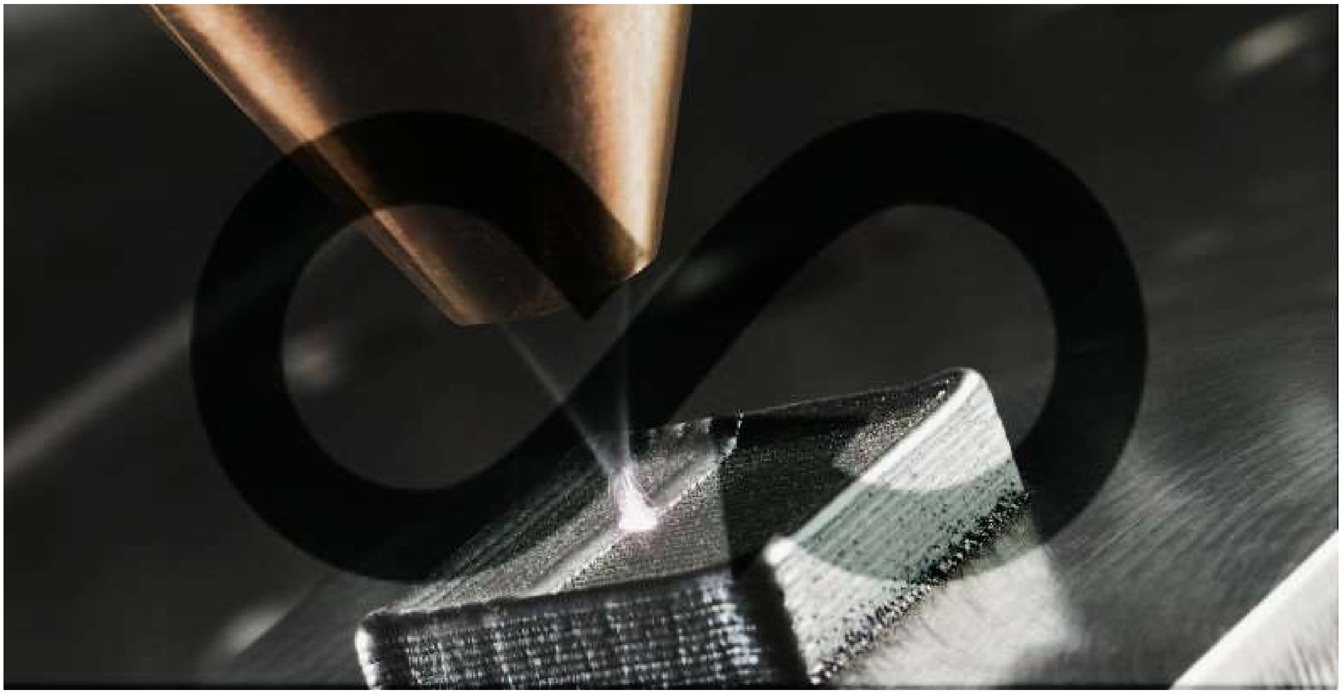

Circularity in Aero-engine components production through additive manufacturing at GKN Aerospace Sweden

Master's thesis in Industrial Ecology

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Schematic image showing a symbol representing additive manufacturing with the circular economy icon.

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Abstract

The thesis explores the potential of additive manufacturing to promote the circular economy in aero-engine component manufacturing, focusing on GKN Aerospace Sweden´s resource optimization and waste reduction. The research identifies possible circular flows for the future material flow in the aero-engine components production through additive manufacturing. The study examines GKN Aerospace's various aero-engine production methods and identifies potential circular approaches, such as the reuse and recycling of metal powders, the implementation of closed-loop systems and recommendation of circular approaches to enhance sustainability. Furthermore, the thesis elucidates the role of additive manufacturing in ReSOLVE Framework to enable circular economy principles. The research also provides recommendations for a strategy plan to incorporate Additive Manufacturing technologies (AM) into a circular economy framework within the GKN Aerospace context.

Keywords: Circular Economy, Sustainability, Additive Manufacturing, R´s strategies, Circular Indicators, ReSOLVE framework, Aero-engine components, Aerospace.

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SRI RAM GNANESH, 2024

Abbreviations

Below is the List of Abbreviations that have been used in this thesis work

3D	Three Dimensional
AM	Additive Manufacturing
CAD	Computer Aided Design
CE	Circular Economy
DED	Direct Energy Deposition
DfAM	Design for Additive Manufacturing
EIGA	Electrode Induction Gas Atomization
LCA	Life Cycle Assessment
LPBF	Laser Powder Bed Fusion
OEM	Original Equipment Manufacturer
OOS	Out Of Specification
PBF	Powder Bed Fusion
PREP	Plasma Rotating Electrode Process
VIGA	Vaccum Induction Melting Inert Gas Atomization

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1 Introduction

1.1Background

In the aerospace industry, aero-engine components need to withstand extreme temperatures, high pressure, and stress, and they also need to have high corrosive resistance and weight reduction. As a result, selecting these materials is highly valuable and expensive. Those materials are titanium alloys and nickel-based alloys. The most commonly used Ti alloy is the TI-6Al-4V alloy, which is a combination of titanium, aluminum, and vanadium. It has an excellent strength-to-weight ratio, high corrosion resistance, and can withstand high temperatures (Boyer, 1996). Titanium sponge serves as the raw material for the titanium alloy. The global production of titanium has been estimated to increase by 6.6% between 2022 and 2023 (US Geological Survey, 2024); this rate can affect the titanium resource in the upcoming years. On the other hand, nickel-based superalloys are a group of many alloys, typically composed of elements such as nickel, iron, chromium, aluminum, molybdenum, niobium, tantalum, titanium, and tungsten (Kollova, 2022). The composition of these alloys includes critical rare minerals. This underscores the significance of consuming these essential resource materials. This urges us to adopt sustainable and circular economy practices in resource and material usage.

A circular economy is a system where the resources coming into the economy are not allowed to become waste or lose their value. Instead, this economy would recover those resources and keep them in productive use for as long as possible (Benton, et al., 2017). The opposite of a circular economy is a linear economy: extract raw materials, produce goods, sell them, use them and dispose of them – which is predominantly the case at present. The environmental consequences of the linear economy are extensive and cannot be sustained in the long term. By depending on large resources and producing large quantities of waste, it leads to the loss of resources, pollution in the environment, and consumption of energy (Popović & Radivojević, 2022). This has negative impacts on ecosystems, biodiversity, and human well-being and economic security. The goal of the Circular economy (CE) is to protect the environment through the efficient utilization and recycling of natural resources. However, for CE to be widely adopted by businesses and policy makers, it is necessary to identify possible challenges, opportunities, and advantages that could benefit economies and business organizations (Kumar, et al., 2019).

GKN Aerospace is a leading global tier-one supplier of airframe and engine structures, landing gear, electrical interconnection systems, transparencies, and aftermarket services. It supplies products and services to a wide range of commercial and military aircraft and engine prime contractors, and other tier-one suppliers. GKN Aerospace Sweden is the parent company for the GKN Aerospace engine systems business group within GKN Aerospace. Based on its diverse range of capabilities and close partnerships with major aero-engine OEM’s (Original Equipment Manufacturers), GKN Aerospace leads the industry in the fabrication of advanced engine structures, cases and frames. The company provides tailored repair and overhaul services, supporting customers around the world, and also offers electric wiring solutions for propulsion systems. For two decades, the company has led the way in the application of additive manufacturing (AM), and its components are in use across numerous platforms. It can create high-performance parts out of vast, intricate geometries with this technique. All of these initiatives are a part of our dedication to improving the efficiency of the aviation sector, which is advantageous for the environment and our company.

The aerospace industry has been engaged in additive manufacturing and conducting various research endeavors aimed at advancing engine manufacturing for the future. While the potential of AM as a driver for a circular economy is well-documented in the existing literature and scientific papers, its practical implementation within an industrial setting remains a challenge and a subject of inquiry. In response to this, the company is actively exploring opportunities to integrate AM technologies into its aero-engines production processes, with a focus on fostering circularity and sustainability. The company currently employ with advanced additive manufacturing techniques for their metal components, including Laser Powder Bed Fusion (LPBF) technologies and Direct Energy Deposition (DED) methods of both powder and wire. The theoretical framework of these technologies are discussed in the next chapter providing a comprehensive explanation of these innovative technologies. The company's ultimate objective is to create a procedure that is safe, economical, and sustainable that takes into account the advantages and disadvantages of AM while developing a circular process by utilizing the technology.

The establishment of a strong theoretical foundation for this thesis was aided by the literature review and interviews. Through the analysis of the theories and models employed in previous research on additive manufacturing, a deeper understanding was obtained regarding the fundamental principles of the area. This information’s influenced the creation of the circular approach framework of the thesis. The identified circular approaches based on the literature reviews are, R-strategies, Circular Indicators, and the ReSOLVE framework.

1.2 Purpose & Scope

The thesis explores how additive manufacturing technologies can support the transition towards resource-efficient and waste-reduction aspects in the context of GKN Aerospace´s aero-engine component production. Moreover, the goals of this thesis are to look at the circular practices in the current production, identify the circular loops, and recommend strategies to improve the current production to achieve circularity.

1.2.1 Delimitations

The below section defines the delimitations of this thesis work, which include:

1. The research is carried out using data that is particularly associated with GKN Aerospace Sweden. This restriction guarantees a focused examination that is pertinent to the particular operational context of the company.
2. The thesis focuses primarily on resource efficiency and the notions of circularity in waste reduction. It doesn't discuss ideas connected to energy, emissions and economic aspects associated with the production process.
3. The scope of Additive Manufacturing concepts refers to the range or extent of ideas and principles related to the process of creating objects by adding material layer by layer. The thesis seeks to explore the underlying principles of Additive Manufacturing. The level of detail regarding the mechanisms of production processes is not extensively explored.

By setting these boundaries, the thesis guarantees a concentrated and feasible research area, enabling a thorough and contextually appropriate examination within the restrictions of time and data accessibility.

1.3 Research Questions

The main research question for this thesis is the following:

How can additive manufacturing contribute to improving resource efficiency and waste reduction in the production of aero-engine components at GKN Aerospace, and what strategies can be incorporated to achieve these improvements?

This research question aims to investigate how GKN Aerospace's aero-engine component production process could utilize AM to reduce waste and maximize resource efficiency. This includes comprehending the potential advantages of AM technologies in producing engine components with reduced material waste and enhanced production efficiency as compared to conventional manufacturing processes.

The research also seeks to find strategies that can be integrated into GKN Aerospace's production processes by examining specific additive manufacturing techniques and their applications. This requires analyzing design optimization, material utilization, production workflows, and the feasibility of recycling and reusing materials in the additive manufacturing process. The goal is to provide a thorough examination of how AM could contribute to the implementation of more sustainable and circular manufacturing methods in aero-engine production. Thus, to achieve this, quantitative and qualitative approaches of methodology are incorporated.

1. **How is GKN Aerospace enhancing circularity with their existing manufacturing methods for aero engine components?**
   This research question aims to identify the existing circular economy practices in the manufacturing of aero-engine components. The goal is to develop new

possible circular approaches to enhance the sustainability and efficiency of existing industrial practices. To address this question, material flow of the current production processes are mapped with the different R-strategies and circular indicators are calculated for material efficiency.

2. **How is additive manufacturing technology being adapted at GKN Aerospace to support resource efficiency and waste reduction throughout the value chain of aero engine components?**
   This sub-research question examines the application of additive manufacturing (AM) technology by GKN Aerospace to enhance resource efficiency and minimize waste in the production of aero-engine components. It focuses on the comparison of GKN Aerospace's present AM practices with the most recent developments in the field. The primary goal to identify and recommend strategies that can further improve the circular economy practices in the production of future aero-engine components. To address this equation, circular indicators for material resource usage are calculated and a review of the current production of AM with the ReSOLVE framework.

This chapter gives a concise overview of the research objectives and the questions it aims to answer. Chapter 2 explores the core ideas required to understand the research findings. Chapter 3 provides a comprehensive explanation of the research methods used to acquire the circular economy findings and explores the concepts created for evaluating the findings. Chapter 4 showcases the most important findings. Chapter 5 discusses the answers to every research question. Chapter 6 provides the final conclusions of the thesis. The thesis includes a list of all cited references at the end of the last chapter.

2 Theoretical Framework

The following theoretical framework provides as an introductory overview, providing valuable understanding of significant topics and technologies that are pertinent to the thesis.

2.1 Circular economy

The circular economy is a regenerative industrial system that replaces the traditional 'take-make-dispose' model with a focus on restoration, renewable energy use, toxic chemical elimination, and waste reduction through superior material and product design, promoting disassembly and reuse cycles (MacArthur, 2013). In our present economy, we extract resources from the Earth, transform them into products, and ultimately dispose of them as waste. This process follows a linear model. The linear model, despite its some advantages, has several drawbacks in terms of environmental pollution, accumulation of waste, ineffective waste management and unwise utilization of natural resources and energy, resulting in a depletion of natural capital, unsustainable development, an increase in poverty, and socio-economic inequality. In contrast to this concept, the circular economy is based on an urge to minimize all of these drawbacks (Popović & Radivojević, 2022). In a circular economy, waste generation is stopped from being generated in the first place. The circular economy is also defined as a concept aimed at promoting sustainable development through the reduction of waste and the efficient utilization of resources (Reike, et al., 2018).

The circular economy is a system receiving growing interest among scholars and professionals as a strategy to advance sustainability. The objective is to separate economic expansion from the extraction of resources and the resulting environmental damage. The basic principles of the circular economy include the preservation and enhancement of natural resources, maximizing the productivity of resources, and eliminating harmful negative effects. This paradigm entails shifting from a linear economy model characterized by the actions of extracting resources, manufacturing goods, and disposing of them to a model that emphasizes repairing, refurbishing, and recycling, with the goal of maximizing the lifespan of materials and products.

In a circular economy, companies strive to optimize the utilization of material resources while limiting the overall consumption of resources, generation of waste, release of pollutants, and emissions linked to their business operations. At the global scale, a CE could facilitate the industrialization of developing countries and the reduction of vulnerability to resource price difficulties and an increase in wellbeing in developed countries. However, it would not impose unsustainable pressure on natural resources or violate environmental limits (Preston, 2012). The majority of companies CE initiatives focus on operational enhancements including the recovery of production waste, an increase in the utilization of renewable energy. The second most common activities are associated with the usage of renewable materials and recycled content. Moreover, almost half of the company’s involve in supporting recycling and resource recovery infrastructure through recycling campaigns or initiatives with suppliers

(Stewart & Niero, 2017). The circular economy focuses on the closing, slowing down, and narrowing of resources. Closing loops involves the process of utilizing materials again through methods such as recycling, reusing, repurposing, etc. Slowing loops refers to the practice of utilizing products for a longer period of time by designing them to have a longer lifespan and extending the life of products. On the other hand, narrowing loops involves minimizing the amount of resources used in the production process and associated with the product (Bocken, et al., 2016). The CE objective is to consistently maintain the maximum usefulness and worth of products, components, and materials while minimizing any adverse effects on the natural environment and separating economic expansion from the strain on limited natural resources. The transition to a Circular Economy entails comprehensive transformations that cover innovation, technological systems, politics, society, business models, and finance (Kirchherr, et al., 2023).

2.1.1 Circular Indicators

According to (Waas, et al., 2014), "an indicator is the operational representation of an attribute (quality, characteristic, property) of a given system, by a quantitative or qualitative variable) (or function of variables), including its value, related to a reference value". The indicators refer to a value or reference used for comparison. The reference value can be a baseline with the undefined target or a baseline with either specific (quantitative) or non-specific (qualitative) targets (Moragaa, et al., 2019). A performance indicator is a term used to describe an indicator that is associated with a criterion, objective, or target. An index is created when multiple indicators are merged, whereas a bigger issue is represented by a collection of indicators (Bakkes, et al., 1994). An indicator has a primary significance in decision-making, simplifies important characteristics, and quantifies, measures, and communicates relevant information. An indicator can be classified as either qualitative or quantitative, although in practice the latter is more advantageous (Lundin, 2003).

Circular indicators are quantitative measures used to evaluate and quantify the degree of circularity represented by products, services, materials, processes, or systems within the framework of a circular economy. These indicators assist in assessing the effectiveness of resource management in a closed-loop system, where items are intentionally intended for reuse, repair, remanufacturing, and recycling to decrease waste and optimize resource efficiency (Moragaa, et al., 2019). It is widely recognized that in order to promote CE, it is vital to provide monitoring and evaluation methods, such as indicators, to assess and quantify the progress (Saidani, et al., 2018). Circular Indicators assist organizations, policymakers, and academics in monitoring advancements toward circular economy objectives, pinpointing areas that need enhancement, and making well-informed choices to foster sustainability and the preservation of resources (Pascale, et al., 2020).

The literature explains that circular indicators primarily focus on three scales: the micro, meso, and macro levels of indicators (Moragaa, et al., 2019). The indicators focus mainly on a single material, product, or company, denoted by micro-level indicators.

The meso-level indicators then concentrate on intercorporate or industrial symbiosis, while the macro-level indicators concentrate on the regional or global perspective. The analysis yielded a range of circular indicators that can be used to enhance circularity inside the company. Since the research primarily focuses on resource efficiency and waste reduction in the production of aero-engine components, the micro-level circular indicators are specifically selected with a focus on materials or products. The efficiency indicators are calculated based on economy based, physical (material) based and both economy-physical efficiency (Maioa, et al., 2017) (OECD, 2008). Resource efficiency significantly enhances sustainable resource usage by decreasing the need for new resources in the socio-economic environment (Idowu, et al., 2013). Furthermore, apart from various literature reviews on circular indicators, material resource efficiency indicators were adopted in this thesis to understand the materials intensity in the flow of the materials in the aero-engine components production. Since the company is researching circular economy aspects, developing efficiency indicators on materials will be foundational data for future circular economy practices and strategies. Improving material efficiency is important for decoupling resource scarcity and the resulting environmental impacts from economic development (Zhanga, et al., 2018). The material resource efficiency indicator calculation method and results are shown in the later sections 3.3 and 4.2 respectively.

Furthermore, some of the indicators identified are from interview knowledge and the company's aero-engine component production´s material flow based on the literature (Graedel, et al., 2011), showing the flow map related to the simplified life cycles of metals and the recycling of production scrap. The following list shows the various circular indicators based literature reviews pertinent to product production.

1. Circular Economy performance Indicator, represents the ratio difference between the actual environmental benefit, as achieved by the current recycling option, and the ideal environmental benefit based on quality (Huysman,et al., 2017).
2. Recycling process efficiency rate, it is defined as how efficient the recycling process is performed with the total generated scrap material (Graedel, et al., 2011).
3. Circularity Product Indicator, determines the performance of a product in relation to circularity (Angioletti, et al., 2017).
4. The Longevity indicator, aims at illustrating the duration for which a substance remains within a product system, through product usage and reuse as well as material recycling, such circulations serves as a way to maximize resource exploitation within the same product system (Franklin-Johnson, et al., 2016).

2.1.2 R strategy and Material Flow Mapping

Historically, the circular economy has been guided by the three fundamental principles known as the 3R principles: Reduce, Reuse, and Recycle. However, advances in academic studies and real-world applications have allowed these ideas to grow into a more complex and broad framework called the 10R strategy. Although the 3R framework has been successful in encouraging fundamental circular economy activities, the complex and extensive nature of contemporary environmental issues requires a more comprehensive and systematic approach. The conventional 3R techniques mostly focus on managing the last stage of a product's life cycle. However, in order to attain a really sustainable circular economy, it is imperative to take into account the complete life cycle of products, encompassing the design, manufacture, and usage stages. The 10R framework (Kirchherr, et al., 2017) is discussed below in *Table 1* on the basis of three criteria: efficient utilization of materials, prolonging lifespan of products, and maximization of material use (Popović & Radivojević, 2022).

Table 1: R strategies list with description

Strategies		Description
Efficient utilization of materials	**R0: Refuse**	Completely eliminating the use of hazardous and virgin materials, designing product to reduce waste (Morseletto , 2020).
	R1: Rethink	Refers to the act of thoroughly reviewing and rethinking ideas, processes, methods, concepts, and the utilization and subsequent use of products (Andrews, 2015).
	R2: Reduce	Reducing involves the act of lowering the utilization of virgin resources or materials, as well as reducing the amount of waste deposited in landfills. Also it refers to dematerialization, referring to utilizing less materials in the production phase of the material. (Reike, et al., 2018)
Prolonging the lifespan of products	**R3: Reuse**	Refers to the practice of utilizing a product that is still in good shape and able to perform its original purpose for a second time (Castellani, et al., 2015).
	R4: Repair	Repair refers to the act of fixing a faulty or failed parts so that it can fulfill its intended function (Jayaraman, 2006).
	R5: Refurbish	Refurbish refers to continuous enhancement of the product to uphold its quality throughout its extended lifespan, in order to meet the requirements of users (Stahel, 2010).
	R6: Remanufacture	It is the process of returning or bringing back the value of a used or discarded product as a like-new-condition product (Gray & Charter, 2007).
	R7: Repurpose	Repurpose refers to the utilization of materials after they have been used in the manufacturing of other products, but with a different intended function (Morseletto, 2020).

Maximization of Material Usage	**R8: Recycle**	It refers to the method of handling used materials without altering their nature, and then utilizing them in subsequent manufacturing processes (Oberoi, 2022).
	R9: Recovery	Refers to the process of recapturing energy from incineration (Potting, et al., 2017).

The first criterion (R0-R2) relates to the more intelligent manufacturing and utilization of materials. The objective of this criterion is to use fewer resources and to provide the same level of developed product function. The second criterion (R3-R7) relates to prolonging the lifespan of products and their components in order to increase their value to the highest. The Next criterion is that by recycling and recovering these materials, they can be transformed into raw materials for the development of new products. (Paula Pinheiro, et al., 2018)

In this thesis research, the R strategies are projected on the production chain. The Circular mapping of material flow aids in visualizing the flow and life cycle of materials, enabling the identification of crucial areas for action. The incorporation of the 10Rs strategy in the thesis, guarantees that all possible circular economy principles are taken into account and put into action. This holistic approach promotes resource efficiency, prolonging the lifespan of products, and establishing closed-loop systems that continuously reuse resources. This strategy aims to minimize environmental impact and encourage sustainable economic growth (Popović & Radivojević, 2022). In general, The R strategy were incorporated as a comprehensive framework to steer industries, governments, and individuals in embracing more sustainable practices and shifting towards a circular economy paradigm (Popović & Radivojević, 2022). By integrating these concepts into decision-making processes and daily activities, stakeholders can actively contribute to optimizing resource utilization, minimizing environmental footprint, and enhancing long-term sustainability.

2.1.3 ReSOLVE FRAMEWORK

In the context of sustainability and the circular economy, the "RESOLVE" framework is a strategic approach that helps enterprises and organizations make the shift from a linear "take-make-dispose" model of production to a more sustainable, circular model. By intention and design, this framework aids in the development and implementation of restorative or regenerative processes (Ellen MacArthur Foundation, 2014). Moreover, several researchers have highlighted the importance of the ReSOLVE framework for reaching a circular business model and a circular economy (Mendoza, et al., 2017). ReSOLVE was selected because, according to the literature analysis, it is a prominent CE framework utilized in academia and industrial businesses. By aiding in the definition of the CE and offering illustrations of CE solutions in specific case circumstances that may stimulate innovations and ReSOLVE can serve as a guiding checklist for CE innovations. The ReSOLVE framework has been used extensively in research to find business models from a strategic perspective (Paula Pinheiro, et al., 2018). The ReSOLVE concept proposes six complimentary and synergistic dimensions are: **Regenerate, Share, Optimize, Loop, Virtualize, and Exchange** (Mendoza, et al., 2017). In this project, the ReSolve framework is used to check on the possibilities of enhancing circular economy in additive manufacturing in GKN Aerospace.

Regenerate:

It encourages restoring, preserving, or enhancing natural systems and minimizing the use of non-renewable resources (Geissdoerfer, et al., 2017).

Share:

According to (Dias, et al., 2022), this dimension emphasizes maximizing product usage through customer sharing. This covers sharing resources, making use of and recycling used goods, and prolonging the life of objects through disassembly and upgrades so that several users can utilize them. Moreover, procedures including product repair, remanufacturing, design for durability and recyclability and product-service system (PSS) deployment are essential to this sharing model. With an emphasis on access over ownership, PSS provides integrated product and service solutions to satisfy customer needs. For instance, car and home sharing business models.

Additive manufacturing uses CAD file software to design the 3D model and feed it to the built chamber. The 3D model Files can be shared securely and transparently between the designers of various places or manufacturing sites across the globe to maximize the use of designs and to encourage collaboration (Tavares, et al., 2023). This dimension promotes the ideology of a decentralized system for DFAM. A network of dispersed additive manufacturing hubs might be built as an alternative to depending solely on centralized manufacturing facilities. By placing these hubs in institutions, different manufacturing sites or even customer sites, the gap between creation and consumption can be significantly closed. Peer-to-peer operation of this network can optimize production efficiency while cutting emissions and logistics costs. Orders are automatically directed to the closest hub with available capacity and required capabilities (Ford & Despeisse, 2016).In the sharing economy, Product Service Systems (PSS) for the aero-engines represent a revolutionary business paradigm. This promotes sustainability, efficiency gains, and long-term connections. This strategy encourages the more sustainable and efficient use of products, which naturally supports the circular economy concepts. Sharing designs can facilitate a feedback loop where users and manufacturers iteratively improve products based on real-world usage and testing. This feedback can lead to designs that are not only more efficient but also more tailored to sustainable practices, further enhancing the environmental benefits of products. In addition, Additive Manufacturing (AM) facilitates repair and maintenance approaches by allowing for on-site production of replacement parts and damaged components. This helps to minimize transportation expenses, decrease reaction times, and prolong the lifespan of aero-engine components. This method is in line with the ideas of the circular economy, which aims to maximize the lifespan of products and minimize waste (Mani, et al., 2014) (Hettiarachchi, et al., 2022).

Optimize:

The objective of this dimension is to increase the performance and efficiency of products and services, minimizing waste and the use of resources. The optimize dimension seeks to reduce waste in the supply chain and manufacturing processes in order to improve product performance and the economical use of material resources. In order to achieve the circular objectives related to optimization in the aerospace industry, three main methods have been identified for application: (i) improving product performance; (ii) eliminating waste in the production and supply chain; and (iii) implementing big data, automation, remote sensing, and direction.

DfAM (Design for Additive Manufacturing) takes advantage of AM's capacity to create intricate, well-optimized structures, like strong, lightweight lattice or honeycomb structures that require less material than solid structures. Additionally, by combining several components into one intricate part, this method can cut down on assembly time and material use. The subtractive process in traditional manufacturing can generate a large quantity of waste materials. For example, more than 50% of the material may be removed and perhaps wasted during the machining of a sophisticated aerospace component from a solid block of titanium. Additive manufacturing, on the other hand, constructs the part layer by layer, utilizing material only where necessary. In addition to reducing waste, this procedure makes it possible to design and produce complicated geometries that would be unfeasible or extremely costly to produce using subtractive methods. AM provides the opportunity to produce products in a multi-functionality model (Dias, et al., 2022). AM provides an opportunity to embed additional functions into the existing components. By facilitating the manufacturing of components in proximity to their intended location, AM can optimize supply chains and minimize the environmental impact of transportation (Kravchenko, et al., 2020).

Designing to attain a net shape will reduce waste in production and post processing’s. Ability to produce optimized geometries with near-perfect (compared with wrought material) strength-to-weight ratios (Mani, et al., 2014). Enhancements in print algorithms have the potential to yield substantial process optimizations in additive manufacturing. These algorithms regulate the print, layer thickness, deposition speed, and other factors that impact the effectiveness and quality of the printing process. It is possible to shorten print times, use less material, and enhance the final product's mechanical qualities by fine-tuning these parameters. Energy efficiency can be improved by maximizing the build volume. The energy consumption in AM can be reduced by improving capacity utilization. AM pre-process optimization along with the optimal part design can also minimize energy consumption (Liu, et al., 2018). In addition, AM has the capability to enable functional design, enabling the production of intricate internal features, environmentally-friendly designs, or sustainable process designs that would be difficult or unattainable using conventional manufacturing techniques. The ability to adapt the design can result in enhanced utilization of resources and less environmental consequences during the whole lifespan of the product. (Xia, et al., 2020)

Loop:

The goal of the loop dimension is to maintain materials and product components in closed loops and prioritize and enhance the inner loops. The "loop" highlights the importance of product design in achieving more resource circularity. This implies that a product should be made using the cradle-to-cradle principle in order to promote its extended life in the future. Therefore, to ensure longevity and a resource loop, product design should ensure ease of repair, remanufacturing, recycling, and resource reuse.

AM has the potential to encourage the reuse, remanufacture and recycling of products (Tavares, et al., 2023). The reuse of additive powders from blown powder bed technologies after each built in the chamber. The powders can be used for multiple cycles of built instead of disposing of the powders. The use of recycled materials as a raw material for AM technology will be a futuristic approach that enables reduction of the use of virgin materials and promoting zero waste will be a circularity target approach with AM. In other words, in comparison to conventional manufacturing techniques, this implies that materials can be reintroduced into the production process with more ease. The combination of additive manufacturing and recycling has the potential to achieve 100% materials usage and 0% waste production, thus significantly decreasing the cost and energy consumption during production (Xia, et al., 2020).

Virtualize:

The goal of virtualize dimension is to reduce the requirement for material resources by substituting digital processes or products for physical ones. It entails dematerialization and the provision of virtual services, such as the development of electronic books, manuals, and other documents; online sales, purchases, and support activities; and the utilization of telecommunications to reduce the need for physical facilities.

The Virtualize dimension of the ReSOLVE framework can be particularly relevant to AM. Virtualization in the context of the ReSOLVE framework refers to the dematerialization of resource-intensive services. In the context of AM, this could refer to the use of digital technologies to optimize the design and manufacturing process, thereby reducing the amount of material used and waste produced. Using AM in a distributed manufacturing strategy will lower the cost of shipping and inventory management. As a result, AM increases an agile supply chain's responsiveness to guarantee that there are no stock outs by implementing a build-to-order strategy (Hettiarachchi, et al., 2022). AM facilitates On-demand manufacturing by incorporating on-site production by sending CAD file 3D models to the customer location, creating the opportunity to develop digital inventory. Allowing the companies to create their own virtual warehouse for their materials having designs in a file format. AM leverages digital files and virtual designs, decreasing the need for physical prototypes and reducing the material usage during the design and testing phase. This shift to digital reliance reduces the carbon footprint associated with the production and transportation of physical prototypes and parts.

Exchange:

Exchange promotes switching to more modern, environmentally friendly materials and technology in place of outdated ones. This calls for implementing cutting-edge, less environmentally harmful materials and procedures. For instance, the electric motors will replace internal combustion engines.

According to (Ellen MacArthur Foundation, 2014) (Paula Pinheiro, et al., 2018), each dimensions represents a major circular business opportunity. These activities all, in different ways, boost the utilization of physical assets, extend their useful lives, and switch from using finite to renewable resources for resource consumption. Additionally, every action boosts and promotes the performance of every other action.

2.2 Additive Manufacturing

The process of additive manufacturing is a near-net-shape production that employs a layer-by-layer technique to produce intricate parts through joining materials (Shah, et al., 2014). Additive manufacturing is often known as 3D printing, a recognized word for the process that used to be referred to as rapid prototyping. This technology enables direct fabrication of models generated using a 3D CAD (Computer Aided Design) system without the need for process planning. Rapid Prototyping (RP) is a phrase used in several sectors to refer to a technique of quickly generating a representation of a system or part before it is officially released or made available for commercial usage. In short, the focus is on rapidly producing a prototype or initial model that will serve as the foundation for future iterations, and ultimately, the final product (Gibson & Brent Stucker, 2015).

AM provides a more efficient material utilization by producing with minimal scrap, which is a viable alternative to conventional manufacturing processes, such as machining, which involves cutting of material from a block (Cawley, 1999).In recent years, there has been a significant surge in the utilization of additive manufacturing technology for fabricating components for end products. AM can be defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (Oettmeier & Hofmann, 2016). Additive manufacturing is a diverse manufacturing method that encompasses various different methods. The three additive manufacturing technologies covered in this thesis include Laser Metal Deposition (LMD) using both powder and wire and Laser Powder Bed Fusion (LPBF). These technologies were chosen because the company is currently incorporating only with the Metal Additive Manufacturing (MAM) technologies for the production of aero-engine components. This information was obtained from interviews conducted with additive specialists at GKN. Therefore, these three technologies have been explained in detail in the theoretical framework section of my thesis. Thus, the following three additive manufacturing technologies are discussed below.

2.2.1 Laser Metal Deposition – Wire

Laser metal deposition, otherwise called adirect energy deposition process in which focused thermal energy is used to fuse materials by melting as they are being deposited. The materials used as a feedstock for this technology is wire or powder. Wire-fed LMD is an advanced manufacturing technique that produces metal parts by repeatedly melting and depositing metal wire layer by layer using an intense laser beam. The process starts with a laser gun that produces a concentrated, high-energy laser beam. This accurately melts the metal wire that passes into its path. When the wire reaches the focus point of the laser, it undergoes melting and forms a small pool of molten metal. This molten metal is then placed onto a substrate, which can either be a flat plate or an existing component that needs to be developed. The precise positioning of the material is achieved through the controlled movement of the substrate or beam, in accordance with the specified design requirements. The process involves the quick cooling and solidification of each deposited layer, enabling the steady buildup of the part through the successive addition of layers. The technology provides several advantages, such as high precision resulting from the rigorous control of the electron beam, efficient use of materials with low wastage, and the ability to work with a wide range of materials, making it well-suited for applications in aerospace, automotive, medical, and various other industries (Gibson & Brent Stucker, 2015).

2.2.2 Laser Metal Deposition – Powder

Laser metal deposition (LMD) is a unique technology that enhances material utilization by allowing the production of high-precision, near-net-shaped components from powders (Selcuk, 2013). It uses a deposition head to deposit material onto a substrate, which can be either a flat plate or an existing part. In this LMD technology, the feedstock is the powder fed through a nozzle. Deposition is controlled by relative differential motion between the substrate and deposition head. The laser generates a small molten pool on the substrate, which solidifies as the powder enters the pool. The passing of the beam creates a thin track of solidified metal deposited on and welded to the layer below, with a layer formed by overlapping tracks. The deposition head moves away from the substrate by one layer thickness after each layer is formed (Frazier, 2014).

2.2.3 Laser Powder Bed Fusion

Powder Bed Fusion methods were among the initial additive manufacturing (AM) processes to be commercialized. All processes using the PBF method possess a fundamental set of properties. These consist of one or more thermal source that initiate fusion between powder particles, a method for precisely regulating the fusing of powder to a specific area of each layer, and mechanisms for applying and leveling powder layers. Lasers are the most prevalent heat sources used in PBF (Frazier, 2014). Laser Powder Bed Fusion (LPBF) is an advanced 3D printing technique that uses laser energy to fabricate metal components with exceptional accuracy and intricate designs. The technique begins by uniformly distributing a fine layer of metallic powder on a building platform. Subsequently, a laser with a high energy intensity is used to scan and melt the powder, causing it to solidify into a solid layer. The process is repeated iteratively, where the platform descends after each layer and a fresh coating of powder is deposited, until the complete item is fabricated. A cool-down period is typically required to allow parts to come to a low enough temperature uniformly for handling and exposure to ambient temperature and atmosphere. The technology provides several advantages, such as high-quality of printing parts and fine resolution for building complex structures (Gibson & Brent Stucker, 2015).

2.3 Additive Feedstock

Additive feedstock refers to the type of materials that are deployed in different additive manufacturing technologies. The most common metal additive feedstock materials are wire and powder (Gill, et al., 2022), which are used in LMD and PBF AM processes. To understand the circular economy of additive manufacturing, it is also important to know about their various production processes. The Wire feedstock is normally drawn from the rod coils to a wire. Whereas the powder for AM needs to undergo an atomization process to turn into usable fine powders. The Atomization technology discussed in this thesis are gas atomization and plasma atomization processes

2.3.1 Wire feedstock production

Metal rods or tubes undergo a series of dies to reduce their diameter and shape them into wires. The fundamental concept of wire drawing is that a wire passes through a single or a series of circular openings in a drawing die (Cubrová, et al., 2020). This process is mainly conducted to increase the length of the wire and reduce its cross section.

2.3.2 Atomization Technology

Atomization is a method by which molten metals break down into tiny droplets and consolidate into powders subsequently while in motion within a collection chamber filled with an inert gas. During atomization, it is typical to add a high-pressure gas flow to propel the liquid at a high velocity through a small nozzle. The interaction between the air and the fluid causes friction, which leads to the disruption of the stream, resulting in the fragmentation and subsequent formation of droplets. Another method to cause droplet breakdown for atomization is by utilizing centrifugal force, which can be generated by spinning a disk with a liquid coating on its surface. This phenomenon is frequently referred to as the primary breakup regime. Over time, the droplets will continue to break apart and undergo the process of solidification, resulting in the formation of powders while they are in flight. This regime is usually referred to as the secondary breakdown regime. Additionally, in industrial atomizing operations, it is typically necessary to use a high quality inert gas like Argon (Ar) or Helium (He) in order to reduce the presence of oxygen and prevent contamination. The atomization technique encompasses various specialized procedures, each characterized by distinct specifics. Nevertheless, all these procedures have three crucial processes in any case: melting, atomization, and solidification. These steps are essential for the production of finely spherical powders (Soong, et al., 2023).

2.3.2.1 Gas Atomization

In gas atomization, metals or metal alloys are melted in a crucible furnace, which is protected in order to ensure the composition of the liquid metal becomes uniform over time. Following that, the molten metal substances drop from the crucible furnace to a nozzle made of heat-resistant metal and these are then transformed into small liquid droplets by a forceful flow of inert gas under high pressure. Finally, the liquefied droplets undergo a transformation into spherical or almost round particles as they fall within a chamber filled with an inert gas (Kassym & Perveen, 2020). Even though interstitial components in gas atomized powders can be tightly controlled, there are still some contamination issues. The most relevant contamination for non-static essential components, such as aero-engine parts, is refractory materials that can come from the ceramic crucibles and atomizing nozzles that are utilized. An effective approach to address this issue is to employ Electrode Induction Melting Gas Atomization (EIGA). It is a method in which a metal rod is introduced into the atomizer and melted by an induction coil prior to entering the atomization chamber.

2.3.2.2 Plasma Atomization

In this method of atomization, plasma is applied to create highly pure powders. The technique has the capability to generate powders consisting of highly spherical particles and possessing low levels of oxygen concentration. The material utilized in plasma atomization is in the form of metal wire. The material is introduced into plasma torches, where it undergoes a transformation into droplets that are then consolidated into a powdered state. A variation on plasma atomization known as the Plasma Rotating Electrode Process (PREP) uses a rotating bar of feedstock in place of a wire feed. As the rotating bar enters the atomization chamber, its extremity is melted by plasma torches, causing material to be released from its surface (Dawes, et al., 2015).

2.4 Traditional Manufacturing

Traditional manufacturing processes are the traditional techniques that are employed to manufacture products and components on a big scale. These processes have endured for centuries and continue to be significant in contemporary industry. Below, some of the primary categories of traditional production methods are explained.

2.4.1 Casting

Casting is a process of pouring a molten metal into a mold and allowing it to cool and harden, so that it takes the desired mold shape. It is a simple way to produce products near to the net shape. For decades, castings have been produced by pouring molten metal into sand molds. The contemporary manufacturer of industrial castings utilizes these similar abilities, but enhances them with a comprehension of the essential principles of fluid dynamics, heat transfer, thermodynamics, and metallurgical microstructural evolution. These advanced engineering skills are utilized to assist in the creation of a system that enables the metal caster to produce a flawless casting without any defects such as sand inclusions, slag, or cracks. Additionally, the system ensures that the casting has the precise dimensions and desired mechanical properties to meet the requirements set by the designer for its intended application (Rundman, 2018). Modern industrial castings are manufactured using investment casting, which is mostly used in aerospace due to the oxygen sensitivity of titanium. These processes differ from each other in terms of the material used for the mold, the method of introducing molten metal into the cavity and the state of the mold cavity.

2.4.2 Forging

Forging is a manufacturing technique in which metal is subjected to intense pressure, either through pressing or hammering the hot workpiece between the die halves to create durable components (Poli, 2001). The metal is often heated to the appropriate temperature before being worked, allowing for a hot procedure. Forging is employed to fabricate some of the most highly stressed components found in aircraft, automobiles, and tools.

2.4.3 Machining

Machining is a subtractive manufacturing procedure in which material is removed from a work piece, typically in the form of chips. In the process of machining, the removal of material from a work piece is achieved through the utilization of either a cutting tool or an energy source (Huda, 2020). The majority of forging and casting procedures yield dimensions and surface conditions that require machining in order to attain the desired shape and dimensional accuracy. Component parts created by additive techniques also require extra machining to attain the desired fit and finish for utilization in a final assembly.

3 Methods

This chapter explains the methodology used in the thesis. The methods include reviewing existing literature, conducting interviews, formulating research questions, collecting and analyzing data, and ultimately framing the results and developing conclusions.

The method used for this thesis involved an extensive review of the literature on qualitative assessment methodology. Based on the article (Basias & Pollalis, 2018), the structured five-step method was developed, includes: 1) Defining the research scope, 2) Conducting a literature review and semi-structured interviews, 3) Formulating research questions, and 4) Data collection and analysis and 5) Conclusion and discussion. This step-by-step method offers a simplified framework for conducting the thesis.

First, the methodology includes the framing of the research scope with respect to the topic. The first step in the research process is to clearly define the scope and goals of the study. It is done by determining the parameters of the study that defines the research scope, which ensures concentration and coherence throughout the research process.

During this stage, a thorough examination of the literature is carried out to get an in-depth understanding of the current knowledge, theories, and research discoveries pertaining to the subject being investigated. The literature study involves examining relevant scholarly publications, books, reports, and grey literatures to discover knowledge gaps, patterns, and theoretical frameworks that are applicable to the inquiry. In addition, this step entails conducting interviews with experts in the field to collect insights, viewpoints, and direct experiences that might contribute to the research process. In the next phase, based on the knowledge obtained from the literature study and interviews, concise and targeted research questions are developed. These questions function as fundamental principles that guide the study, leading the investigation toward particular areas of inquiry. Research questions must be exact, pertinent, and in line with the research's aims, enabling a methodical approach to gathering and analyzing data.

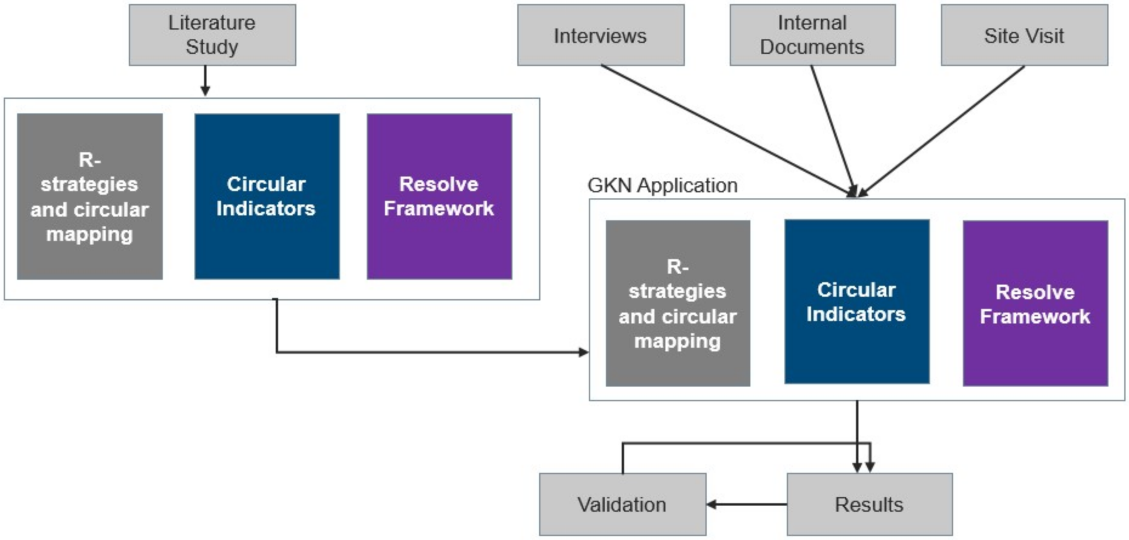

Figure 1: Methodology

In the data collection and analysis phase, the techniques for collecting data are chosen based on the research questions and objectives. This involves qualitative techniques such as interviews depending on the nature of the research. Data collection was put into action to collect applicable data from participants of the interviews. Afterward, the gathered data is methodically examined to uncover relationships that relate to the research objectives. In this section. The three different concepts of circular economy are developed and applied in the case company (GKN Aerospace) with respect to the research questions. These concepts are utilized as a main key driver to attain the purpose of the thesis. Then the findings of the investigation are explained and validated. The data analysis results are synthesized and structured to give valuable insights into the research issue. Findings are communicated via narrative descriptions, and visual representations, together with an analysis and discussion of their significance.

The ultimate stage is deriving conclusions from the study findings and addressing the research questions and objectives. This part offers a conclusion to the research process, concisely summarizing the primary discoveries and their implications for the wider field of study.

The flow chart below outlines a methodology for developing a concept using various sources of information. Initially, the process involves gathering inputs from four key sources: literature study, interviews, GKN Aerospace internal documents, and site visits. The inputs from the literature helped to create a circular approach into the concept development phase, which is structured around three main elements: circular mapping and R-strategy, circular indicators, and the ReSOLVE framework. Circular mapping and R-strategy involve outlining processes and possible strategic loops for circular economy principles like reuse, recycle, and reduce. Circular indicators focus on defining metrics to measure circularity. The ReSOLVE framework is applied to further refine the concept in adhere to the research questions. Once the concept is developed, it undergoes a validation phase to ensure its feasibility, effectiveness, and alignment with objectives. The validations of the findings are checked with the GKN Aerospace supervisors and with the interviewee´s. Finally, the validated concepts are presented as results, offering actionable insights and recommendations. This methodology ensures a comprehensive and practical approach to concept development in the thesis.

3.1 Literature Review

The thesis conducted a thorough review of the available literature and considered a range of academic search engines, including Scopus, Web of Science, and Google Scholar. Scopus and Google Scholar were selected because to their comprehensive coverage and indexing of papers pertaining to the categories being reviewed, following a thorough assessment. The search strings were constructed using several combinations of terms that included different areas of additive manufacturing, circular economy and sustainable manufacturing. The following keywords were used: "additive manufacturing," "circular economy," "aerospace," "aero-engine," "recycling," "reuse," "sustainable development", "indicators", "circular business models," and "additive powders.", etc,. Additional filters such as "barriers" and "opportunities" were also applied. This comprehensive methodology guaranteed the retrieval of pertinent papers that covered different aspects of the research issue. The Boolean syntax was employed to improve the final search phrase in the Scopus database, allowing for accurate and focused retrieval of articles that satisfied the required criteria. This methodological approach improved the effectiveness and precision of the literature search process. Furthermore, several academic books were studied during the literature review to understand the various topics discussed above. Also, academic courses presentation slides of my master´s program were reviewed to revise the basic concepts related to the thesis. The literature review provided a solid basis of knowledge for this thesis, presenting a thorough overview of the existing research in additive manufacturing and circular economy. The review comprehensively examined scholarly articles to get insights into recent technical advancements, significant challenges, and effective approaches used in prior research efforts.

3.2 Interviews

As a part of the methodology, interviews were conducted with various employers from GKN Aerospace to understand the current manufacturing practices of aero-engine production and to gain knowledge on the current circular practices and challenges. A semi-structured interview is a method of gathering data in which the interviewer is not required to follow predetermined, formal questions. Instead of using a direct question and answer format, the interviewer is required to offer open-ended questions that allow for discussion with the respondents or interviewees. A combination of closed- and open-ended questions are used in semi-structured interviews, which are conversationally conducted with one respondent at a time and frequently followed up with why- or how-questions (Adams, 2015). This type of interview was selected because they are very suitable for a variety of research assignments, particularly when open-ended questions require more in-depth investigation.

Employees from several departments within the production areas of forging, casting, and additive manufacturing were interviewed using semi-structured interviews. The purpose of these interviews was to collect extensive knowledge on various aspects of the production processes, such as design, materials, knowledge in additive manufacturing techniques (such as Powder Bed Fusion and Directed Energy Deposition), logistics, environmental practices, recycling initiatives, and procurement strategies in different production areas. They offered significant perspectives on the company's present production processes, including an idea of how workflow dynamics, resource usage, and efficiency measures are implemented. In addition, interviews provided data on the movement of materials inside the manufacturing regions, which helped analyze material flows and identify places that could be optimized or improved. Furthermore, interviews provided valuable information about the company's existing circular economy measures, such as recycling initiatives, waste management methods, and sustainable procuring procedures.

Interviewee Selection: Participants were chosen from company supervisors and recommended by the other co-workers of the company, based on their specialized knowledge and positions within the organization, guaranteeing a varied range of expertise in the production sectors being investigated. The interview participants consisted of experts who were skilled in additive manufacturing design, casting and forging, particular additive manufacturing processes such as powder bed fusion and directed energy deposition, logistics, environmental management, recycling, and procurement. The interviewees are the most experienced employers in the aero-engine component production process at GKN Aerospace. Table 2 below assigns alphabets to each interviewee to highlight the different information each participant will provide in the upcoming chapters. The interviewees are the employers from the different departments as listed below. The

Table 2

Table 2: Interviewee´s participated in the interview process

Role	Interviewee
Casting process specialists	A
Forging process specialists	B
Casting & Forging Procurement specialist	C
AM PBF process Specialist	D

AM DED process Specialist	E
AM Design Specialist	F
AM Procurement Specialist	G
AM Customer strategy specialist	H
Environmental Manager	I
Recycling Specialist	J

The interview questions were aligned with the primary objectives of the thesis, with the intention of obtaining valuable perspectives on different aspects of the manufacturing process, circular economy practices, and the difficulties encountered by the organization. The questions were intentionally constructed to be open-ended and flexible, enabling the investigation of many viewpoints and personal encounters. The questions are described in the appendix of the thesis. In addition, the questions underwent iterative development during the interviews, integrating feedback and ideas from earlier sessions to enhance comprehension and address developing topics.

The majority of interviews were performed face-to-face at the GKN Aerospace site for 30 to 60 minutes to enable direct engagement and observation. However, a few interviews were carried out online using platforms such as Microsoft Teams to meet participants' availability and geographical limitations. All interviews were recorded with the participants' consent to guarantee reliable information capture and ease further analysis. In addition, comprehensive notes were made during the interviews to catch subtle details and contextual information that may not be recorded in recordings. The transcriptions of the recorded interviews, coupled with additional notes, were used as the foundation for analyzing the data. *Table 3* illustrates the need for the interviews for the thesis by explaining various outcomes and their usage in the thesis to each interview participant.

Table 3: Interview outcomes and usage

Interviewee	Knowlege gained	Thesis Usage
A	1) The material flow of casting process from cradle to gate. 2) Overview of the components produced from casting process 3) Current casting sustainability and circularity practices.	Utilised in the formation of Casting Material flow mapping and indicators

B	1) The material flow of forging process from cradle to gate. 2) Overview of the components produced from forging process 3) Current forging sustainability and circularity practices.	Used in the formation of forging Material flow mapping and indicators
C	1) Collected data on purchased materials for aero-engine production.	Utilized in the formation of circular indicators
D	1) The process of PBF AM technology. 2) The material flow of AM process from cradle to gate. 3) Overview of the components produced from PBF AM process. 4) Reuse of additive powder strategy. 5) Current production challenges with Challenges with AM PBF.	Utilized in the formation of AM material flow mapping and in the development of indicator. Also, to compare the current process with the ReSOLVE framework to understand the possible circular aspects of AM.
E	1) The process of PBF DED technology 2) Overview of the components produced from DED AM process. 3) Current production challenges with Challenges with AM PBF. 4) The material flow of AM process from cradle to gate.	Utilized in the formation of AM material flow mapping and in the development of indicator. Also, to compare the current process with the ReSOLVE framework to understand the possible circular aspects of AM.
F	1) Current design process in the AM produced aero-engine components.	Utilized in the ReSOLVE Framework
G	1) Supplier circular practices and their challenges 2)Material flow of AM feedstock materials	Material flow mapping and ReSOLVE Framework
H	1)Current circular practices with the customers	Utilized in the ReSOLVE Framework
I	1) Collected data on total scrap materials generated in aero-engine production.	Utilized in the formation of circular indicators
J	1) Current recycling practice of scrap generated from the aero-engine components production. 2) Challenges associated with recycling of titanium alloy and nickel alloys.	Utilized in the formation Material flow mapping

3.3 Calculation Methodology

This section explains the calculation methodology for the identified circular indicators results in section 4.2. As discussed in section 2.1.1, circular indicators play an important role in the thesis results. The material resource efficiency indicator for the production process is calculated from the material flow analysis of the aero-engine component product chain. The material flow and the data required for this calculation are retrieved from the interviews conducted with the various specialists. Thus, the challenge faced in the thesis to retrieve maximum data in a shorter time and limited information on recycling processes becomes a challenge for the calculation of all indicators associated with the aero-engine component production that are mentioned above in section 2.1.1. However, the calculated indicators are aligned with a focus on material circularity, which prioritizes resources and waste associated with the life cycle of the product.

In order to address the challenges involved in this project, a carefully chosen circular indicator material resource efficiency has been selected, with a strong emphasis on the materials usage in site specific and product specific as important factors. The main focus of this selection criterion is to clarify the mutually beneficial connection between additive manufacturing technologies and CE principles. The calculations for the materials are Titanium alloys and Nickel alloys.

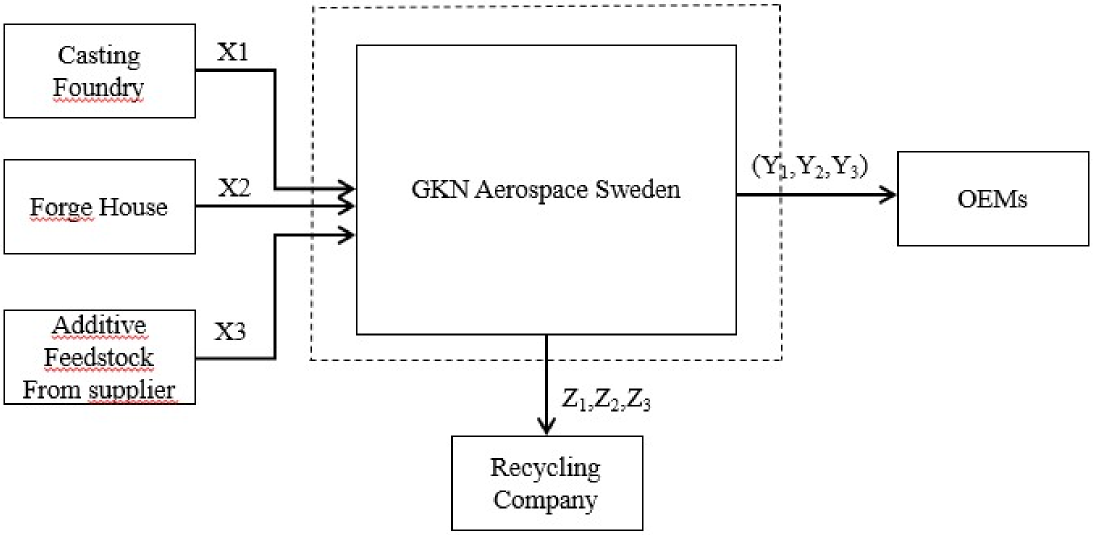

Figure 2: Calculation flow

The analysis of material flow within the GKN Aerospace Sweden boundary serves as the basis for the calculation of material resource efficiency indicators. Moreover, the calculation for these indicators is performed in terms of mass flow in kilograms. The incoming flows of titanium and nickel alloy materials are expressed as X1(X_c), X2(X_f) and X3(X_a) correspond to each production process, including casting, forging, and additive feedstock purchase, respectively. Y1(Y_c), Y2(Y_f), and Y3(Y_a) are the finished output products from each process that leave the GKN Aerospace Sweden boundary to the OEMs. Moreover, Z1(Z_c), Z2(Z_f) and Z3(Z_a) include scrap generated in each production process. The values X, Y, and Z encompass both titanium alloys and nickel-based alloys are based on the year 2023. The calculation relies on the material flow analysis of the manufacturing chain (Graedel, et al., 2011). Furthermore, indicators are calculated using the logic of the mass balance approach (Bringezu & Moriguchi, 2002). According to the mass balance, the materials entering the GKN Aerospace Sweden boundary must be equal to the materials leaving the boundary, the formula developed from the mass balance approach. So, in general,

$$X = Y + Z \tag{1}$$

$$(X_c + X_f + X_a) = (Y_c + Y_f + Y_a) + (Z_c + Z_f + Z_a) \tag{2}$$

Thus, the metric of Material Resource Efficiency (MRE) is an important factor in evaluating how efficiently input resources are used to generate output. The material resource efficiency for Ti-alloys and nickel superalloys is calculated based on the comparison of input materials (X) and the total scrap generated (Z) in the production process. The material resource efficiency of titanium and nickel superalloys are calculated separately by comparing the sum of total materials purchased for the total production processes in the year 2023 with the sum of total scrap generated in all production processes leaving the boundary in 2023. This is a key statistic that shows how effectively company use these materials in their engine component production.

$$MRE = \frac{Material\ entering\ the\ GKNA\ gate\ (Xc + Xf + Xa) - \ Scrap\ generated\ in\ the\ production(Zc + Zf + Za)}{Material\ enetring\ the\ GKNA\ gate\ (Xc + Xf + Xa)} \tag{3}$$

The term Material entering the GKN Aerospace gate refers to the overall quantity of material that is used in the production process of aero-engine components. Scrap generated is the term that refers to the fraction of the material that becomes discarded during the manufacturing process. The Material Resource Efficiency is a measure that quantifies the efficiency of material usage in the manufacturing process. It is calculated by considering the reference value as the material entering the gate. The efficiency of the production process is quantified as a percentage, which represents the proportion of the input material that is efficiently employed to create the end product. Higher percentages indicate a higher level of efficiency and a lower amount of waste.

The next MRE indicators are specific to products. The calculation for this indicator is based on the comparison of the finished mass of the product and the purchased input material for producing the product. For instance, The material resource efficiency of the casting process with titanium alloys is described below. $\mathrm{MRE}_{\mathrm{CTi}}$(F) refers to the material resource efficiency of component F, which is manufactured by casting process with Ti alloy. $X_{\mathrm{C,Ti}}$(F) denotes the mass of Titanium alloy used to produce component F and $Y_{\mathrm{C,Ti}}$(F) refers mass of final weight of the finished component F. Similarly, $\mathrm{MRE}_{\mathrm{CTi}}$(G) and $\mathrm{MRE}_{\mathrm{CTi}}$(H) are calculated and the percentage of MRE for titanium used casting process is calculated by taking the average of these three components (data points).

$$\mathrm{MRE}_{\mathrm{C_{Ti}}}(\mathrm{F}) = \frac{\text{Finished Output Ti Component}(\mathrm{Y_{C,Ti}}(\mathrm{F}))}{\text{Titanium input components}(X_{C,Ti}(\mathrm{F}))} \tag{4}$$

$$\mathrm{MRE}_{\mathrm{C_{Ti}}}(\mathrm{G}) = \frac{\text{Finished Output Ti Component}(\mathrm{Y_{C,Ti}}(\mathrm{G}))}{\text{Titanium input components}(X_{C,Ti}(\mathrm{G}))} \tag{5}$$

$$\mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{H}) = \frac{\text{Finished Output Ti Component}(\mathrm{Y}_{\mathrm{C,Ti}}(\mathrm{H}))}{\text{Titanium input components}(X_{C,Ti}(\mathrm{H}))} \tag{6}$$

$$\mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}} = \frac{\mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{F}) + \ \mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{G}) + \ \mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{H})}{3} \tag{7}$$

$$\mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}} \,\% = \frac{\mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{F}) + \ \mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{G}) + \ \mathrm{MRE}_{\mathrm{C}_{\mathrm{Ti}}}(\mathrm{H})}{3} \ X\ 100 \tag{8}$$

Similarly, the material resource efficiency for AM components is calculated using the same procedure. After performing a quantitative analysis of the indicators, the results are illustrated in a graphical representation.

4 Result

This chapter delves into the findings of the circular concepts that were discussed in the previous chapters in context to GKN Aerospace Aerospace Sweden. As discussed in Chapter 3, the findings are identified and developed based on the interviews, literatures and companies internal documents. The knowledge gained from the interviews are discussed in this chapter and in discussion chapters. Also, the information's gained in the interviews are referenced in the results and discussion sections. From this chapter, the reader will get an overview of the circular concepts that were incorporated in the company and can able to understand the current and the possible future circular economy strategies that are needed for the transition to circular economy.

4.1 Material Flow Mapping

The flow of titanium and Super alloys materials in the aero-engine component production were identified and quantified for production processes, casting, forging and additive manufacturing. The grey lines in the *Figure 3* denotes linear flow, Violet lines characterizes the circular flow, the red lines denotes AM circular flows and the red dotted lines indicates the possible hybrid circular flows. The raw materials used in the production of aero-engine component are titanium alloys and Nickel super alloys. First the raw materials are extracted from the mines, and then the metals are produced from the mined minerals. The metal is then melted, refined, and molded to produce the metal ingots.

4.1.1 Casting Process

The *Figure 3* illustrates the material flow of aero-engine components production through casting processes. The process starts with the Ingot Supplier, who provides the casting foundry with unprocessed material in the form of ingots. During the production of ingots, the supplier incorporates circular activities such as reusing the scrap in their own ingot production.

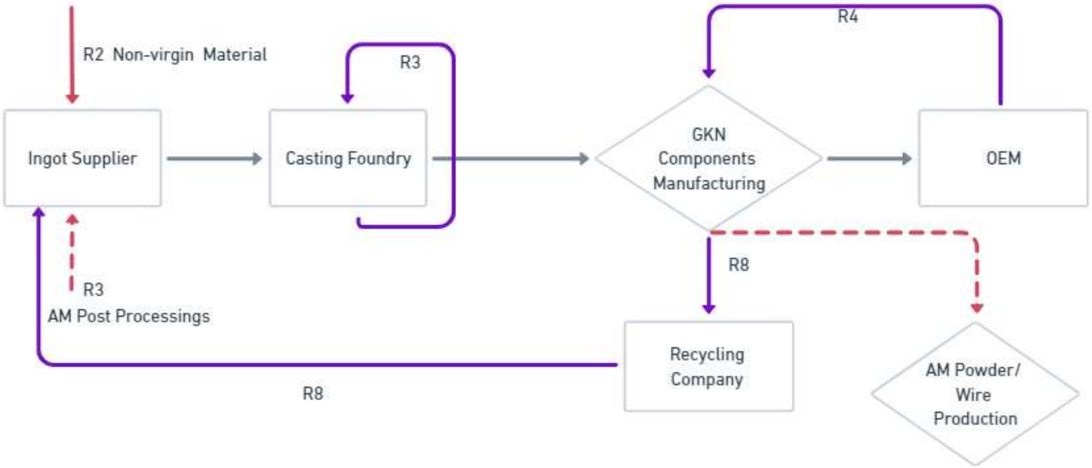

Figure 3: Casting Material Flow

The Casting Foundry utilizes the ingots to produce cast components, which are sent to GKN Aerospace Components Manufacturing for additional processing and assembling. The Reuse Loop (R3) refers to the practice of internally reusing leftover materials in order to reduce waste and enhance resource efficiency (Interviewee A). Once the components are produced and assembled at GKN Aerospace Components Manufacturing, they are subsequently dispatched to the (Original Equipment Manufacturer) OEM for incorporation into the end products. Worn-out components are returned from the OEM to GKN Aerospace Components Manufacturing for repair. The Repair Loop (R4) is designed to rectify and reintegrate repaired components back into the production process (Interviewee H).

GKN Aerospace components manufacturing sends scrap or waste material to the recycling company after the manufacturing process (Interviewee J). This is denoted by the Recycling loop (R8). The red dotted lines indicates the possible circular flows, which are not in action today. But, for the future engines this material flow can be developed and implemented. The dotted line in the upstream denotes the scrap from the post processing of additive manufacturing processes. The scrap includes support structures after the built of components from the built chamber can be used as a raw material in the ingot production for casting and forging processes as a possible strategy. Next, in the downstream, the scrap from the GKN Aerospace manufacturing is of turnings and powders (Interviewee A). This scrap can be used as a raw material for wire or powder feedstock for AM.

4.1.2 Forging Process

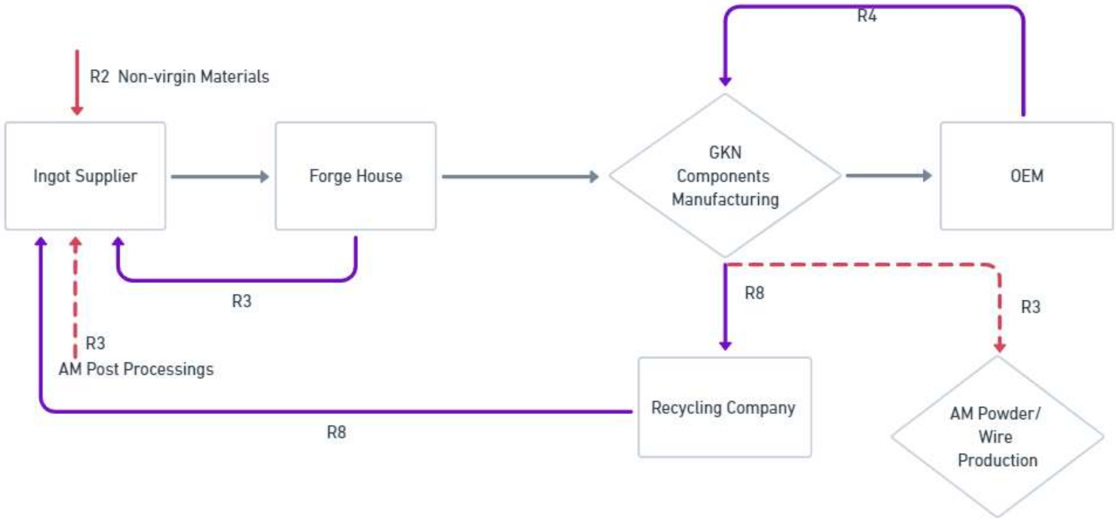

Figure 4: Forging Material Flow

In *Figure 4*, the forging process commences when the ingot supplier supplies the forge house with raw materials. The forge house processes these materials, with a portion of their scrap being returned to the ingot supplier and also some to the casting foundry as well, thereby establishing a Reuse Loop (R3) (Interviewee B). Subsequently, the produced components are transferred to GKN Aerospace Components Manufacturing for additional refinement and assembly. Subsequently, the finished goods are sent to the OEM. Following the manufacturing phase, all materials are carefully identified for recycling and then transported to the recycling company, as represented by the Recycling Loop (R8). Like casting, the possible circularity flows cascading with AM flow constitutes reuse strategy to retain the value of the material.

4.1.3 Additive Manufacturing

The material flow with AM in GKN Aerospace begins by producing powder and wire specifically for AM processing. At now, GKN Aerospace purchase powder and wire from vendors who use various production methods such as EIGA, VIGA, and Plasma atomization for powder production (Interviewee G). The company is currently researching and implementing these diverse types of powder production processes. Additionally, the wire feedstocks are manufactured through the process of pulling from a rod coil. Although the AM supply chain is still developing within the organization, the red lines represent circular loops that have been recognized as solutions for future production. Additionally, a range of internal techniques were implemented to procure the powder/wire for additive manufacturing, with the use of circular efforts. Research has shown that there is a loss of 20-23% of metal powder during the powder production process (Daraban, et al., 2019). Out of this, 15-16% of the metal powder is successfully recovered and utilized in subsequent powder manufacture. In the *Figure 5* displays the initial projection of circular loop R3. Additionally, a percentage ranging from 20 to 23 of the powder is retrieved and can be utilized in the additive manufacturing built chamber. The powder is referred to as a refurbished powder (R5), which means that its quality has been improved and it may be directly used in the built chamber. GKN Aerospace now use the L-PBF additive manufacturing technology, the sintered powder is in a loose state and which can be easily recovered. Additionally, the company is currently conducting research on the feasibility of reusing powder. GKN Aerospace current status in powder reusing cycles is lower than state-of-the-art research due to the regulations present in the industry. The organization employs a Single batch technique, wherein a solitary batch of powder (consisting of virgin particles) is utilized in several build cycles (Interviewee D). After each cycle, the powder is sieved to eliminate sintered agglomerates or distorted angular particles. The sieving is conducted using a mesh size opening that is greater than the upper cut of the Particle Size Distribution (PSD) employed. The powder batch can be reused until it deteriorates or no longer meets the specified requirements, or until there is not enough powder left to complete the next build cycle.

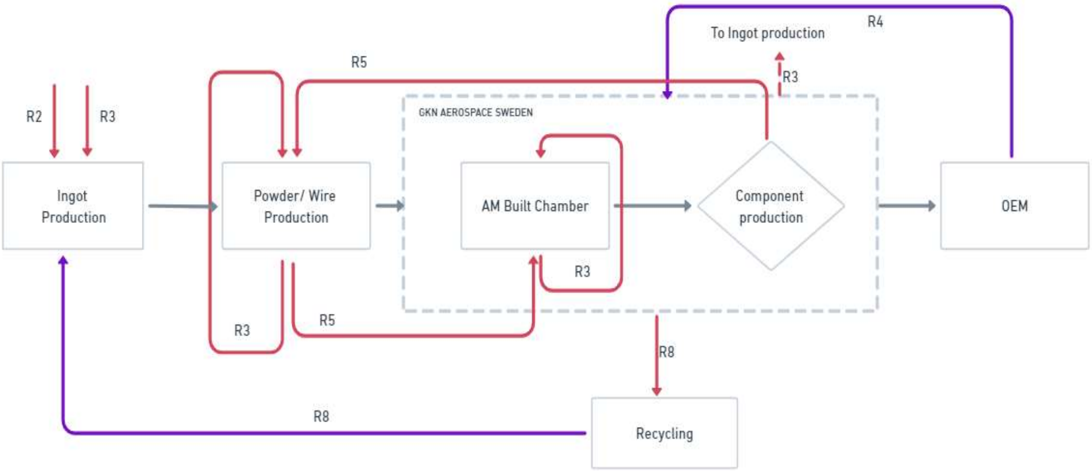

Figure 5: AM Material Flow

Powder degradation include alterations in the chemical composition, density, porosity, morphology, flowability, and reduction in the particle size distribution (PSD). Once the powder reaches a certain level of degradation, using it would negatively affect the qualities and quality of the printed objects. After undergoing numerous cycles, the powder is considered to be depleted or out of specification powder. At this stage, the powder needs to be sent for recycling. Presently, the organization is collaborating more extensively with their OEMs in the repair industry, as indicated by the violet line (Interviewee H). Next, the circularity loop will involve utilizing scrap material generated during the post-processing of AM fabricated parts. The scrap can be recycled within the value chain by transforming it into powder or wire.

4.2 Circular Indicators

The Material resource efficiency indicator for the input materials (Ti alloy and Ni alloy) used in the aero-engine components production.It is based on the GKN Aerospace Sweden site material usage and it was calculated by comparing the mass of the scrap generated with the mass of the input materials purchased for producing aero-engine components production. Based on the equation (3), the *Figure 6* displays the rates at which Ti alloy and Nickel alloys are utilized. The data indicates that the utilization rate for Ti alloy is 54%, but Nickel alloy exhibit a higher utilization rate of 78%. These results are derived from assessment of the procurement data, ie the mass of the total materials (Ti alloy and Nickel alloy purchased for producing various components of an aero-engine and the data of the total scrap generated in the year. The increased utilization rate of Nickel alloy implies that these materials are more effective in terms of material use, resulting in a lower amount of waste compared to Ti alloys relative to the material entering the GKN Aerospace gate. By examining these indicator more thoroughly, the company will gain a more detailed picture of how resources are allocated and used effectively in the field of additive manufacturing.

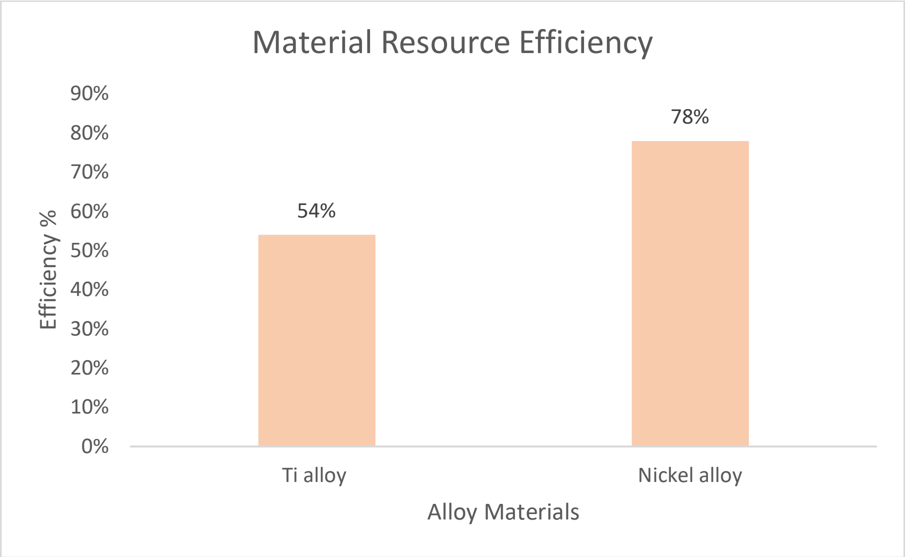

Figure 6: Material Resource Efficiency - Site Specific

Next indicator is the material resource efficiency calculated for each materials (Ti alloys and Nickel super alloy) with respect to each production processes castings, forgings and AM. This indicator is based on the product specific. The metric is determined through the ratio of the combined mass of output materials (Y) to the combined mass of input materials (X). The equations used for the calculations are explained in section 3.1.2. To calculate this indicator, the data are obtained for certain aero-engine components. The data point illustrated below in *Table 4* represents the number of data collected (finished weight and input weight) on different aero-engine components. So, the data points with respect to the material and the production process are shown below.

Table 4: Data Collection

Process	Material	Data Points
Casting	Ti alloys	3
Casting	Ni alloys	1
Forging	Ti alloys	3
Forging	Ni alloys	4

First, for the calculation of material resource efficiency with specific to the production processes either castings or forgings or AM, the data collected involves the mass of the input material used to manufacture an aero-engine component and the mass of the finished aero-engine components with respect to the corresponding production processes. For example, in *Table 5*, component F uses 85 kg of Ti alloy material to produce the final finished product with a weight of 59.5 through the casting process. Overall, the Ti alloy casting material efficiency is calculated based on equation (6). For all the three data points associated with Ti alloy castings, MRE is calculated separately, and the average of the three data points is calculated. Thus, it is assumed that the calculated value is the MRE of the casting process of Ti materials. The same procedure is applied to the Ti forging, Ni alloy casting, and forgings, respectively.

Table 5: MRE Data – Traditional Manufacturing

Components	Purchased Input material weight (Kg)	Final Output material weight (Kg)	Material	Process
A	242.9	182.9	Ni alloy	Casting
B	284	73.9	Ni alloy	Forging
C	294	106	Ni alloy	Forging
D	328	47	Ni alloy	Forging
E	185.5	18.5	Ni alloy	Forging
F	85	59.5	Ti alloy	Casting
G	35.06	19.37	Ti alloy	Casting
H	42.1	24.06	Ti alloy	Casting
I	209	36.5	Ti alloy	Forging
J	66.1	17.7	Ti alloy	Forging
K	262	94	Ti alloy	Forging

This research focuses on comparing resource efficiency metrics obtained from both forging and casting processes within the company´s aero-engine production. The *Figure 7* illustrates graphical representation of the indicator. The main focus of this investigation is that titanium-based components have a resource efficiency mere 27% when subjected to forging process, while their efficiency within the casting is much higher at 60%. This metric value highlights the complex relationship between process methods and resource utilization dynamics. In this context, the casting process is seen as a predictor of increased resource efficiency compared to the forging process. Similarly, the discussion also applies to the use of nickel super alloys, where a similar difference in resource efficiency measurements between casting and forging operations becomes prominent. In the context of nickel super alloys, the casting process stands out as a prime example of resource efficiency, with an impressive efficiency ratio of 75%, compared to the less impressive efficiency statistic of 30% in the forging paradigm. Upon examination, it becomes clear that the difference in resource efficiency indicators is directly linked to the complexities of each production process. In the process of forging, reaching the highest level of resource efficiency is a difficult task because of the unavoidable material loss and inadequacies that are inherent in the forging process.

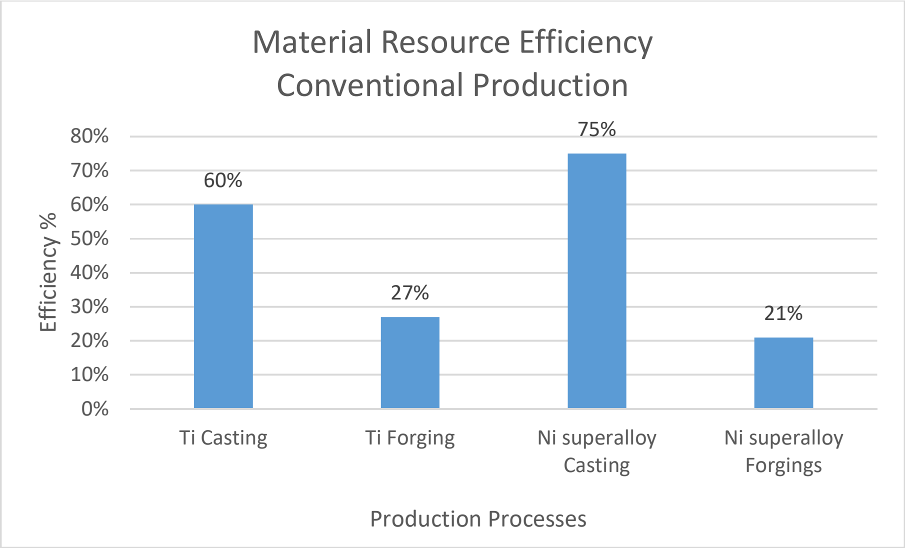

Figure 7: Material Resource Efficiency - Product Specific

On the other hand, the casting process stands out as a prime example of resource optimization due to its ability to create complex shapes and minimize material waste when comparing with forging process.

Next indicator is the MRE for AM produced components, which is product specific as well. The AM produced aero-engine components are calculated based on the data from the current production and R&D projects. The calculation performed is same as that did with the MRE for traditional manufacturing processes. *Table 6* shows the calculation results of the MRE of each component with respect to their AM process.

The data points collected for AM DED is 6 and PBF is 2. The result are derived based on this data points.

Table 6: MRE Data - AM

Components	Purchased Input material weight (Kg)	Final Output material weight (Kg)	Material utilisation rate of each components	AM Processes
A	113	36.5	0.32	DED
B	36.06	19.37	0.53	DED
C	42.10	27.45	0.65	DED
D	145	47	0.32	DED
E	21.5	18.5	0.86	DED
F	172	64.5	0.37	DED
G	172	59.5	0.34	PBF
H	53.1	17.3	0.32	PBF

The material resource efficiency of four production processes is shown in the *Figure 8*. It has been seen that casting is the most resource-efficient method among those compared, as proven by its exceptional efficiency of 67%. In contrast, forging exhibits the lowest efficiency at 24%, indicating substantial material waste. Traditional forging is significantly outperformed by DED, despite its moderate efficiency of 51%. The efficiency of PBF is also higher than that of forging, at 34%. This data points out a distinct trend toward the adoption of Additive Manufacturing processes such as DED-Wire and PBF. The effectiveness of these AM technologies will probably continue to improve, potentially widening the gap with traditional processes such as forging, as they continue to develop. This trend represents a transition in the manufacturing industry toward more resource-efficient and sustainable methods.

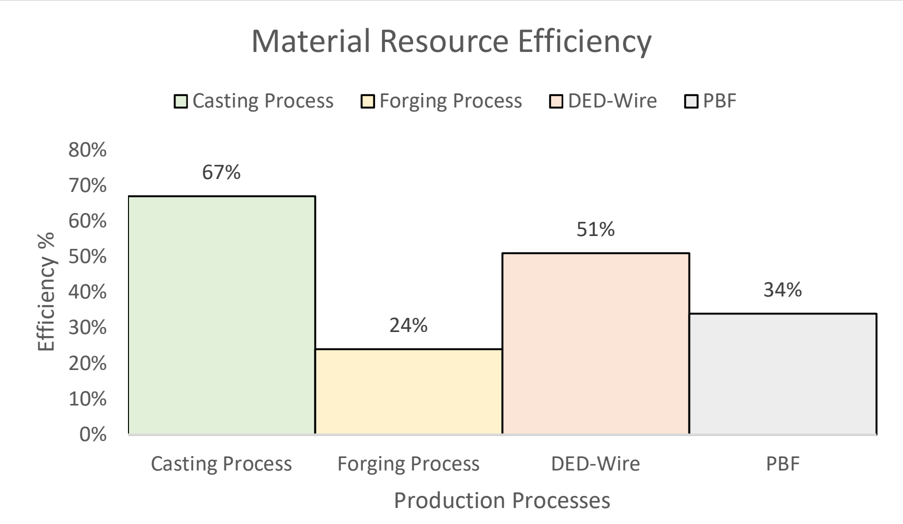

Figure 8: Material Resource Efficiency Comparison Chart

With the help of these indicators, stakeholders can have holistic vision to navigate the challenges in sustainable manufacturing practices. The goal is to highlight the complex relationship between production methods and the need for circularity.

However, acquiring reliable information for these indicators within the company poses a significant challenge. The lack of comprehensive and exact data impedes the ability to deliver accurate outcomes for these measurements. Data sourcing challenges arise from several circumstances, such as insufficient tracking systems, restricted access to dependable data, and the intricacy of quantifying certain aspects of circularity. It is critical to address these data gaps in order to accurately evaluate and enhance the organization's circularity performance. To improve data gathering methods, it is necessary to make coordinated efforts, establish strong monitoring systems, and guarantee transparency and consistency in reporting.

4.3 ReSOLVE Framework

From the theoretical framework section, the general view about the six dimensions of the ReSOLVE framework are clearly understood. Now, to look how metal additive manufacturing technology for aero-engines component production can endorse this framework and enhance the circular economy within the production sector.

In the study of ReSOLVE framework with AM shows that Share, Optimize and Loop dimension plays a significant role in enhancing circular economy. These dimensions are explained and compared with their state of art and their start of practice in GKN Aerospace´s aero-engine components production. The challenges faced by the company to adopt CE within the framework are identified and specific circular strategies are proposed for the future development of technology with CE.

SHARE

Industrial Practice:

The OEMs businesses with their customers by offering services based on flight hours rather than the engines themselves (Interviewee H). This strategy is an example of a product as a service. In this case, providing a service takes priority over selling an item that is physical.

Challenges:

AM produced components frequently engage numerous suppliers and contractors, resulting in fragmented supply chains that hinder the effective coordination of resource sharing. Overcoming this challenge necessitates essential collaboration and communication among various stakeholders.

Strategies

The engagement and communication within the stakeholder such as designers, manufacturers and OEMs involved in additive manufactured components across various production sites can improve the possibility of facilitating a feedback loop system, which could be a driver for circular economy in building business models.

OPTIMIZE

Current Practice:

The company is in research with the optimization of AM produced components, ie. In the process of reduced weight per part, AM can incorporate Topological optimization structure to reduce the weight of the parts i.e. reduce the use of more raw materials (Interviewee F). The companies LCA studies proved that the many components built with AM has the potential to use less materials for their final component production. It is also seen that the wire feedstock DED has more than 90% of material utilization rate. Which can be determine to be a zero waste in manufacturing through wired DED (Interviewee E). The company is also working to attain net shape in both DED and PBF (Interview F). In PBF, by deploying study with object orientations to reduce the support structures and attain the net shape of the component (Interviewee D).

Challenges:

1. Current L-PBF AM processes generate more scrap materials. The exact parameters for optimizing these processes are not well understood.
2. Designs currently not include end-of-life disassembly or recycling mechanisms.
3. Attaining full net shape is not yet achieved and the knowledge to attain full net shape is limited within the company.
3. Limited knowledge in support structure elimination.
4. DFAM doesn't exists yet for critical part due to lack of trust in AM from OEMs
5. Long Certification time in the aerospace industry hinders the implementation of feedback loops in short time period.
6. The technical challenges in reusing and recycling involving material degradation, separation of mixed materials, contamination and quality control of the scrap materials.

Strategies:

1) To achieve the product's net shape in the near future, the company should invest in research and development to optimize design and control AM parameters and should establish a closed-loop system to monitor material usage and waste generation throughout the supply chain. From material utilization circular indicator, AM technologies has a potential to reduce the material usage and the incorporation of optimized AM can ultimately use less material and create less waste in their production processes.
2) Incorporate the Design for Recycling (DFR) and Design for Disassembly (DFD) concepts into the product development process. Work closely with design engineers to include features like easily separable materials and modular components that make end-of-life disassembly and material recovery easier.

3) Research and development should be allocated towards the resolution of technological obstacles associated with the elimination of support structures in additive manufacturing techniques.
4) Company should encourage cooperation and information exchange between academic institutions, research centers, and industry players to solve technical issues with AM optimization and circularity. Together work with partners at each stage of the value chain to provide comprehensive solutions that tackle the complex problems associated with recycling and remanufacturing in AM.

LOOP

Industrial Practice:

The reuse of powders in L-PBF is one of the significant circular strategy enhancing circular loop with powdered-additive manufacturing. The company is working on with research of reusability of additive powders with the single batch strategy (Interviewee D). On the other side with wire DED, the Company have started researching on reparability with AM, which is seen as a highly optimistic circular business models (Interviewee H). The company is deployed with repairing of components with AM is to boost the performance of the component and to repair the wear parts surfaces through AM-DED. Also, the current research on the possibility of recycle of production scrap into a high valued-AM-feedstock can be an optimistic future circular economy practices (Interviewee G).

Challenges:

1. Absence of effective recycling protocols for AM materials means that materials are less likely to be looped back into the production cycle. However, the lack of effective recycling systems for AM-specific materials, like certain Ti-alloys used in aero-engines, hinders this loop.

2. The efficient recycling of AM materials is hindered by material contamination, deterioration during printing, and a lack of infrastructure.

3. The Titanium powders reactivity in reusing of powder is unknown. So, within the company only limited cycles of AM built is achieved.

4. The quality of the scrap material in the downstream of the supply chain after sent to the recycling company is unknown.

Strategies:

1) Enhance the current recycling mechanisms for AM materials to enhance effectiveness. Furthermore, promote the development of additive manufacturing parts and components that prioritize recyclability.
2) Allocate research towards the improvement of titanium material characterization and quality control processes in order to guarantee the uniformity and integrity of recycled materials.

3) Invest in research to develop the PBF AM's powder reuse mechanism. This can maximize the reuse of powder in the built chamber.
4) Establish a Circular Supply Chain to engage in collaborative efforts with suppliers and customers to develop a closed-loop supply chain specifically for additive manufacturing materials.
5) The company also need to make the recycling loop closer, by looking on the opportunity of recycling by themselves instead of doing with the other recycling companies.

5 Discussion

In this section the research questions formulated in Section 1.3 will be discussed and answered.

Research Question 1

How GKN Aerospace is currently enhancing circularity with their existing methods for aero engine components?

The company is currently improving the circularity of aero-engine component manufacture by incorporating various activities such as reusing, repairing, and recycling at different phases of the manufacturing process. An essential element of the company's attempts to achieve circularity is the adoption of the Reuse Loop, in which the practice of internally reusing recoverable scrap materials contributes to waste reduction and improves resource efficiency in the company's operations. By incorporating these scraps back into the manufacturing process, the company effectively decreases waste and eliminates the necessity for new, unused supplies. This not only improves the efficiency of resource utilization but also supports the principles of sustainability. Before, the challenges associated with the establishment of reuse strategies need to be addressed and the solutions need to be identified. Next, the organization has been actively engaged in the Repair Loop, which is of utmost importance in prolonging the lifespan of components. Worn-out parts are sent back from the OEM to GKN Aerospace components manufacturing, where they undergo repair procedures. After undergoing cleaning and repairing, these components are reinserted into the supply chain, thereby decreasing the need for new parts and reducing the overall consumption of raw resources. This loop not only preserves resources but also reduces the environmental effect linked to the manufacturing of new components. The company's dedication to circularity is additionally exemplified by the recycling Loops. Scrap materials are gathered and delivered to a recycling company once the manufacturing process is finished. This approach guarantees that valuable resources are not squandered but are instead consistently reintegrated into the production process, promoting a circular economy and decreasing landfill trash.

Within the field of additive manufacturing (AM), the organization is making progress in promoting circularity by employing inventive techniques to recover and recycle metal powder. Studies reveal that a substantial amount of metal powder is reclaimed and recycled during the powder manufacturing process. The company utilizes a Single Batch Technique (Moghimian, et al., 2021), in which a batch of virgin powder is employed for multiple build cycles. Following each cycle, the powder undergoes a sieving process to eliminate any sintered agglomerates or distorted particles, hence preserving the powder's purity. This process enables the powder to be reused several times until it no longer meets the required specifications and is subsequently sent for recycling. In addition, the company is investigating the viability of utilizing refurbished powder, which has undergone enhancements in quality and can be immediately employed in the built chamber, thereby further decreasing material waste.

The company promotes circularity in the production of aero engine components by utilizing both conventional manufacturing techniques, such as casting and forging, and additive manufacturing, despite the latter's limited supply chain. According to Interviewee A, titanium castings can utilize 85% recycled material. Also, in the current production of Nickel alloy casting production utilizes the ratio of virgin material to non-virgin material at 40:60 percentage. Interviewee B mentioned that static sections in the forging process can be created from up to 100% recycled material, but this percentage may vary depending on market conditions. Original Equipment Manufacturers (OEMs) place limitations on the usage of recycled materials for high-performance rotating parts. In addition, the company implements rigorous recycling and waste management procedures by transferring the majority of scrap materials to recycling companies and some to suppliers, as per established agreements. These activities collectively showcase the company's dedication to a circular economy by decreasing dependence on new materials, optimizing resource utilization, and limiting waste, therefore contributing to sustainability in the aerospace industry. The limitation of the thesis with the calculation of circular indicators is that the indicators are calculated only based on data from GKN Aerospace Sweden's operational limits. This constraint enables a thorough and contextually appropriate evaluation of the indications. In addition, certain assumptions were taken into consideration.

The circularity indicators are exclusively calculated for certain aero-engine components. The reason for this decision is the substantial challenge in collecting thorough data for all engine components within the restricted time span allocated for this research. Also, many of the components parts purchased are used in the assembling, this creates the challenge to find which parts are used in which component assembly. Thus, it is very important to create a transparent database for future work. The study ensures depth and accuracy in the data analysis by concentrating on certain components.

Research Question 2

How is additive manufacturing technology being adapted at GKN Aerospace to support resource efficiency and waste reduction throughout the value chain of aero engine components?

The company has been extensively researching the implementation AM technology to improve resource efficiency and minimize waste across the whole value chain of aero engine components. Utilizing Directed Energy Deposition (DED) additive manufacturing (AM) technology is crucial due to its ability to create components that closely resemble the desired shape, resulting in a substantial decrease in waste compared to PBF methods. Currently, with the DED process, the company has in research to attain the net shape of the product. This not only reduces the amount of raw materials used but also supports future projects focused on producing net-shaped components. Furthermore, the company's research demonstrated that DED has a material efficiency rate of more than 90%. Additionally, with the PBF technology, the company is researching the possibility of reusing AM powders after multiple cycles in L-PBF AM and investigating the recycling of production scrap into valuable feedstock. The circular indicators with AM shows that AM especially DED has the potential to prevail over the forging process completely in the future aero-engine productions. Furthermore, in PBF technology, there are still more challenges to overcome, such as the lack of knowledge for reusability and recycling of additive materials, insufficient understanding of how to eliminate support structures, design limitations and technical difficulties manufacturing caused by material contamination and degradation. In order to effectively include additive manufacturing in its circular economy plan, the organization needs to give priority to these difficulties and create specific solutions. This involves improving the current recycling protocols and infrastructure to facilitate a smooth transition into a circular model.

Nevertheless, GKN Aerospace encounters many obstacles in implementing a circular economy framework utilizing additive manufacturing. A major obstacle is the lack of communication and inadequate collaboration across various divisions within the organization, hindering the successful execution of circular objectives. The lack of integration between different departments and the limited exchange of information can hinder the implementation of cross-functional initiatives that are necessary for a successful transition to a circular economy. Furthermore, although AM is praised for its waste reduction capabilities, it can still produce substantial waste in the form of OOS powders or support structures that may not necessarily be recyclable or reusable within the AM system. This difficulty emphasizes the necessity for additional investigation and advancement in material retrieval and recycling technologies that are specifically tailored to AM processes.

Furthermore, the components now offered at GKN Aerospace are not designed specifically for AM repair, which presents an additional challenge to achieving circularity. Incorporating repair and remanufacturing considerations into component design is essential for prolonging product lifespan and reducing waste within a circular economy framework. Additional issues that have been found include limitations in the AM cell, a lack of knowledge in design optimization for reducing support structures, a limited understanding of material reactivity when reusing titanium powder, and a limited supply chain for additive manufacturing with less mass flow. These problems highlight the necessity for ongoing research, innovation, and collaboration within the industry to overcome the obstacles in implementing a circular economy model employing AM. By addressing these difficulties comprehensively, GKN Aerospace can adopt a more circular and sustainable method for producing aero-engine components utilizing additive manufacturing. By embracing the potential of AM and effectively tackling the related obstacles, the company may not only enhance resource efficiency and minimize waste but also establish itself as a frontrunner in sustainable production methods in the aerospace sector.

6 Conclusion

The thesis highlights the significant potential of additive manufacturing to improve resource efficiency and minimize waste in the production of aero-engine components at GKN Aerospace Sweden. AM can reduce production waste by optimizing material usage and promoting local manufacturing, hence minimizing transportation-related environmental consequences. First, the company needs to improve communication between its various departments and stakeholders throughout the aero-engine component value chain. To create sustainable and circular economy awareness programs within the organization to educate employers regarding the benefits of those practices. The company needs to invest in more research and develop additive feedstock material characterization, quality, and design to attain net sales for both DED and PBF AM technologies and the possibility of full usage of non-virgin materials in the current production processes. Moreover, to enhance circularity, GKN Aerospace can use various techniques, including leasing additive manufacturing components, improving process parameters, designing products for recycling, and establishing closed-loop recycling and reusing operations. Furthermore, the company can set up various measures to trace the materials and energy usage in the upcoming years. Nevertheless, it is essential to overcome challenges such as enhancing intra-organizational communication and resolving technical issues pertaining to material quality, contamination and degradation. The thesis proposes a holistic approach that includes implementation planning, involving stakeholders, allocating resources, and continuously monitoring to incorporate AM into a circular economy framework effectively.

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Appendix

Interview Question to the Interviewee´s

- What are the current or future aero-engine components (will be) producing through AM (PBF)? And could you explain in detail of any aero engine component with complete closed loops?
- What are the existing closed loops or **initiative** focused on remanufacture, repair, recycle or material reuse?
- Where do the wastes from the different production processes end up with? How the value of the material is retrieved?
- In Reuse of Powder, what strategy do GKN Aerospace employ? Is Single batch Strategy or Top-up strategy or Spherodization
- How many cycles the powder is currently reused in the AE components produced through AM?
- What are the powders characterization currently deployed? (PSD,O2,Porosity,homogenity)
- What are the challenges associated with topological optimization or honey-comb or lattice structure in order to reduce weight of the product in terms of material usage or design ?
- How is the concept of "circular design" incorporated into the development of PBF manufacturing processes and products, with a focus on optimizing material use and end-of-life considerations?
- What are the challenges associated with implementing closed-loop systems in additive manufacturing?
- How current production looks in RESOVE Framework?
- Who are all the suppliers for additive powder and wire?
- How do they produce powder, is it atomization process or another? Are these produced “sustainably”?
- Same question for wire.
- Are there current collaborations with suppliers to advance circularity in additive powder/wire procurement?
- For what products do we currently buy additive wire/powder?

- How does refurbishing AM powder/ wire align with our overall business strategy and objectives?
- Are there any specific challenges or issues you face in sourcing additive powder/wire materials?
- How is the suppliers engagement looks with sustainability and circularity?
- What is the dependence direction with these suppliers? Do we have the power to influence them to be more circular?
- Are they transparent with regards to their sustainability and circularity performance?
- what PSD TI/Superalloys powders are procured currently ?
- Can you discuss any strategies employed to optimize costs in additive powder/wire procurement?
- How do you ensure the quality and reliability of the additive powder/wire materials sourced from suppliers?
- Do you prioritize the use of recycled materials in AM powder/wire procurement business?
- Are there opportunities to leverage technology or new business models to drive innovation and differentiation?
- What are the current products or Aero-engine components produced through Casting/forging? And could you explain in detail of any aero engine component with complete closed loops?
- What are the type of wastes associated with the casting/forging process with respect to each stage in the process and how such wastes are handled or disposed?
- How much of the recycled materials is used in the casting production to replace virgin raw materials?
- How does GAS work with circularity in casting/forging?. What are the existing closed loops or **initiative** focused on remanufacture, repair, recycle or material reuse?
- In your opinion what aspects in the casting product production need to be enhanced on circularity? Or closing the cycle?
- How is the concept of "circular design" incorporated into the development of casting/forging manufacturing processes and products, with a focus on optimizing material use and end-of-life considerations – Design for recyclability?
- How do you see the development of AM. What is your view on AM with comparison of advanced casting/forging technique?

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