Establishing direct communication between the two sites (Filton and GKN Trollhättan) will facilitate learning and collaboration.

Direct communication between the Filton site in England and GKN Trollhättan is vital for facilitating learning and collaboration. The current lack of direct interaction hinders the exchange of knowledge and expertise, which is essential for addressing uncertainties and refining manufacturing processes. By establishing direct communication channels, both sites can collaborate more effectively, share insights, and ensure that the transition of responsibilities is smooth, leading to improved manufacturing outcomes and innovation.

- **Challenge-23** Collaboration and communication between teams are crucial for optimizing designs and making necessary adjustments.

Close collaboration and communication between design, simulation, and manufacturing teams are essential for optimizing designs and making necessary adjustments. This collaborative approach helps identify problem areas early in the process, ensuring that parts are designed to withstand manufacturing processes and meet quality standards. Integrating the expertise of simulation specialists and manufacturing engineers can enhance the accuracy of simulations and refine designs to match the intended final product, thereby improving overall efficiency and product quality.

- **Challenge-24** Lack of communication between the cross functional depart-

ment.

The absence of effective communication between cross-functional departments leads to inefficiencies and missed opportunities for optimization. Different departments, such as design, simulation, and manufacturing, often operate in silos, hindering the flow of information and collaborative problem-solving. Establishing a standardized, step-by-step communication approach and ensuring that all relevant departments are closely collaborating with AM experts can bridge these gaps. This unified approach helps in aligning goals, sharing insights, and leveraging collective expertise to enhance the overall design and manufacturing process.

## B.6 Simulation Software issues

### B.6.1 Lack of standardized Simulation software platform

- **Challenge-25** The problem is that simulation softwares lacks accuracy and reliability.

Currently, simulation software like Simufact are used for process simulations, but its accuracy and reliability are not always sufficient (Interviewee K). This limitation affects the ability to predict and manage manufacturing outcomes effectively. While exploring alternatives like Amphyon, Ansys Workbench, and other simulation software is a key goal to find software that can provide more reliable and precise simulations (Interviewee B& D). Accurate simulations are crucial for optimizing additive manufacturing (AM) processes and ensuring high-quality results.

- **Challenge-26** Challenges arise in interpreting simulation results due to insufficient experience and knowledge.

Running simulations is relatively straightforward, but interpreting the results requires substantial experience and knowledge. This challenge is compounded by the variability in expertise among different team members (Interviewee B, K & D). Even with advanced software, the ability to make informed decisions based on simulation outputs depends heavily on the user's understanding of both the software and the AM process. Training and experience are therefore critical to effectively leveraging simulation tools.

- **Challenge-27** Lack of common AM software platform impedes collaboration among departments, hindering efficiency and communication.

Different departments using various simulation software leads to inconsistencies and communication challenges (Interviewee B). This lack of a common platform prevents seamless collaboration and can result in data integrity issues, especially during file conversions. Establishing a unified software plat-

form, such as integrating Siemens Simcenter across all departments, aims to create a digital thread from design to manufacturing. This common platform would enhance efficiency, reduce data loss, and facilitate faster iterations, ultimately improving the overall workflow and collaboration between design and manufacturing teams.

### B.6.2 Errors in file conversions for AM printing

- **Challenge-28** Designers may prefer alternative methods for part orientation and support structure design. Software file conversion and saving processes can result in loss of geometric information.

Designers often seek the most effective tools for part orientation and support structure design, sometimes opting for specialized software like Magics over more comprehensive suites like Siemens (Interviewee B,C & D). This preference for alternative methods can lead to inconsistencies, especially when file conversions between different software platforms are involved. The process of converting and saving files can result in the loss of geometric information, which compromises the integrity of the design and affects the final product quality. Ensuring data fidelity across different software tools is crucial for maintaining the accuracy of complex designs.

- **Challenge-29** Adapting to diverse file formats poses potential challenges in data compatibility.

The use of various simulation and design software introduces challenges in data compatibility, as different programs often require specific file formats. For instance, reliance on STL files can complicate the integration and consistency of design data across platforms. This lack of standardized guidelines and common file formats hampers seamless collaboration among departments, leading to potential data loss or corruption (Interviewee B,C & D). Establishing a unified software platform and minimizing file conversions can help maintain data integrity, streamline workflows, and enhance overall efficiency in additive manufacturing processes.

## B.7 Difficulties in Front Loading in AM work

### B.7.1 Availability of right AM Material

- **Challenge-30** There are very few materials available for additive manufacturing and selecting right material is crucial.

In AM, the limited selection of available materials presents a significant challenge. Choosing the appropriate material is critical, as it impacts the part's performance, durability, and overall quality. To address this, close collaboration between design experts, AM specialists, and process engineers is essential. These cross-functional teams can evaluate material properties and ensure that

the selected material meets the specific requirements of the design and manufacturing process. Additionally, these teams can address knowledge gaps and provide support throughout the design process, ensuring that the chosen material is compatible with the intended application and manufacturing constraints. By expanding the pool of AM experts and enhancing communication between departments, organizations can better navigate the complexities of material selection and improve the reliability and quality of AM parts.

- **Challenge-31** Integrating lattice structures demands early planning, but verifying them poses analytical and material inspection challenges.

Integrating lattice structures into additive manufacturing designs requires careful consideration from the initial concept stage. These structures offer significant benefits, such as weight reduction and enhanced strength, but they also present complex verification challenges. Analytically, lattice structures are difficult to calculate and qualify due to their intricate geometry. This complexity extends to material inspection, where ensuring the absence of defects is particularly challenging. For instance, closed-cavity lattices can trap powder residue, complicating the inspection process. Even with open lattice designs, detecting defects remains problematic. Despite these hurdles, addressing the verification and inspection challenges is crucial for fully leveraging the advantages of lattice structures. Using tools like topology optimization and generative design software such as nTopology, designers can create sophisticated structures like gyroids and other TPMS designs. However, these tools necessitate substantial manual adjustments and verification to ensure manufacturability and performance, underscoring the need for early planning and robust inspection methods.

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