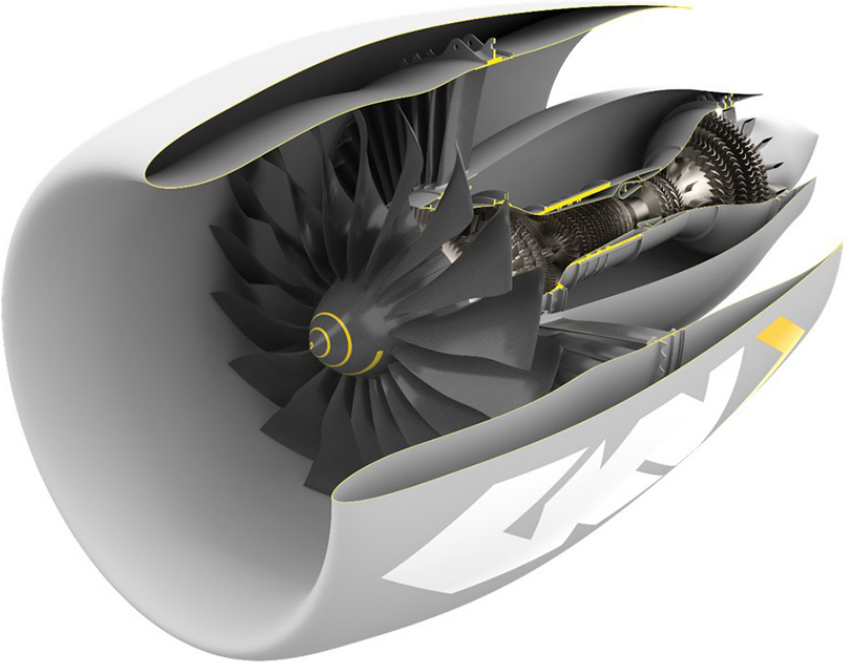

Sustainability management of jet engine repair business: How component repairs benefit the aerospace industry

Master's thesis in Management and Economics of Innovation

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Cover: A model of a jet engine (GKN Aerospace, 2023)

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Abstract

Climate transition in industry has received a lot of attention and research the last years and the aerospace industry is no exception. The industry has a reputation to be a contributor to global emissions and holistic changes are needed to achieve long-term economic and environmental sustainability. The regularly maintenance and repair of jet engines have created a considerable aftermarket. However, little empirical research on the sustainability impact of engine repair has been done. The study aims to investigate economic and environmental sustainability of a parts repair business in the aerospace industry. Literature, interviews and internal documents laid the foundation for mapping and calculating environmental and financial impact of the activities. Subsequently, the results was put in relation to literature on the topic of life cycle management, technological cycles, sustainable business model and stakeholders to assess the strategic portfolio. Main findings are that repair has considerable positive environmental impact, yet being cost efficient, which creates economic opportunities for the case company. However, the environmental impact differs between repair methods, where additive manufacturing proved to be the most environmental sustainable. Further, the study claims that distributing the benefits between stakeholders is essential for a viable business model innovation.

Keywords: life cycle management, environmental management, sustainable business, sustainable business innovation, MRO, aerospace industry, jet engine repair, technological cycles

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1

Introduction

The Aviation industry is a global multi-billion dollar industry making more than 800 billion USD before the COVID-19 pandemic, and almost 472 billion USD in 2021 (Statista, nd). Airplanes connect the world globally, and the industry's importance is raised by the United Nations Secretary-General António Guterres in "[...] connecting societies and delivering vital goods to supporting millions of livelihoods and contributing billions to the global economy." (United Nations, 2021). However, the issue of the industry being unaligned with the 1.5-degree goal of the Paris Agreement is also raised, underlining the issue of high emissions in aviation. The industry has a reputation to be a contributor to global emissions and stands for a total of 3.5 % of the total emissions (Ritchie, 2020). Because of this, environmental sustainability and climate transition of the industry has become an important topic on the agenda for aviation companies and aerospace organizations.

One way for industries to manage climate transition is to prolong the life length of the products. In the aerospace industry, the jet engine is an advanced product that is in use for up to 30 years. To ensure safe and efficient operation of the engine, it regularly goes through repair. Currently there is a need for higher capacity in the repair market. Because of the lack of capacity and repair's positive environmental impact and potential business opportunities it is interesting to investigate how a repair business may be structured to grow in the most sustainable way.

1.1 Aim and research questions

The aim of the thesis was to investigate the sustainability of a parts repair business in the aerospace industry and assess the balance between the economic and environmental sustainability, in order to build a strategic business portfolio. Social sustainability will also be touched upon, however, the main focus will be on the economic and environmental dimensions.

In order to fulfill the aim of the thesis, two research questions have been developed. The first question aims to investigate the optimization of the repair portfolio both from an environmental and financial point of view.

1. How can the repair portfolio be structured in order to both grow and optimize sustainability and profit for the repair business of the case company?

The second question further investigate how the portfolio can be structured by taking a broader approach and putting the results in to context. By including the perspective of supply network, the business relations of the case company, and the dynamics of the market over time the strategic options are evaluated. A suggestion on how to strategically structure the repair business to thrive in the complex network and dynamic future market is the result of the second research question. Hence, the second research question is:

2. How can the business case be structured?

1.2 Limitations

In order to specify and limit the scope to a reasonable size, following limitations have been set:

- This report does only investigate the current part repair business of one company within the aerospace industry.
- The study investigates processes within the gates of GKN Aerospace, and production of the raw material including meltings and forging. This mean that aspects such as transportation and other material processing, as well as the user phase is not included.

2

Topic Overview

The following chapter provides an overview of the relevant theories for the study. The first sections take a general perspective of climate transition and life cycle management, as well as technology cycles and stakeholders. Following, an industry specific perspective of the aerospace industry and the case company GKN Aerospace are provided.

2.1 Climate transition in industry

The climate change is undeniable, and a global issue affecting every living object on earth. Increased global temperature, rapid changes in the atmosphere, ocean, biosphere and cryosphere, and extreme weather are some of the results by the unsustainable lives and business of humans (Lee and Romero, 2023). While all sectors implement adaptation and actions, they are not ambitious enough to limit climate impact and meet the Paris Agreement (Lee and Romero, 2023; United Nations, 2023b). According to the UN, the science, innovation, expertise and tools are available to make the necessary change, but the actors have to raise their goals, and act upon them. The Paris Agreement was agreed upon in 2015, legally binding 193 states and the European Union, to environmental commitments and limitation of climate change (United Nations, 2023c). The industries have since then made efforts to go green.

2.2 Life cycle management

Traditionally companies' efforts to act on the climate change have had an internal approach. In the early 1990s, the environmental management within companies mainly focused on incremental improvements, trying to improve the internal operations, save costs and to manage risks of the company (Rebitzer, 2015). However, with the current business and climate challenges, to stay competitive while also contributing to sustainable development, the traditional environmental management is no longer sufficient. There is a need for strategies with an expanded scope to understand the complete value chain of the company. In response to the traditional environmental management, life cycle management and thinking was developed in the early 2000s (Jensen, 2001). The concept go beyond business for profit, and provide a holistic view including environmental and social factors to create a balanced, long-term view on the company and its operations (Rebitzer, 2015; Nilsson-Linden et al., 2018).

Life cycle management is a broad framework that is integrated into the objective of an organization (Hunkeler et al., 2003). Integration is key for successful life cycle management, implying that there is a need for continuously working on life cycle management for full integration into the organization (Nilsson-Linden et al., 2018). Top management support is also considered a key factor for successful implementation of life cycle management (Remmen et al., 2007; Hunkeler et al., 2003), however (Nilsson-Linden et al., 2018) also found the support from middle management essential. Top management support for promoting sustainability is not enough if not supported by existing tools, KPIs, etc. that are aligned with the sustainability goals. By integrating life cycle thinking at all levels of the organization, the company can manage decisions that influence the sustainability impact of the product throughout it's life-span. To reach all levels of the company, including everything from R&D, marketing, and purchasing, to strategic planning and corporate management, the life cycle management must stay flexible and implement a variety of concepts, frameworks and techniques (Hunkeler et al., 2003).

A variety of concepts and techniques can be used within life cycle management, depending on the goals and the level of ambition of the individual company (Sonnemann et al., 2015). Broad policies and strategies that encapsulate the mindset of life cycle management are sustainable development, the triple bottom line, dematerilization, eco-efficiency and industrial ecology. Some techniques that can be applied for analytical calculations are life cycle assessment (LCA), life cycle costing, material flow analysis and input-output analysis (Sonnemann et al., 2015). The next section will describe strategies and concepts of life cycle management in the relation to develop sustainable business models.

2.3 Strategies for managing the life cycle

Strategies linked to life cycle management are ways of managing the sustainability challenges that are present in today's society. Circular economy can be defined as slowing or closing the loop of systems, by creating regenerative systems and minimizing waste and emissions (Lüdeke-Freund et al., 2019). The strategies go beyond incremental improvements and is achieved by long-lasting designs, maintenance and repair and reuse of existing products. Working towards circular economy of societal systems requires changes on all levels, makro-, meso- and micro-level. For changes on micro-level, i.e., individual companies, there is a need of adapting a cradle to cradle approach to their business instead of the cradle to grave approach that traditionally has been favoured in companies' way of doing business. Hence, a key to achieve circular economy and sustainable business as a company is to innovate the business model (Lüdeke-Freund et al., 2019; Bocken et al., 2014; Boons et al., 2013).

There are several definitions of business models, but the definition used for this report is from Bocken et al. (2014) and Lüdeke-Freund et al. (2019) and is built on three main elements: the value proposition (the product or service offered), value creation and delivery (key activities and resources), and value capture (cost structure and revenue streams). Innovation of the business model can be done by re-conceptualizing the purpose and the value creating logic of the firm, and by rethinking the perceptions of value (Bocken et al., 2014).

Connecting sustainable innovations to new business models is often a win-win situation for the economic performance and the environmental sustainability (Boons et al., 2013). Seen from a business model perspective, three aspects are essential for sustainable innovation:

- The value proposition is built around the exchange of value and not around a specific product.
- The company is aware of being part of a larger system, like with the customer interface and their supply chain.
- Costs and benefits are distributed between all actors involved.

Companies can use several strategies and capabilities to innovate their business models to become more sustainable (Bocken et al., 2014). Sustainable business model is defined by Lüdeke-Freund (2010) as "a business model that creates competitive advantage through superior customer value and contributes to a sustainable development of the company and society". One strategy for developing a sustainable business model is to deliver functionality rather than ownership (Bocken et al., 2014; Reinhardt, 1999). Another strategy for sustainable business model innovation can be related to the technology archetype. By using low carbon manufacturing, lean manufacturing or additive manufacturing, material and energy efficiency are maximized. Further, creating value from waste by applying circular economy mindset and closing the loop of system is also a strategy that can be integrated in the business model to make it more sustainable (Bocken et al., 2014).

In particular, the switch from product-to-service focus is emphasized as a way for companies to do sustainable business (Boons et al., 2013; Reinhardt, 1999; Bocken et al., 2014). By rethinking the notions of property rights, companies can switch from selling a product to sell a service (Reinhardt, 1999). By shifting the ownership of products from the customer to the producer, the link between profit and production breaks (Bocken et al., 2014). Further, it creates incentives and opportunities for the manufacturer to handle through-life and end-of-life issues, and to prolong the life span of products by maintenance and repair (Reinhardt, 1999), which can be linked to the literature on circular economy and slowing or closing the loop of systems. Borland et al. (2019) also elaborate on strategies for sustainable business in line with the aforementioned articles. Bocken et al. (2014) distinguished between a transitional and transformational strategy, where the transitional strategies aim to reduce the negative impact, however, it still operates within the linear cradle-to-gate perspective of traditional business strategy. The transitional 5 R’s presented by (Borland et al., 2019) are: reduce, reuse, repair, recycle and regulate. The transformational strategy on the other hand is about rethinking, reinventing, redesigning, redirecting and recovering to create a fully circular business strategy. Rethinking what the product is and reinventing of the concept are related to the ideas of Bocken et al. (2014) and Reinhardt (1999), where switching the ownership of products is a strategy for sustainable business.

A key challenge for firms adopting sustainable business models is to find a way of capturing the economic value through delivering social and environmental benefits. It is not always clear how environmental and social value can be translated into profit and competitive advantage for the individual company (Bocken et al., 2014). Economic value can be captured by integrating sustainability into the company's business thinking by looking at environmental problems as traditional business problems. By applying traditional business strategies to environmental issues, companies are able to act systematically and realistically about environmental problems, and identify when environmental investments will pay off with positive returns or reduced risks (Reinhardt, 1999).

2.4 Managing the supply chain

Including the upstream activities, i.e. the supply chain, of a company is an important part in order to expand the scope and integrate life cycle management to the strategy. The following section provides a brief introduction to supply chain management.

Also the supply chain is affected by climate change, and the increase in extreme weather create great challenges and disruptions to the global network of interdependent supply chains (Woetzel et al., 2020). The resilience and risk management has been proven insufficient in a number of recent events, among them the blockage of the Suez Canal and the COVID-19 pandemic. In order to make the supply chain more resilient, the company can apply dual source, invest in insurance, collaborate with suppliers in asset hardening, and practice emergency procedures (Woetzel et al., 2020).

The industry of mining and metals are a low tier supplier in many supply chains. The industry of rare earth metal are at increased risk due to the climate changes. For example, calculations have shown that heavy rain in the southeaster parts of China would cause a drop of at least 20 % output of heavy rare earth metals, which would in turn result in deficiency and increased prices (Woetzel et al., 2020). Further, the mining industry have social impact at both national and local level (Mancini and Sala, 2018). The positive local impacts are the stimuli to local economy, and increased job and business opportunities, and the mines may also stimulate development of infrastructure development in the local area (Mancini and Sala, 2018).

However, the negative impacts are often the most prominent, first of all unfair distribution of benefits and the change of traditional livelihood may lead to increased poverty. Further, the labor may be controversial, either forced, child labor and even dangerous working conditions. Accidents may infringe on the safety and health of the locals, as well as the mining may lead to environmental pollution, and water scarcity. Further, the land used for mining may be taken from the locals increasing poverty and limiting land to live of for the rural population. Only in the area of "employment" the positive impact exceed the negative ones, indicating that mining may be beneficial for the employees in the mining industry, but otherwise it will mainly have negative impacts for the local population not employed in the industry.

Focal companies are given increasingly responsibility for activities in their supply chain, which make it important to assess and handle environmental and social risks upstream. It is difficult to affect the low tier suppliers due to their low visibility and susceptible to environmental pressure from consumers. Therefore, Tachizawa and Wong (2014) suggests different approaches and mechanisms a company can use to manage a multi-tier supply chain and the lower tier suppliers. The type of industry influence the effectiveness of the impact of environmental efforts. Static industries typically invest more and are more successful in environmental change in the supply chain than dynamic ones. This is because standards may be less effective if there is much technological change.

Further, firms in higher polluting industries tend to get more institutional pressure, and do therefore develop capabilities and productiveness in sustainability (Tachizawa and Wong, 2014). The ability of the focal company to manage the supply chain is also affected by it's relative power, either economic power or industry influence. Dependency also impact the influence. Joint dependency have a positive impact on the sustainability management, whereas a dependency on the lower tier suppliers may have a negative impact.

The approaches suggested by Tachizawa and Wong (2014) are direct, indirect, work with third parties, and don't bother. Direct approach can be utilized when the focal firm have direct contact with the lower tier suppliers, and can monitor, govern and collaborate with them. The indirect approach is used when the focal firm govern and monitor a supplier through another supplier. This can be done by exerting power to first tier suppliers and make them monitor their suppliers, and thus utilizing cross-tier collaboration to manage compliance through the whole supply chain. Standards is an effective indirect mechanism for coordination. However, for this approach to be effective it is essential with effective communication systems.

The approach of working with third parties suggests collaborating with entities like NGOs (non-governmental organizations), governments or competitors to elaborate sustainability standards, industry regulation, or utilize third parties sustainability database to monitor low tier suppliers. Lastly, the don't bother approach is suitable for firms with less resources that can only manage their first tier suppliers.

2.5 Stakeholders

A firm must be part of an ecosystem of stakeholders to be able to capture and create a feasible value for customers (Dorobantu et al., 2018; Zhang, 2019). Taking stakeholders into the business equation deviates from traditional shareholder management approach by applying a broader perspective on the business' impact, which also is in line with the life cycle thinking. The term stakeholder is defined in the original work by Freeman (2018) as "any group or individual who can affect or is affected by the achievements of the organization's objectives". However, more narrow definitions have also been used which usually solely focus on groups who can affect the company, and not those who are affected by, which often lead to exclusion of the environment as a stakeholder (Dorobantu et al., 2018). Also including groups who are affected brings a proactive element to the stakeholder analysis, because those groups affected by the business today may gain power to influence the business in the future and should thus be taken into account (Freeman, 2018).

As the world of business is moving towards more sustainable and responsible manners, the relationships with stakeholders are to a greater extent being considered (Dorobantu et al., 2018). Businesses must prosper over time and urge to benefit all stakeholders, from employees, customers and suppliers, to the communities in which they operate. Zhang (2019) express that the key to successful sustainability transition is to consider the innovation ecosystem in, which the stakeholders play a huge role, particularly the intermediate user.

The different stakeholder groups may have different and or conflicting interests, making it difficult for the company to please all (Dorobantu et al., 2018). With conflicting interests the company must prioritize. It may act to maximize shareholders value which is the suggestion of financial theorists, or manage in the interest of stakeholders which stakeholder theorists suggest will increase the chances to achieve competitive advantage (Dorobantu et al., 2018). Further, it is important that the profits, benefits and costs are distributed through the network of stakeholders in sustainable business models (Boons et al., 2013; Bocken et al., 2014). Actually, Boons et al. (2013) deem this essential for any sustainable innovation to succeed.

2.6 Technological life cycles and first mover advantages

Anderson and Tushman (1990) propose an evolutionary model for technological change in which an innovation, a technological discontinuity, induce an era of technological variation called the era of ferment, followed by selection of a dominant design, and lastly continuous incremental innovation of the technology. The technological evolution is cyclic and the last phase of incremental innovation may be disrupted by a new discontinuity starting a new cycle.

The discontinuity brings radical advancements in cost or quality of the technology, either of a product or the process behind (Anderson and Tushman, 1990). The era of technological variation is characterized by high variation in the product offer because actors fight for different technological regimes, and within the regimes to become the dominant design. In other words actors will try to retain the old technological regime and destroy the new one, particularly faced with competence-destroying innovations because of the uncertainty and the wish to keep existing know-how. Meanwhile, other actors may hurry to understand and implement the new technology to make their own differentiated offer and reap of early-mover advantages. In Utterback and Abernathy's dynamic model of innovation this phase is called the fluid phase and is primarily characterized by high uncertainty in technology and the market (Allan, 2003).

In case of a competence-enhancing disruption, the resistance is lower and the innovation is faster adopted by the actors (Anderson and Tushman, 1990). The competition ends in the selection of a dominant design, a product which architecture becomes standard and the basis for close future innovation (Anderson and Tushman, 1990), complementary markets and the development of effective competition based on performance, costs and scale (Utterback and Suárez, 1993). If there is low appropriability, e.g. little protection from intellectual property rights (IPRs), and few ways to protect the design, there will emerge only one dominant design because of the easiness for others to imitate (Anderson and Tushman, 1990). However, with high appropriability due to well functioning IPRs, the company may control the diffusion through licensing and it become a strategic decision to make it a dominant design or not. Adopting another design than the dominant design is unfortunate because the company must either pay switching costs at later stages or avoid switching to the standard and miss the benefits that would come with it like economies of scale and infrastructure connected to the design. Companies that fail do usually possess inferior technological resources and are slower in development (Utterback and Suárez, 1993)

Lieberman and Montgomery (1988) write about the advantages an early or first mover may achieve by pioneering on the market with a new product or process. The advantages can arise from three sources; technological leadership, preemption of assets, and buyers switching costs. Technological leadership can be derived from a lead in the experience or learning curve, or by winning in patent races. Preemption of scarce assets can be achieved through the acquisition of scarce assets due to superior information (Lieberman and Montgomery, 1988). By being a first-mover, the company can enter the most profitable niches. Lastly, buyer switching costs give root to first mover advantages as late entrants must spend extra resources to attract the buyer to switch supplier.

While the advantages are many, there are also disadvantages with being a pioneer in the industry. Lieberman and Montgomery (1988) listed four main sources of first mover disadvantages; the ability to free-ride on first movers investments, technology- and market uncertainties, disruptive technologies that provide "gate-ways" for new firm entry, and incumbent inertia which reduce the company's ability to adapt to change. There are great risks of moving early, when there is a lot of uncertainty in the industry regarding the technology and market. However, if the company can influence the selection of dominant design, it may be beneficial to enter during times of uncertainty. The gate-ways effect consider the next technology cycle, where "late movers" are able to act upon shifts in technology and customer demand, and replace incumbents.

2.7 The aerospace industry

The aerospace industry is large, global, and growing. The global aircraft fleet is expected to grow continually the coming years, and the passenger traffic will increase with more than 70% by 2041 compared to 2022 (Stan and Bob, 2022). The industry is highly regulated at all stages to assure safe operations (European Aviation Safety Agency (EASA), 2018). Further, it is characterised by long innovation cycles and large investment costs.

In the aerospace industry radical innovations appear approximately every third decade, when new innovative engine designs are introduced (Epstein, 2014). This can be illustrated by the case of Pratt & Whitney's (P&W) release of the V2500-engine in 1989 (P&W, 2023) and the release of their next radical engine innovation, the PW1000G engine generation in 2016 (Wall, 2016), which almost perfectly harmonizes with the a cycle of 30 years. Based on the technology cycles, two generations are simultaneously in operation in the industry today. These two generations can be classified as Generation 0 (Gen 0) and Generation 1 (Gen 1), where Gen 0 are engines released 30-40 years ago, for example the V2500 from P&W or the CFM56 engine from GE and Safran entering into service in 1982 (CFM International, 2019a). Gen 1 are the next radical innovation of engines, the PW1000G from P&W and the LEAP engine from GE and Safran, both released in 2016 (CFM International, 2019b; Wall, 2016).

Further, the commercial pressure force companies to sell below the manufacturing cost, making it impossible to earn short term profit (Epstein, 2014). The positive cash-flow arise once the engines need maintenance, repair and overhaul (MRO), which can be seen in Figure 2.1. A result of the long cycles and high initial investments of creating new engine technology is a late break even point (Epstein, 2014).

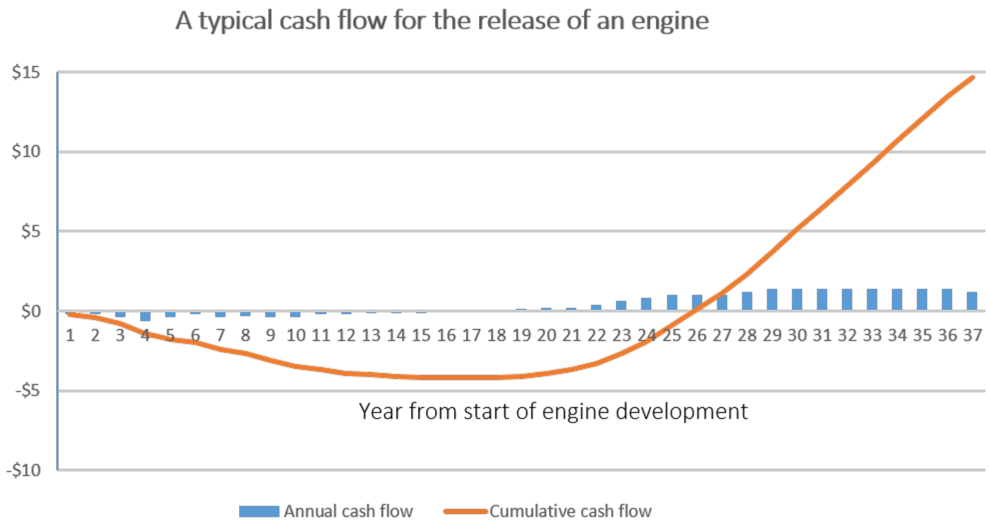


Figure 2.1: *An illustration of the cash flow during the process of developing and selling a jet engine. Inspired by (Epstein, 2014)*

2.8 Climate transition in the aerospace industry

Many initiatives have been taken within the aerospace industry to manage the climate transition. For instance, the International Air Transportation Association (IATA), representing the companies of the industry, initiated Fly Net Zero which is a commitment of the industry to reach net zero carbon emissions by 2050. Further the International Civil Aviation Organization (ICAO), a United Nations specialized agency, has proposed a carbon offsetting and reduction scheme as a guide to this goal (IATA, 2021).

The European Union's Clean Aviation Joint Undertaking is a research and innovation program founded for transforming aviation to become a sustainable and climate neutral industry in the future (Clean Aviation, 2023). Several research programs, such as Clean Aviation and Clean Sky 2, are taking place within the Clean Aviation Joint Undertaking, which all are aiming for innovating new technologies in different parts of the industry, in order to reach net zero in 2050. A majority of the emission of an engine arise in the use phase, estimated to more than 90 % (personal communication, Nylander, 2023.02.02). The main driver for CO_2-emissions in the use phase is the fuel consumption, hence research on optimizing the weight of components has been essential in the aerospace. Another trend in the industry that can be related to increased sustainability and climate transition is the switching from product-to-service taking place, where so called flight hour agreements have been increasingly popular, especially for civil jet engines, and is expected to grow further the coming years (MRO Business Today, 2022).

2.9 The jet engine

The majority of the modern large scale aircrafts are powered by the jet engine (MIT, 1997). The operation process of the jet engine can be summarized by four steps. First, the air is drawn into the intake and are compressed to rise the air pressure. Then fuel is added to the compressed air for burning it in the combustion chamber, placed in the core of the engine. The combustion heats the air resulting in a rapid expansion that produce a high speed, hot airflow. Momentum arise as the hot air flows out through the exhaust nozzle in the end of the engine, which creates energy propelling the aircraft forward. An illustrative picture of an jet engine can be seen in Figure 2.2 below.

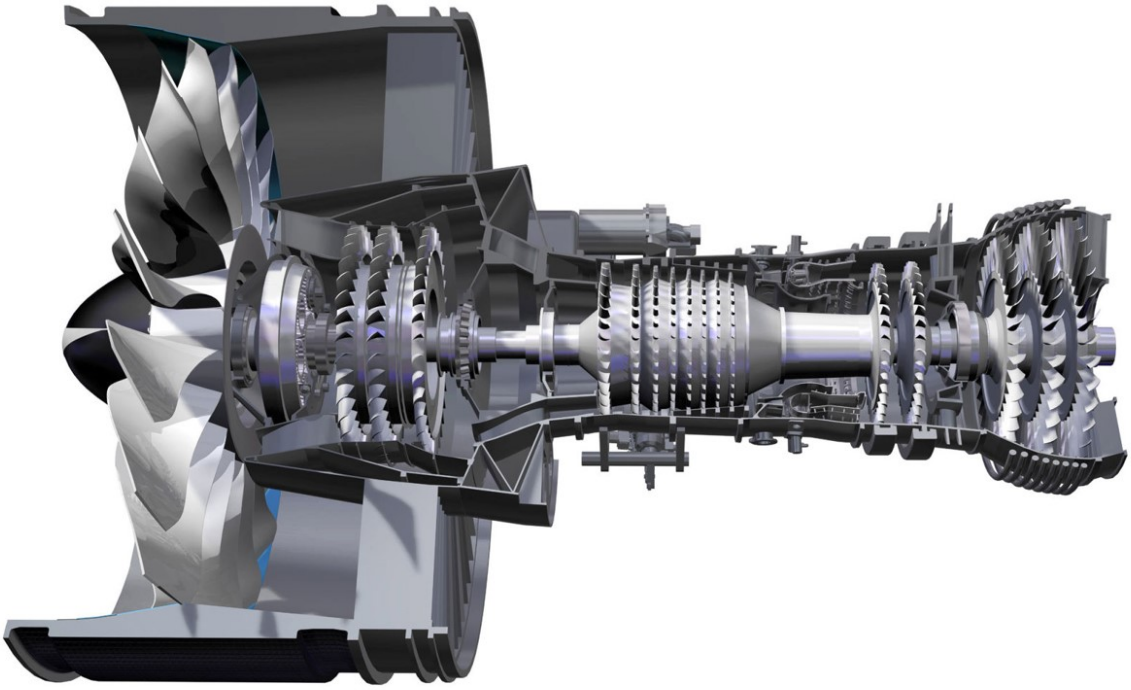


Figure 2.2: *An illustration of the modern jet engine. Source: (Pratt & Whitney, 2023)*

2.10 Materials used in the jet engine

There are high requirements on the materials used in a jet engine, and primarily materials able to withstand high temperature and corrosion are needed (Rolls Royce, 2015). The temperature in the engine varies, being low in the front and increasing towards the combustion chamber, and then decreasing towards the back of the engine. This require the materials close to the core of the engine to be heat resilient and the options of materials are thereby limited. The fuel consumption of the jet engine depends a lot on the total weight of the aircraft, making the weight of materials and components an important aspect to optimize. Figure 2.3 show the types of material and where they are used in the jet engine. As seen, the materials can be categorized into six different categories depending on their characteristics.

The picture also illustrates that the warmer core of the engine demands steel material that are non-corrosion. According to the figure, fan blades and fan disk consist of titanium alloy, while the blisks are made of titanium alloy or a heat resisting and refractory alloy (Rolls Royce, 2015). In newer engines, fan blades is made of composite or aluminium (personal communication, Wallin, 2023.05.19).

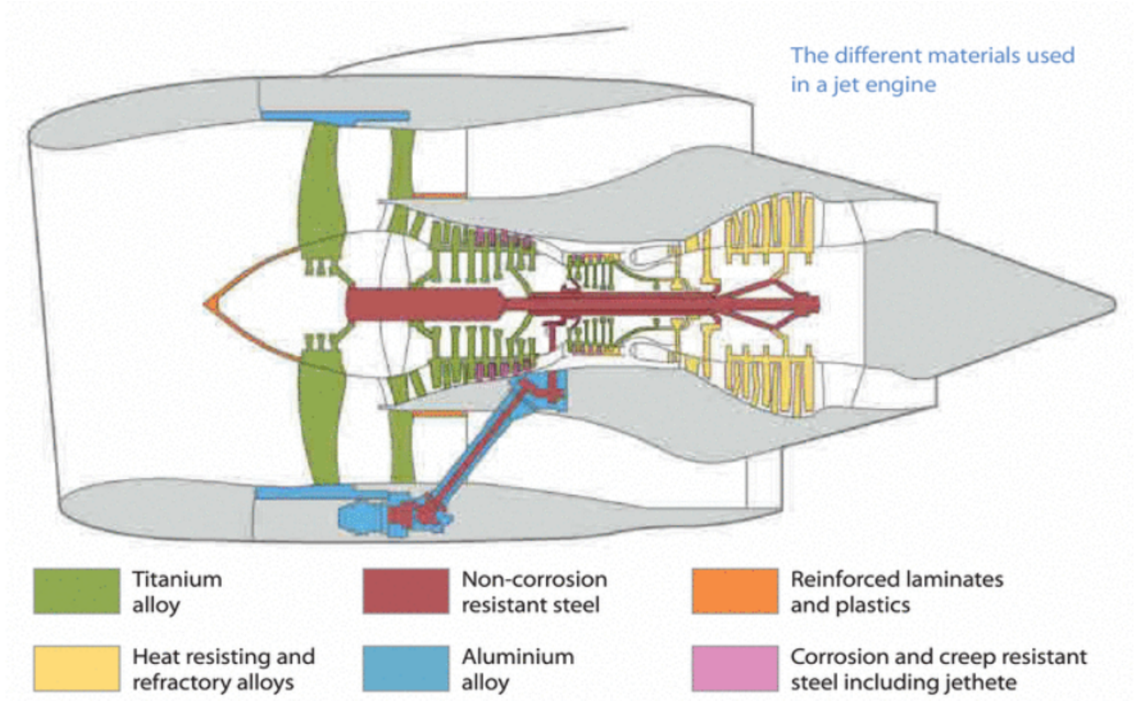


Figure 2.3: *An illustration of the materials most often used in the jet engine.*

Titanium is a widely used metal in the aerospace industry (Malandruccolo and Gialanella, 2020). The properties of titanium and its alloys makes it an advantageous material for aerospace engine parts and it is characterised as a superalloy, which means it can operate at a high fraction of its melting point. Titanium has good corrosion resistance and high specific strength, and also low density, which is an important element in the aerospace industry. Titanium can also go through several production processes; forging, hot-rolling, welding, machining, as well as powder metallurgy techniques such as additive manufacturing (Malandruccolo and Gialanella, 2020). There are a variety of different titanium based alloys matching various purposes and requirements for several industries. The alloy used for the components in this study is Ti64, consisting of 90 % titanium, 6% aluminium and 4 % vanadium.

Other common superalloys in the industry are based on nickel. The material has high corrosion resistance and high strength, and is more heat resistant than Ti-alloys. Ni-alloys are often used for critical components such as the later stages of blisks in the compressor (Malandruccolo and Gialanella, 2020). The specific NI-alloy included in this study is INCO718, consisting of several elements, where the three main substances are nickel (50-55%), chromium (17-21%), and iron (17%) (Metals, nd). INCO718 also consists Niobium (5%).

Composite is also a commonly used material in the aerospace industry, which are materials made of any combination of two or more phases, that together improve the mechanical properties of the material, which can not be achieved by the components alone (Malandruccolo and Gialanella, 2020). Composite is used in the aerospace industry mainly due to the low density of the material. Carbon fibre based composite is the composite used for the components included in this study and consists of carbon fibre and epoxy polymer (Malandruccolo and Gialanella, 2020). Carbon or glass based composites are vulnerable to unexpected impacts like bird or lightning strikes. A metal can be incorporated into the composite, as the more ductile properties of the metal can prevent cracking (Malandruccolo and Gialanella, 2020).

2.11 EU's list of Critical Raw Materials

Several of the compounds used for materials in the aerospace sector are scarce resources and are on the EU's List of Critical Raw Materials (CRM). The CRM list is a list of raw materials, mostly minerals, that are of strategic interest for the economic development and the industries in EU, and that poses a supply risk (IEA, 2023). The CRM list is part of the EU's action plan for these critical materials, which aims to reduce the dependency on critical materials by circular use of resources, sustainable products and innovation (European Commission, 2020). Further, the European Union should also aim for developing resilient value chains of EU industrial ecosystems. Of the reviewed materials, vanadium, titanium, and niobium are compounds included on the list. To mitigate the supply risk of those minerals, it is important to keep the materials longer in the manufacturing loop by rigid recycling processes. The carbon fibre composite does not consist of any materials listed on the EU CRM list.

2.12 Manufacturing of components

Due to the high requirements on structure and quality of the material used in the engine components, the raw materials must go through several melting processes (Personal Contact 2023.02.27). When melting super alloys there are three possible methods to use; Vacuum induction melting (VIM), Electro Slag remelting (ESR) and Vacuum Arc remelting (VAR). Following is the casting process, where the melted metals are poured into shapes to form an object (Rolls Royce, 2015).

Additional shaping of the object can be needed, in which the solid pieces of material is formed by force (Scallan, 2003). One common method of forming is bulk forming, where a bulk of metal is heated and put under compressing loading to create the desired shape. Forging is one method of bulk forming. Following the shaping and forming of the object, the components need machining processes to be further refined into their final shape (Rolls Royce; Personal Contact 27/02). Machining processes involve some sort of removal of material from the unfinished object (Scallan, 2003). These processes are very precise and allow for fine details, but require more resources in terms of labor, energy, waste and time (Scallan, 2003). The left over scraps and metal powder after machining is taken care of and recycled (personal communication, Dahlin, 2023.02.27).

Additive manufacturing is an alternative manufacturing process to the one described above. Instead of subtracting materials for finalizing the component, the component is built up layer by layer by adding material (Ford and Despeisse, 2016). The technique is not new to the industry, however there is a shift towards production of final components using additive manufacturing and not just for rapid prototyping. Additive manufacturing can be used with different materials, among these metal components which will be further described.

Additive manufacturing using metal compound is highly attractive to the aerospace industry, as it matches the requirements and high standards on quality need for the components (Monteiro et al., 2022). There are currently four metal additive manufacturing methods, where the two processes Direct Energy Deposition (DED) and Powder Bed Fusion (PBF) are the most commonly used for applications in the aerospace industry (Garcia-Colomo et al., 2020). DED build the component layer by layer using metal compound as a wire or powder, and the compound is simultaneously deposited and melted in the process (Monteiro et al., 2022). The additive process, building the component layer by layer instead of subtracting it, results in an increased material efficiency with reduced waste in the production process (Ford and Despeisse, 2016; Monteiro et al., 2022).

If a component is made of more than one material there is need for joining the two parts of different material. This is done by joining processes, which include welding, adhesive bonding, brazing and mechanical fastening (Scallan, 2003; Rolls Royce, 2015).

Moreover, components often go through surface treatments such as shot peening and coatings. Shot peening is a process which increases mechanical qualities and durability of the material (personal communication, Dahlin, 2023.02.27). In the coating process, the component is coated with melted metals, alloys, carbides or ceramics to improve corrosion resistance of the material (Makhlouf, 2011; Scallan, 2003).

The components need to hold a very high standard and several methods for weakness and quality testing are used during the manufacturing. The material is ultrasound scanned after the forming, to find any weaknesses in the material structure (personal communication, Dahlin, 2023.02.27). As a last step in the manufacturing process, the component goes through a thorough inspection involving a penetration control to ensure that there are no cracks in the material.

2.13 Repair in the aerospace industry

Aircraft engines must regularly go through maintenance, repair and overhaul (MRO) which has created a large aftermarket for engine MRO, which actually exceeds the market of original equipment of engines (personal communication, Dahlin, 2023.05.31). Historically, capabilities for MRO of engines were developed internally between airlines and MRO companies (Weerasekera, 2020). However, with the entrance of Original Equipment Manufacturers (OEMs) to the aftermarket and advancement in global logistics, the industry is now characterized by specialized repair shops and global transportation of components in need of repair.

MRO of aircrafts and engines is required in order to operate safely during the life time of the engine (Rolls Royce, 2015). The manufacturer have set recommendations for how long a component can fly until it must be inspected and maintained, and requirements for the time intervals are agreed upon with relevant airworthiness authorities (Rolls Royce, 1996). The engines are often inspected on the aircraft, but when they fail to meet the requirements they are taken off for overhaul.

There is also planned overhaul when a stipulated amount of engine flying hours have been reached, called time between overhauls (TBO). TBO is decided on with the operator, manufacturer and airworthiness authorities and is affected by the experience with the engine program, type of operation, utilization and climate. Because of the increasing experience after the engine's launch the TBO may increase up to four times the original required TBO.

Unscheduled overhauls are needed when the engine is damaged. Once the engine has been disassembled it is transported to cleaning. During the overhaul the parts are inspected and decided on renewal or repair for the parts that hamper the overall performance or cannot serve the required quality until the next scheduled overhaul.

2.14 The case company: GKN Aerospace

GKN Aerospace is a world's leading multi-technology aerospace supplier (GKN Aerospace, 2022a). It is a global company with over 15,000 employees at 38 locations in 12 countries around the world. In 2022 the total sales of the company was 3.6 billion USD (GKN Aerospace, 2023). The product portfolio of GKN Aerospace consists of aero structures, advanced engine systems and special products, as well as engine MRO. A simplification of the supply chain in the aerospace industry is presented in Figure 2.4 below. As seen in the figure, GKN Aerospace is not directly in contact with the end customers, but is a tier-1 supplier to aircraft and engine OEMs.

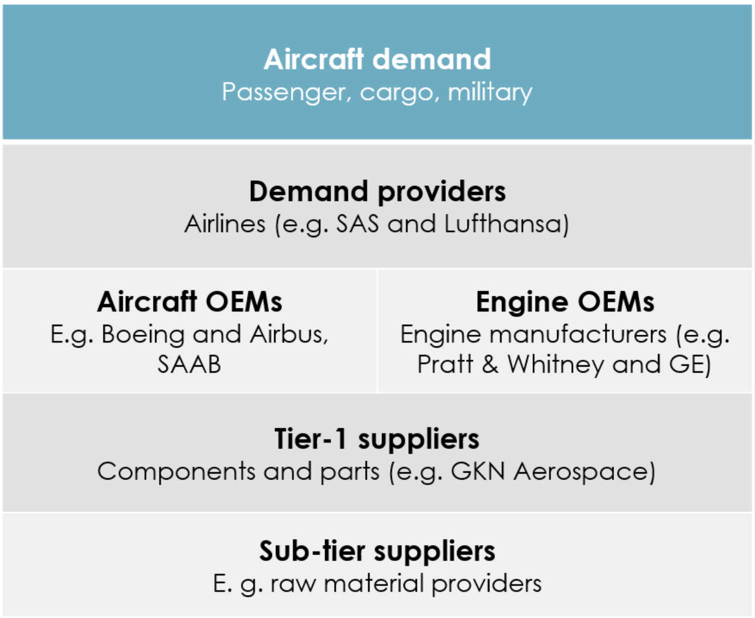


Figure 2.4: *A simplification of the supply network in the aerospace industry, showing the position of GKN Aerospace. Source: Own creation (personal communication, Wallin, 2023.02.20)*

Components manufactured by GKN Aerospace was present in 90% of the aircrafts operating in 2022. GKN Aerospace has provided repair services since the end of the 2nd world war, and has since then expanded the business from military engines to also include civil engine programs and industrial gas turbines (personal communication, Wallin, 2023.02.22).

2.15 Environmental management at GKN Aerospace

The environmental dimension is only one of the three pillars together forming what is defined as sustainability. This definition is known as the 'triple bottom line' and includes the three dimensions of environmental, economic, and social sustainability (Elkington, 1997). All three dimensions must be taken into consideration to achieve sustainability. GKN Aerospace use the approach of the triple bottom line visualizing sustainability with nested circles (Flint, 2010), implying that the three dimensions of sustainability are not just overlapping, but also dependent on each other.

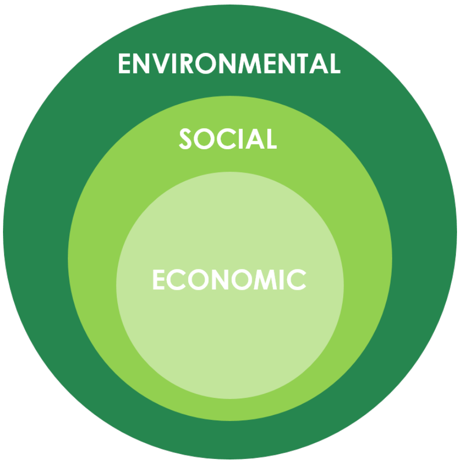


Figure 2.5: *The approach to the triple bottom line definition of sustainability used by GKN Aerospace. Source: Own creation based on Flint (2010).*

Environmental sustainability is at the heart of the business at GKN Aerospace as a strategy to stay in the market lead (personal communication, Wallin, 2023.02.22). The company is looking at several areas of their business to increase the sustainability work. The dimension of circular economy of the repair services aligns the company's climate transition the coming years to reach net zero in 2050. GKN Aerospace also strives for supporting the Sustainable Development Goals (SDGs) from the United Nations. The SDGs address the most urgent global challenges the world are facing in 17 development goals for countries, organizations, and businesses to act on to achieve a more sustainable future for all (United Nations, 2023a). The core business of GKN Aerospace are directly contributing towards six of the SDGs (GKN Aerospace, 2022b), see Figure 2.6. However, this report aims to mainly contribute to goal 8,9, and 13.

Figure 2.6: *The SDGs that GKN Aerospace is directly contributing to in the company's goals and operations. Source United Nations (2023a).*

2.16 GKN Aerospace's parts repair business

Within the business unit Civil Aftermarket, GKN Aerospace performs repair of jet engines and industrial gas turbines GKN Aerospace (2022a). The company has a strong focus in repairing fan blades and is the world's largest non-OEM supplier of such repairs GKN Aerospace (2022a). Several additional components are also in the repair portfolio of the company. All components in today's repair portfolio and their position in the engine are presented in Figure 2.7 below.

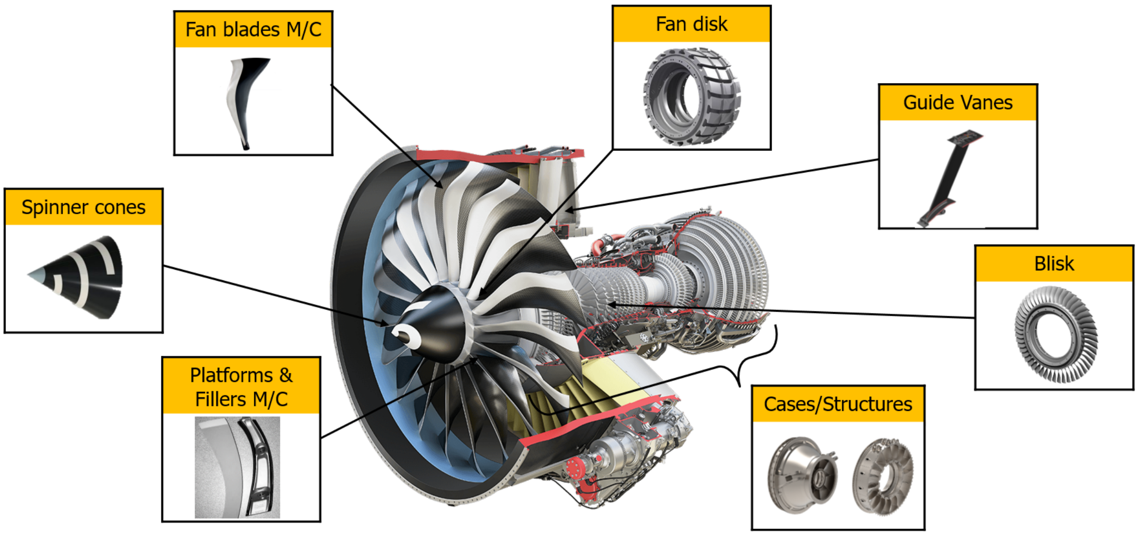


Figure 2.7: *An overview of the repair services provided by GKN Aerospace and where the components are placed in the jet engine. Source: GKN Aerospace (2023).*

The company is expanding its civil aftermarket business and aims to triple the MRO revenue the coming 5-10 years. Investigating the overall sustainability impact of the repair activities is therefore of interest, in order to understand how to achieve sustainable growth.

In the outlook of 2023 and in the future, three of the components in the repair portfolio contributes with approximately 90 % of the total revenue of the civil aftermarket business unit (personal communication, Dahlin, 2023.05.23). These three components are: fan blade, fan disk and blisk. Figure 2.8 below shows the market outlook of the total market for repairing the aforementioned components based on number of shop visits.

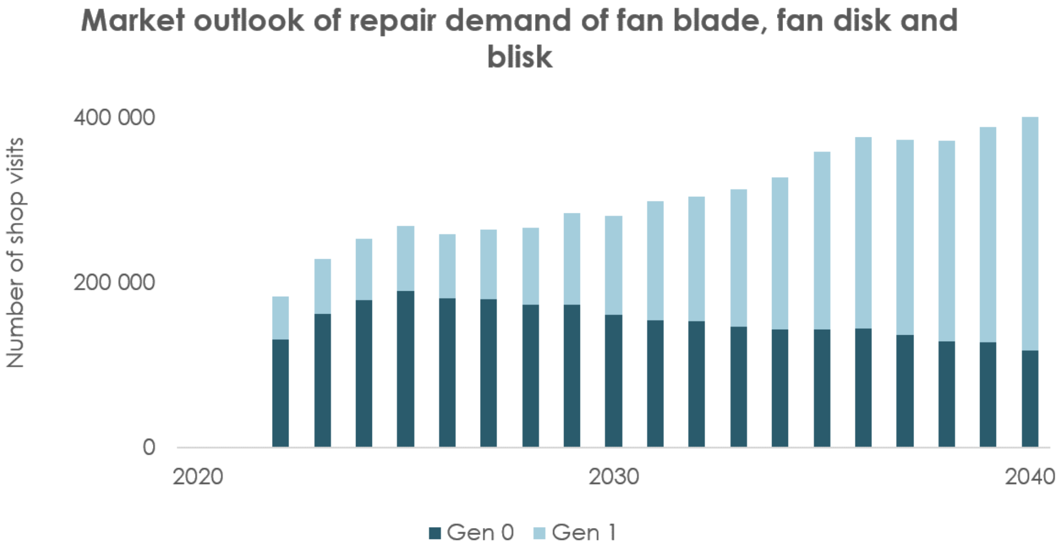


Figure 2.8: *The market outlook of the repair demand for the three components fan blade, fan disk and blisk, based on number of shop visits. Source: GKN Aerospace (2023)*

The components in Figure 2.8 are classified by generations and divided into Gen 0 and Gen 1. The classification is made based on the previous mentioned engine generations in Section 2.7. Among the components of study, the metallic fan blade and some of the fan disks are placed in the old engines, hence corresponding Gen 0. Composite fan blade, blisks and the newer fan disks belong to Gen 1. In the coming years Gen 0 will be phased out and be replaced by the newer engine generation, Gen 1. However, although there is a decline in demand and that Gen 1 eventually will pass Gen 0, many aircrafts operating with engines from Gen 0 are still in service and will be in need of repair for several years to come, as seen in Figure 2.8.

In addition to the change in generation it is clear that Gen 1's increase is faster than the decline of Gen 0, resulting in an overall increased market demand. The picture clearly shows how the total number of shop visits expected to increase year by year in the outlook of 2040.

To understand how the generations impact the repair market for the three components fan blade, fan disk and blisk, Figure 2.9 below illustrates how the components are distributed between Gen 0 and Gen 1.

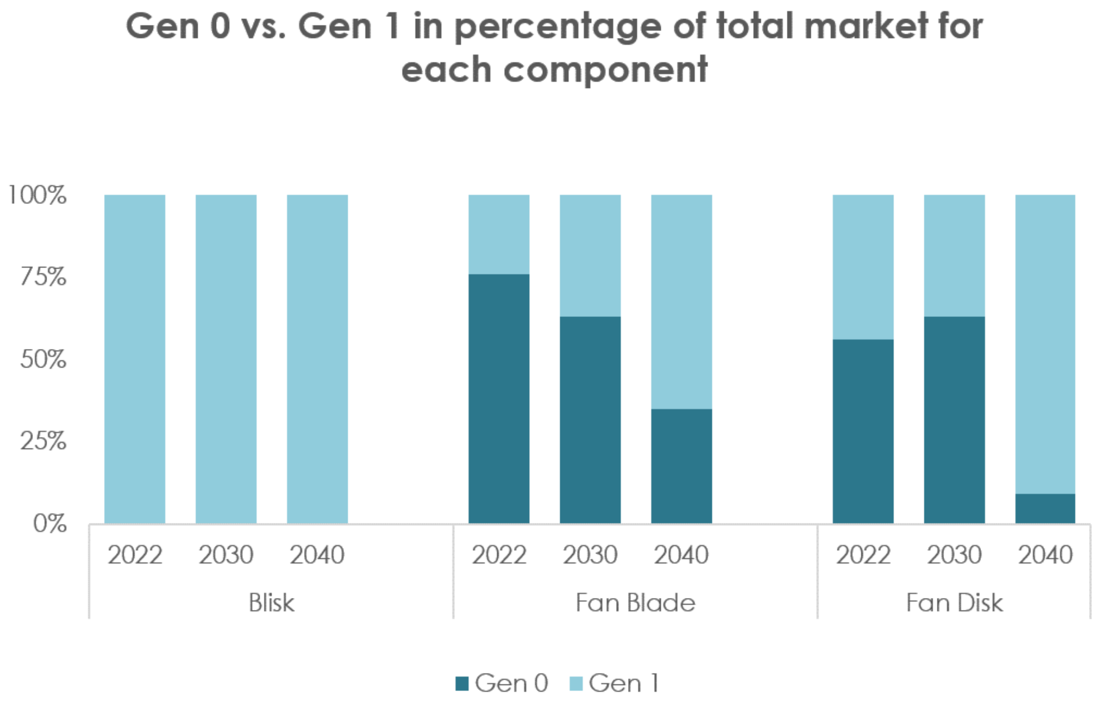


Figure 2.9: *The expected change in numbers of shop visits for the two generations shown by type of component. Source: GKN Aerospace (2023)*

The three components will be further described in the next section.

2.17 Fan blade

The fan blades are part of the fan that is located at the front of the jet engine and is the first compressor. The fan blades are connected to a fan disc which is driven by the turbine through a shaft (Rolls Royce, 2015). The fan rotates and force air into the engine, where it is split in to core and bypass streams. The fan blades position in the front exposes it to several challenges such as icing, bird-strike and ingestion of debris, and the blades are prone to wear and corrosion. There are therefore often need for repair of the blades. There are several types of fan blades, and this report investigate fan blades from the two described generations: metal fan blades of Gen 0 and composite fan blades of Gen 1.

Figure 2.10: *An illustrative view of a composite fan blade. Source: GKN Aerospace (2023).*

The composite fan blade consists of two parts, the metal leading edge in Ti-alloy and the composite body, which are joined together at the end of the manufacturing process, see Figure 2.11 for an overview of steps involved in the manufacturing process.

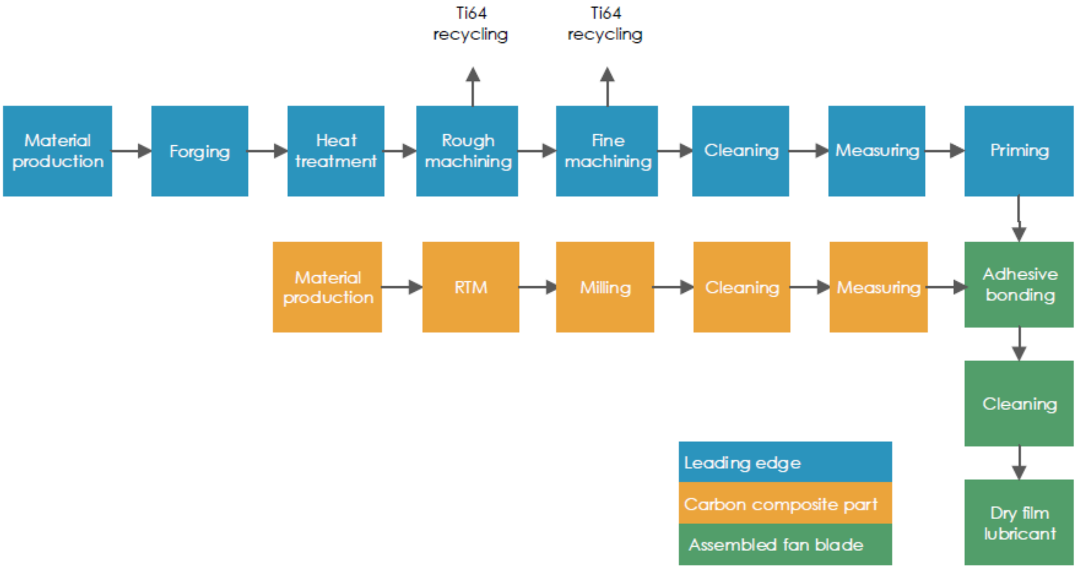


Figure 2.11: *Flowchart of the production process for a composite fan blade.*

As the composite fan blade consists of two parts, the metal leading edge and the composite body, the repair process of the leading edge of a fan blade means that the whole metal part is changed. This means that the repair process is very similar to the one of new production, with the saving of only the epoxy resin body. The replaced leading edge is manufactured from a billet, and due to the shape of the leading edge, the waste is high. The repair processes is illustrated in Figure 2.12

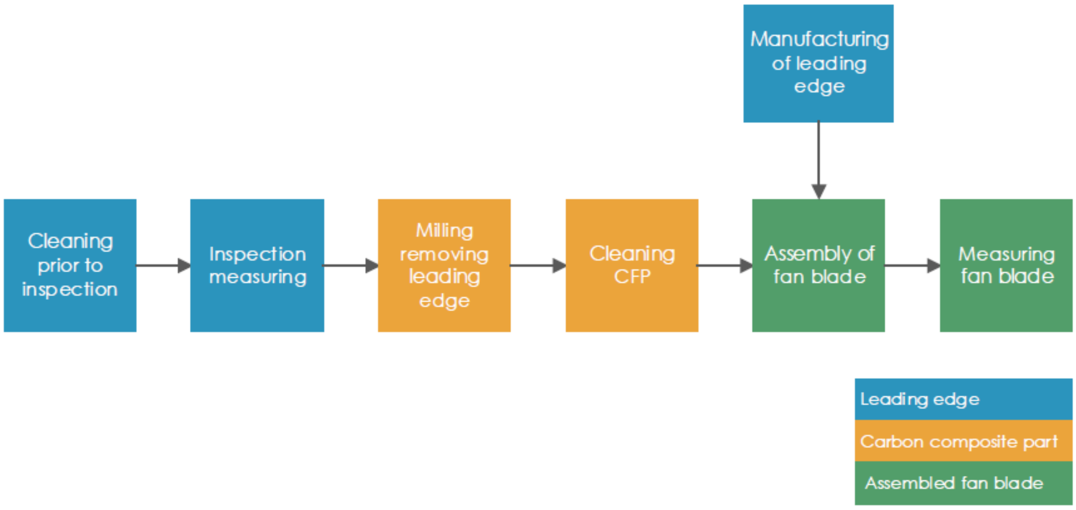


Figure 2.12: *Flowchart of repair process of a composite fan blade.*

The manufacturing process of a metal fan blade differs from the composite fan blade, as it is a one-piece component, made from one solid billet material. Hence, there is no joining process involved. The process can be seen in Figure 2.13 below.

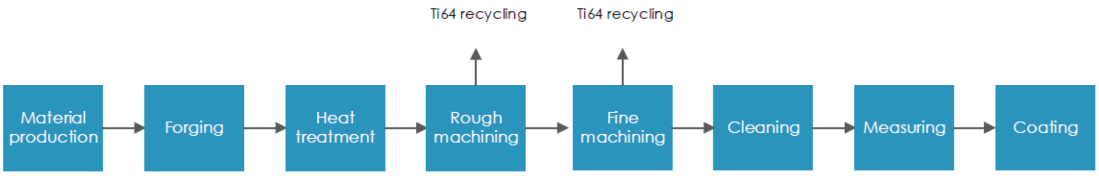


Figure 2.13: *Flowchart of the manufacturing process of a new metal fan blade.*

The simplest repair, basic repair, is when there are no compromises to the components quality. Once it is decided that the fan blade is fit to fly, the component will need a new coating, Cu-In-Ni Thermal spray coating and dry film lubricant to be reconditioned to fly (personal communication, Wallin, 2023.01.26). If there are damages to the fan blade, more comprehensive repair is needed, so called heavy repair. The heavy repair process of a metal fan blade is simpler than the one of the composite fan blade, see Figure 2.14 for illustration of the process. Here, the repair is done using just a small patch of metal. The patch is attached to the fan blade by welding.

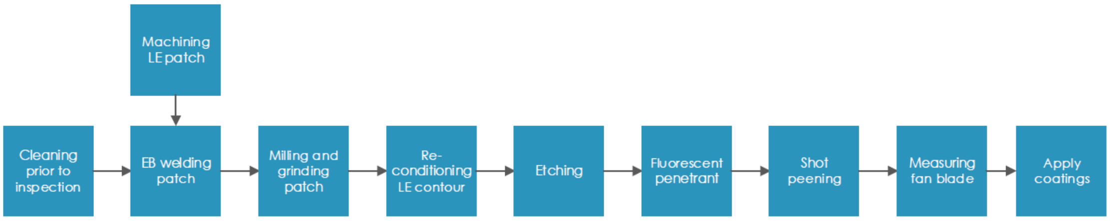


Figure 2.14: *Production process for repairing a metal fan blade.*

2.18 Fan disk

The fan disk is a critical component that provide attachment to fan blades and the nose cone (Rolls Royce, 2015). The function is to react upon centrifugal load from the fan blades, and absorb impact loads. Fan disks are usually made of forged titanium, and the fan disc studied in this report is made of Ti64. The fan disc must resist a centrifugal load of one hundred tons from each blade, and force them to stay in their circular path (Rolls Royce, 2015). Because of all the stress that must be tolerated the fan disks are big and heavy, which makes the design important as weight must be minimized in air crafts.

Figure 2.15: *A model of a fan disk. Source: GKN Aerospace (2023).*

A fan disk is manufactured by processing a solid billet of metal and the steps involved in the manufacturing is similar to the ones of manufacturing a metal fan blade, and is illustrated in Figure 2.16. Due to the shape of the fan disk, the material usage is very high.

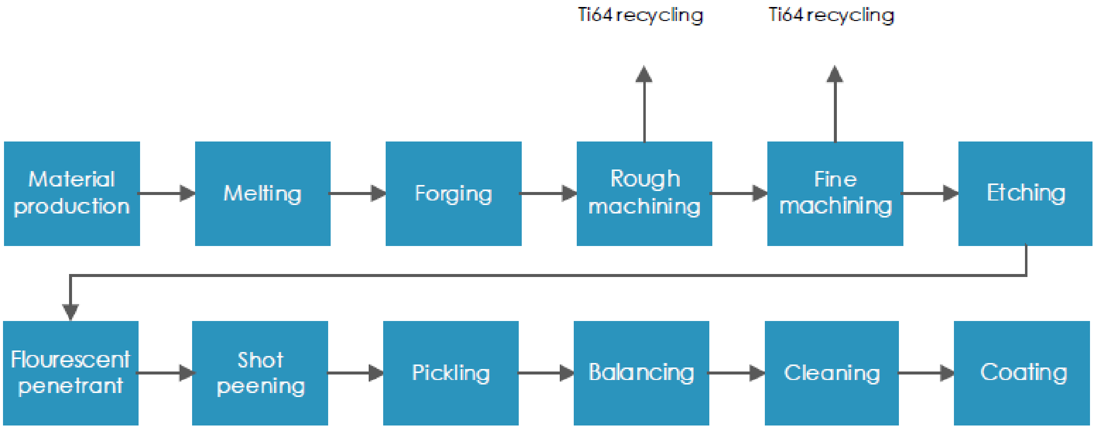


Figure 2.16: *Flowchart of the new manufacturing process of a fan disk.*

The most basic repair of fan disks is similar to that of fan blades. The most heavy repair performed on fan discs is when the disc's dimensions have been deformed and must be restored, see Figure 2.17 for visualization of the repair process. This is done by applying thin layers of new material through plasma spraying (personal communication, Wallin, 2023.09.02). Plasma spraying is a coating method in which material is inserted in a plasma jet, melted and then sprayed on the wanted object (Makhlouf, 2011). Although there are well established repair methods for fan disks, the high requirement of the functioning of the component makes it challenging to repair, and the scrap rate of the components is considerable (personal communication, Dahlin, 2023.01.23).

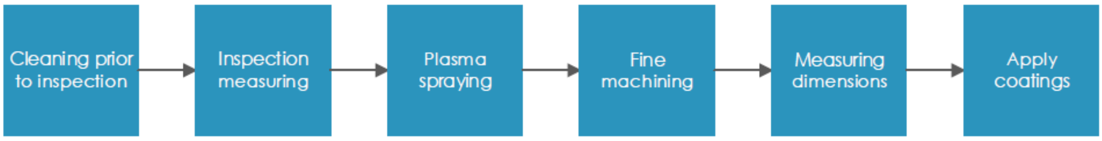


Figure 2.17: *Flowchart of the repair process of a fan disk.*

2.19 Blisk

Blisks are a relatively new design concept within aero engines (Malandruccolo and Gialanella, 2020). In the blisk, the fan blades are directly attached to the disk, which is illustrated in Figure 2.18 below. A modern jet engine contains of about 5-10 blisks located in the compressing part of the engine. Integrating the blades and disk reduces the total weight of the component with up to 30% (Fricke et al., 2021). The blisks improves the engine performance by increased efficiency and reduced fuel consumption (personal communication, Dahlin, 2023.05.30). The risk for fatigue fracture of the blades is also reduced, prolonging the life-span of the component.

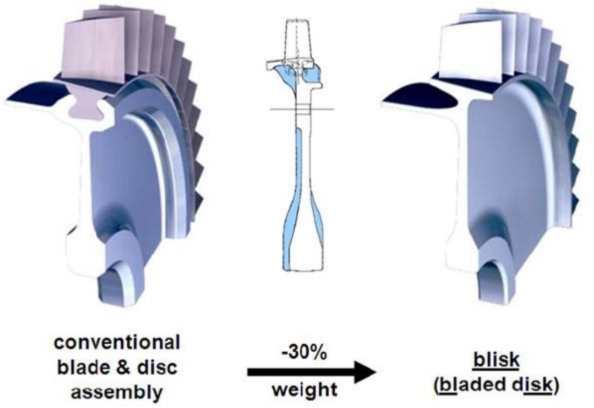


Figure 2.18: *An illustrative view of how the blades and disk are integrated. Source: GKN Aerospace (2023).*

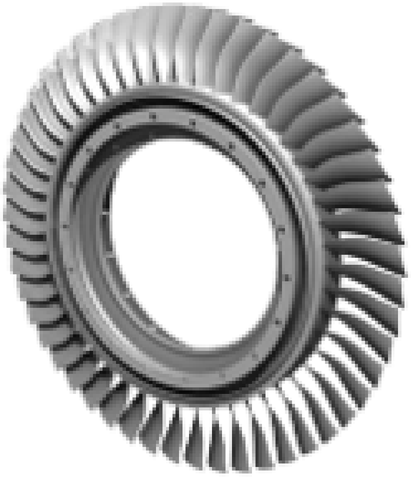


Figure 2.19: *A model of a blisk. Source: GKN Aerospace (2023).*

A blisk is manufactured by milling one solid block of the used raw material, resulting in high material waste in the process. According to a study of blisk manufacturing, only 20 % of the raw material was used for the final component, hence a waste of 80 % (Fricke et al., 2021). Due to the geometry and materials used in a blisk, the manufacturing process is very complex and it is one of the most challenging components in the jet engine to manufacture.

Blisks in the earlier stage of the compressor are often made of titanium alloys, while the blisks in the later stages with increased temperature are made of nickel alloys, because nickel is more heat resistant.

The manufacturing process of a blisk is visualized in Figure 2.20 below. The flowcharts represent the manufacturing process of both the titanium and the nickel blisk as there is no difference in which steps are involved. However, there is a difference in operation time for each step, as the size of the blisk and material properties of the metals differ.

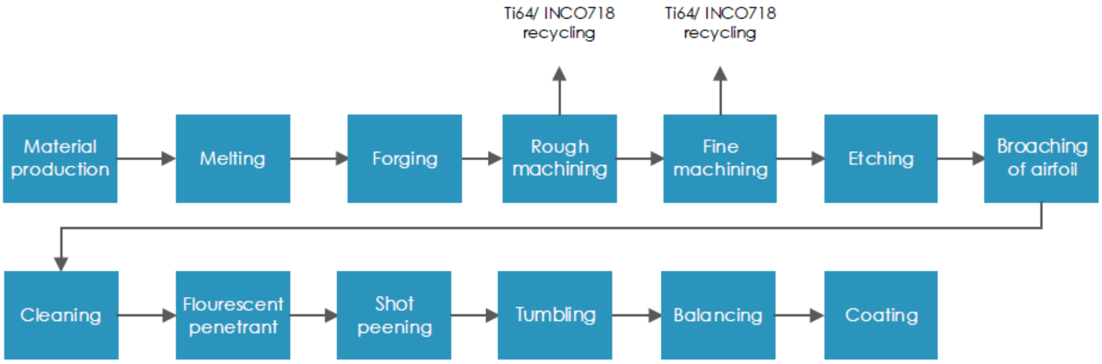


Figure 2.20: *Production process for new manufacturing of a blisk*

Repair of blisks is under development and are not implemented in the industry today, hence the presented flowchart in Figure 2.21 represents the expected process.

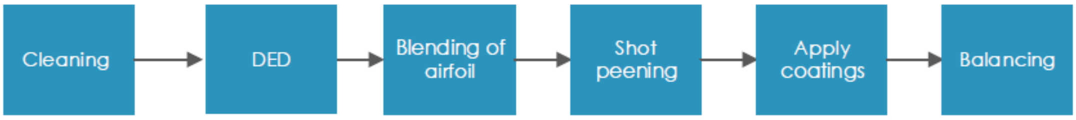


Figure 2.21: *Intended production process for the repairing of a blisk.*

3

Method

The following chapter provides a description of the method used for the study. An overview of the research design of the study can be seen in Figure 3.1 below and then a deeper description and motivations of each step will follow.

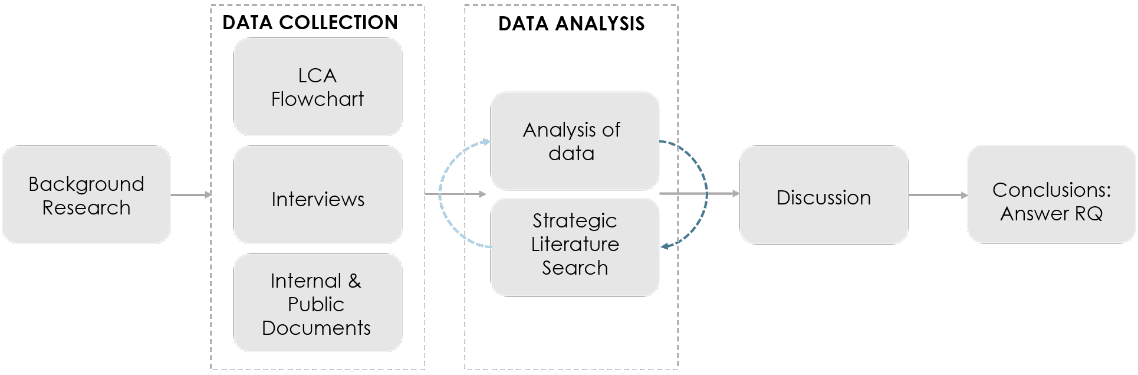


Figure 3.1: *Visualization of the research design of the study. Source: Own creation.*

3.1 Literature and other literature documentation

Many different types of literature has been utilized in the study; Academic articles, public documents and web pages, company internal documents and books. The subjects studied through literature was; the aerospace industry, jet engines, life cycle management, sustainable supply chains, stakeholder theory, technology life cycles and first mover advantages.

Academic articles were found in four ways. Either through suggestion from an academic supervisor, articles from previous master courses at Chalmers University, search in the databases of Chalmers Library and Google Scholar, or through snowball search following the references of relevant literature. The academic articles used in the subjects of life cycle management were suggested by the supervisor or found through search strings of "life cycle management", "environmental management" and "circular economy". The articles used for the subject sustainable supply chains were selected from a SSC course at Chalmers, and found through search strings including "metal mining" and "social responsibility". stakeholder theory, technology life cycle and first mover advantages. These articles were used to build a theoretical framework in which the analysis could take place.

Public documents that was used were found on different official web sites, ie. GKN Aerospace, The UN, and International Air Transportation Association (IATA) and International Civil Aviation Organization (ICAO). These were also the web-pages that were utilized in the report. The web-pages and public documents, e. g. industry reports, were used to understand the industry and environmental context as well as legal perspectives and the industry actors. Search strings used for finding relevant web pages with public documents were "GKN" and "sustainability in aviation" and "United Nations aviation industry".

Internal documents of the company was found through suggestions from sustainability experts, a repair business manager and engineers of the case company. The internal documents were about the subjects of the aerospace industry and jet engines, describing technical aspects and market assumptions. Also, in the investigation of environmental and financial impact of the repair business internal documents were gathered from company representatives through email conversations, some times in the aftermath of an interview. Internal life cycle assessments (LCA) were red to find a suitable method and to understand the main CO_2 drivers in the engine manufacturing and repair processes and energy usage for certain processes. The LCAs were found in an internal database and on the recommendation from internals at GKN Aerospace.

Books were found through search in the databases of Chalmers Library and Google Scholar. They were about the subjects of jet engines, stakeholder theory and life cycle management. They were found through the same search strings as for articles, and the jet engine subject used search words like "jet engine", "manufacturing", "repair" etc.

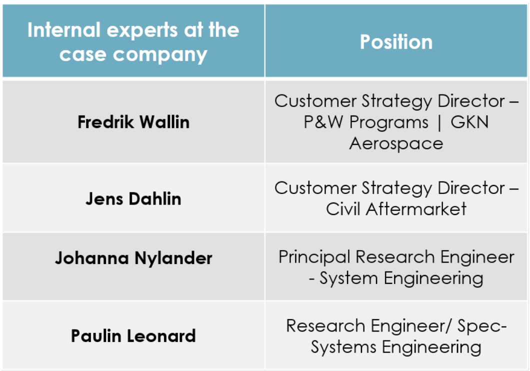
3.2 Interviews

Apart from literature, much data and information was gathered through interviews with company representatives. The interviews were of semi-structured character, and were used to find environmental and cost data, as well as industry and company specific information.

As in the nature of semi-structured interviews, there were a selection of predetermined questions (Bell et al., 2018), ranging from five to ten, for every interview. There were always two interviewers present at the interviews, to facilitate note taking and follow-up questions. Initial interviews were recorded, however this practice was abandoned because of the risk of recording confidential material, and the note taking was deemed sufficient. Any uncertainties were clarified during or after the interview. Most interviews lasted between 25 minutes and an hour, however occasionally they would last for longer, up to two hours. Some interviews were held in person if physical proximity allowed, while others were held over video connection due to distance.

In initial phases of the study, there were interviews with a focus on understanding the industry, and which components that were the most interesting to study. The interviewees for these interviews were company representatives in manager positions. At later stages, interviews with process and product engineers were conducted to gain information on specific repair or manufacturing processes. Often, in the aftermath of interviews with technical subjects, the interviewee would send data over mail, such as numbers on energy consumption and time, manuals or other specifications of interest.

Internal experts at the case company have contributed with valuable insights to the industry and company of investigation. Figure 3.2 summarizes the internal experts with their respective position that have provided information. Their last names will be used when being referred to in the report.



Internal experts at the case company	Position
Fredrik Wallin	Customer Strategy Director – P&W Programs | GKN Aerospace
Jens Dahlin	Customer Strategy Director – Civil Aftermarket
Johanna Nylander	Principal Research Engineer - System Engineering
Paulin Leonard	Research Engineer/ Spec- Systems Engineering

Figure 3.2: *An overview of the internal experts and their respective position at the case company.*

3.3 Environmental analysis

The environmental analysis consisted of material flow charts, CO_2-eq calculations from gate to gate and repair for the five components of study. To do this, data had to be gathered, synthesized and then interpreted to analyse the environmental impacts. The following sections will describe how the environmental data was collected, handled and used for analyze.

Flowcharts were used as a way to structure the data collection. The flowcharts illustrate the processes of manufacturing and repairing the five components of the study. They were created early in the process in order to gain a comprehensive view of the processes that was under study and to give structure to the further data collection. These were created partly during workshops, but also based on information from interviews, internal documents and a study visit at the case company's repair cite. The flow charts is found in Chapter 2 (Topic overview) in the section of respective component.

The equation for the environmental impact of repair and manufacturing was simplified to consist of the impact from the raw material, machining processes and heating processes, including heat treatment in oven, melting and forging. This decision was taken because the background literature search of internal LCAs showed that these factors were the main environmental impact drivers. In total, their impact accumulated to approximately 80 % of the total impact of engine components according to internal component LCAs. Therefore, and because of limited scope and information access, the calculations were simplified to include these aspects and exclude all other small contributors assumed negligible.

The numbers on weight, dimensions and energy consumption of the different processes were collected from interviews, mail conversations, the public database GRANTA and internal documents. The data was given in different measurement units and had to be calculated to fit the right units e.g. we had to use dimensions and material density to calculate weight. In order to have the numbers for the final environmental impact equation, a number of calculations had to be done. Some were specific to one component because of limited information access, e.g. calculate weight as mentioned, whereas many were repetitive and will be described in depth.

First, the CO_2-eq for manufacturing a new object was calculated for each component. Figure 3.3 illustrates the equation used to calculate the impact. The constituting parts will be described further.

$$\boldsymbol{New\ component[kgCO2]} = Input\ material + forging + machining + heat\ treatment\ (oven)$$

Figure 3.3: *The equation used for calculating total CO_2-eq impact of manufacturing any new component.*

The input material impact was calculated with the weight of the material received from the forging supplier for the component in question, multiplied by the material footprint for the specific material. This is illustrated in Figure 3.4. The input weight was calculated with the input volume of the forge multiplied by the density of the material of the forge, also illustrated in Figure 3.4.

$$\boldsymbol{Input\ material[kgCO2]} = Input\ weight\ [kg]\ \times Raw\ material\ \left[\frac{kgCO2}{kg}\right]$$

$$\boldsymbol{Input\ weight\ [kg]} = Input\ volume\ [m^3] \times Density \left[\frac{kg}{m^3}\right]$$

Figure 3.4: *The equation used for calculating CO_2-eq impact of any input material in both manufacturing a new component and repairing a component.*

The material footprint was based on numbers from the public database GRANTA. The material footprint found in GRANTA was assumed to be for double melted metals because this is the typical grade of melting. However, the metals used in the aerospace engine components are triple melted to reach a higher quality. This increase the environmental impact, and had to be accounted for. Therefore, a new formula for impact of triple melted raw material was developed pictured in Figure 3.5. To account for the extra energy of melting the material one more time, the casting energy multiplied by the energy impact of the US grid was added to the original raw material impact found in GRANTA.

$$\boldsymbol{Raw\ material\ tripple\ melted}\ \left[\frac{\boldsymbol{kgCO2}}{\boldsymbol{kg}}\right] =$$

$$Raw\ material\ production \left[\frac{kgCO2}{kg}\right] + casting\ energy \left[\frac{MJ}{kg}\right] \times US\ Grid\ \left[\frac{kgCO2}{MJ}\right]$$

Figure 3.5: *The equation used for the* CO_2/kg *impact of triple melted material in both manufacturing a new component and repairing a component.*

Regarding the forging impact, the numbers found in previous internal LCAs and the one in GRANTA differed. With a relatively limited number of LCAs and no guarantee that the calculations of the LCA would be valid for every of the five components, the average impact number of GRANTA was chosen. The equation for forging impact can be seen in Figure 3.6.

$$\boldsymbol{Forging}[\boldsymbol{kgCO2}] = input\ weight\ [kg] \times forging\ energy\ \left[\frac{MJ}{kg}\right] \times US\ Grid\ \left[\frac{kgCO2}{MJ}\right]$$

Figure 3.6: *The equation used for the* CO_2*-eq impact of forging the material that is received from the forging supplier, primarily in manufacturing but also material for repairing components.*

The components do then go through a number of machining processes and the equation for the impact of these is shown in Figure 3.7. Machining was roughly divided into fine and rough machining, to distinguish the more and less energy intensive processes, assuming very little environmental impact from the other machining processes, such as measuring and coating. The numbers respective weights was either collected directly from engineers or calculated knowing the total weight removed and that the depth of fine machining was 5mm of the surface. The energy consumption for the processes was collected from GRANTA, and multiplied with the CO_2-eq impact of the US energy grid. Much of the machined material went to recycling, and this was also taken into account.

$$\boldsymbol{Machining\ [kgCO2]} = \\ \left(weight\ fine\ machining\ [kg] \times fine\ machining\ energy \left[\frac{MJ}{kg}\right] + weight\ rough\ machining\ [kg] \\ \times rough\ machining\ energy \left[\frac{MJ}{kg}\right]\right) \times US\ Grid\ \left[\frac{kgCO2}{MJ}\right]$$

Figure 3.7: *The equation used for the CO_2-eq impact of machining a certain amount of material, primarily used in manufacturing but also material for repairing components.*

Lastly, the oven heat process, which was applied to components where there had been performed bonding or welding, thus only the composite fan blade, and the repair of the metal fan blade. There had previously been done some internal measurements on oven heating, among others on the exact composite fan blade of the study. This data was applied directly in the calculations of the composite fan blade, and was further used to calculate the heating process for the repair of the metal fan blade. The energy consumption differ depending on if the oven is ramping up, on a plateau or cooling down, and at what temperature these stages are performed. Since the temperature function for the composite and metal fan blades were not identical a qualitative assessment was done to decide on which power to apply at different stages of the metallic fan blade. The general equation for the CO_2-eq impact of the heating process is shown in Figure 3.8.

$$\boldsymbol{Heat\ treatment[kgCO2]} = \\ \frac{(Energy\ ramp\ up\ [MJ] + Energy\ up\ time\ [MJ] + Energy\ cool\ down\ [MJ]) \times US\ Grid\ \left[\frac{kgCO2}{MJ}\right]}{Number\ of\ components\ in\ the\ oven}$$

Figure 3.8: *The equation used for the CO_2-eq impact of heating one object in an argon oven.*

The environmental impact analysis of the repair processes used the same equations as the manufacturing of new components. However, the processes included in the repairs differed more between the components, than the manufacturing processes. Some of the repairs did not require significantly much material nor energy, but the small amounts of material posed social risks to the workers. The material specifications were investigated, and any risks were noted. Also the repair of the blisks differed as the repair method was assumed to be AM, resulting in a lower material usage but additional energy consumption.

Eventually, all data was gathered to calculate the CO_2-eq impact of manufacturing and repairing the five components of the study. The numbers were then analysed by multiplying and scaling them to represent the footprint of an engine shipset, i. e. the quantity of which the component in question occurs in an engine. The potential savings of CO_2-eq were also scaled with the market prognosis of the respective component, to provide insights on the potential CO_2-eq saved by meeting the market demand of repair. Lastly, some of the numbers were normalised to avoid disclosing any confidential information, while still exposing the relations between repair and new manufacturing.

3.4 Economic analysis

The economical data was gathered through company representatives, primarily through email conversation. It was important that the economical analysis did not disclose any of the company confidential information, among others the profit margin. Therefore the cost data was used, which provided information about how costly it is to manufacture vs. repair. Further assumptions could be made on this information to analyze value and economical benefit. There was also a desire for the result to be generalized and applicable for the future, and thus the data had to be independent on market functions and conjuncture. For this, looking at costs was also assumed more reliant as they are detached from profit margins of the case company.

4

Results

The following chapter presents the results of the environmental and financial calculations. The first sections review environmental impact for each of the studied components, followed by comparison of environmental impact between the components. The environmental results are then related to the market outlook of repair visits. Lastly, the financial results are presented.

4.1 Environmental impact of Fan blade in a cradle to gate perspective

The fan blade in composite (Gen 1) has more than twice the environmental impact of manufacturing a new component compared to repairing. As seen in Figure 4.1 the highest CO_2-eq driver is the input material received at GKN, for both manufacturing and repair. The manufacturing processes are close in CO_2-eq impact, and it is from the increased material consumption that the new production gains its large footprint. The positive impact of recycling of the new production is relatively low because the main material, composite, is not possible to recycle, and only leftover metal material can be recycled.

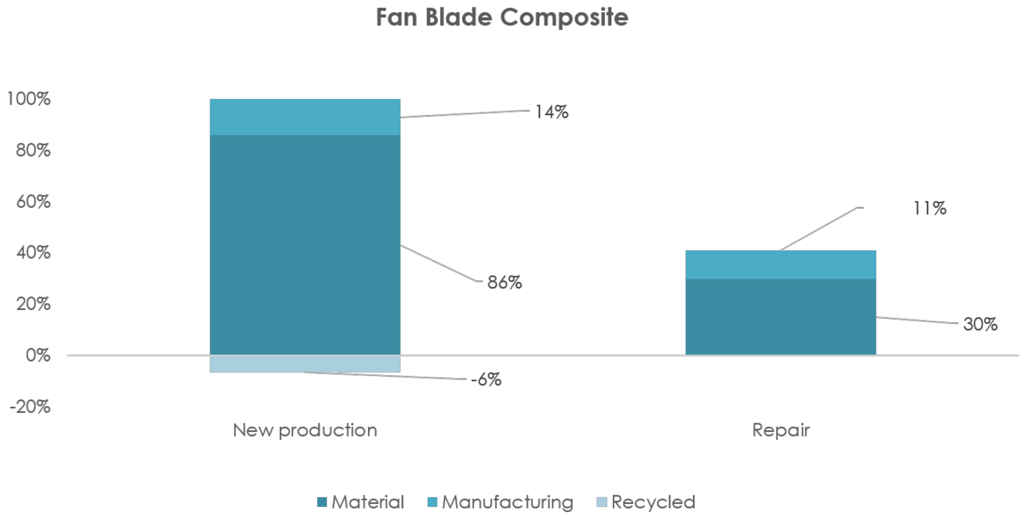


Figure 4.1: *The CO_2-eq of manufacturing and repairing a fan blade in composite.*

The fan blade in metal (Gen 0) has a relatively low impact of repair, close to 15 % of the footprint of new production seen in Figure 4.2. Again, the material is the high CO_2-eq driver, and the main reason to why new production has a higher impact than repair. The material required for repair is only about 4 % of that required for new production. The repair has a higher impact of the manufacturing process than new manufacturing which is caused by the methodology of the calculations in the study. Basically, a new manufactured blade and a repaired blade goes through the same heating processes, but the format of the data available in GRANTA on manufacturing resulted in a majority of the heating processes to be categorized as 'material' as they take place before the material enters the production site. However, the total environmental impact is not affected by the categorization.

Further, the positive recycling impact of new production is higher than the composite blade because all waste material is possible to recycle, while the recycling are assumed negligible for repair.

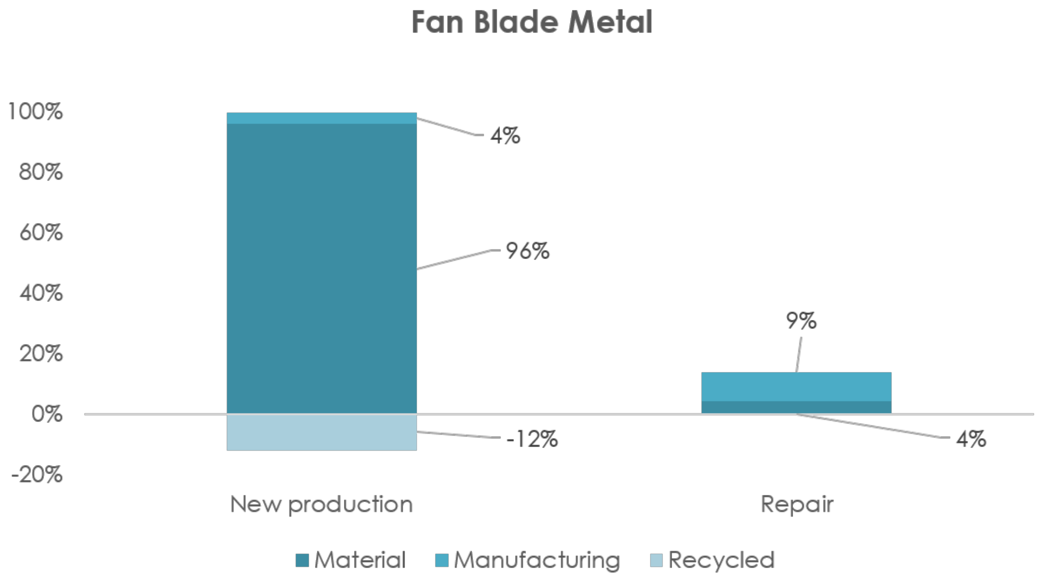


Figure 4.2: *The CO_2-eq of manufacturing and repairing a fan blade in metal.*

4.2 Climate impact of Fan disk in a cradle to gate perspective

Figure 4.3 illustrates that the environmental impact is drastically reduced in repairing a fan disk compared to producing a new one. The fan disk is a heavy component which cause it to have a high impact of the material input, representing more than 99 % of the components impact. Repairing a fan disk is done with very little material, which cause it to have very low impact. The positive recycled impact is close to 14 %, and not far from the same percentage as the fan blade in metal.

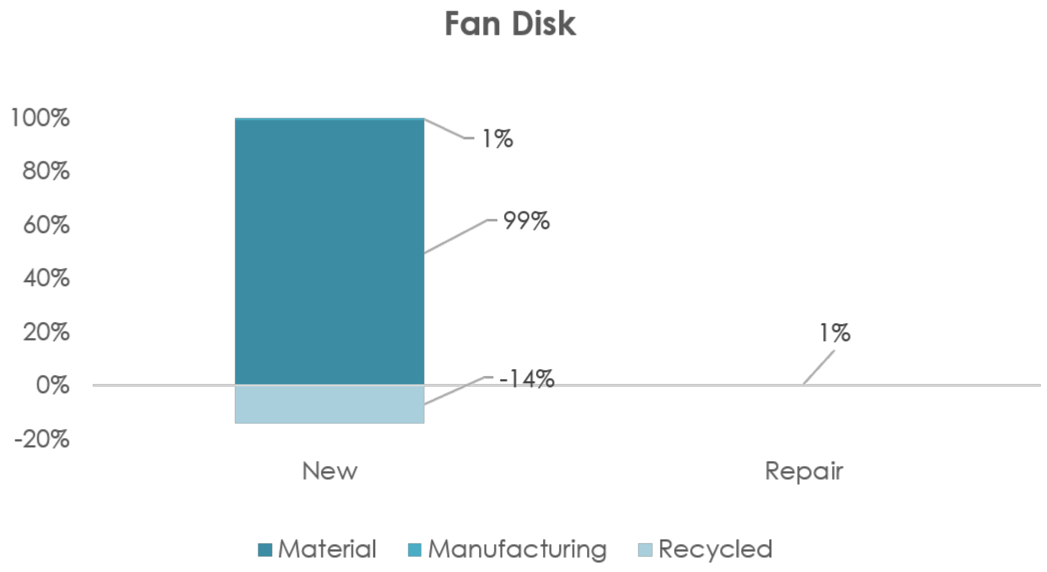


Figure 4.3: *The CO_2-eq of manufacturing and repairing a fan disk.*

4.3 Climate impact of blisks in a cradle to gate perspective

Both nickel and titanium blisks have a close to negligible footprint of repair compared to new production as seen in Figure 4.4 and Figure 4.5. The material contribute with the majority of the CO_2-eq impact, and thus the high material usage in new production compared to the very low in repair can explain the results. The technology of additive manufacturing is used for calculating the impact of the repair processes, which is a very resource efficient process (Ford and Despeisse, 2016) reducing the material consumption drastically compared to traditional repair methods seen in the fan blade repairs. Therefore, there is a very low footprint of the repair.

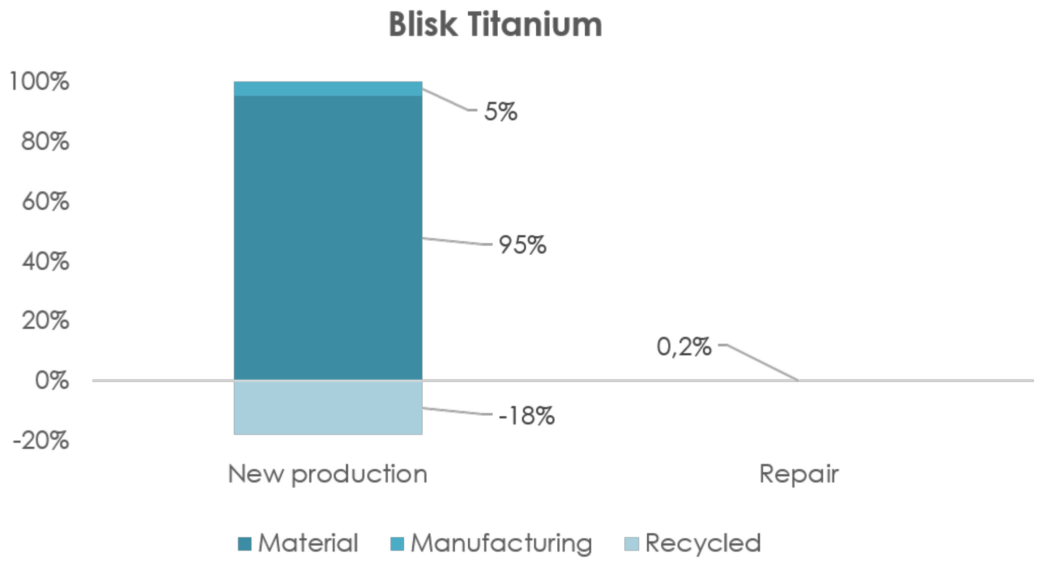


Figure 4.4: *The* CO_2*-eq of manufacturing and repairing a Ti-alloy blisk.*

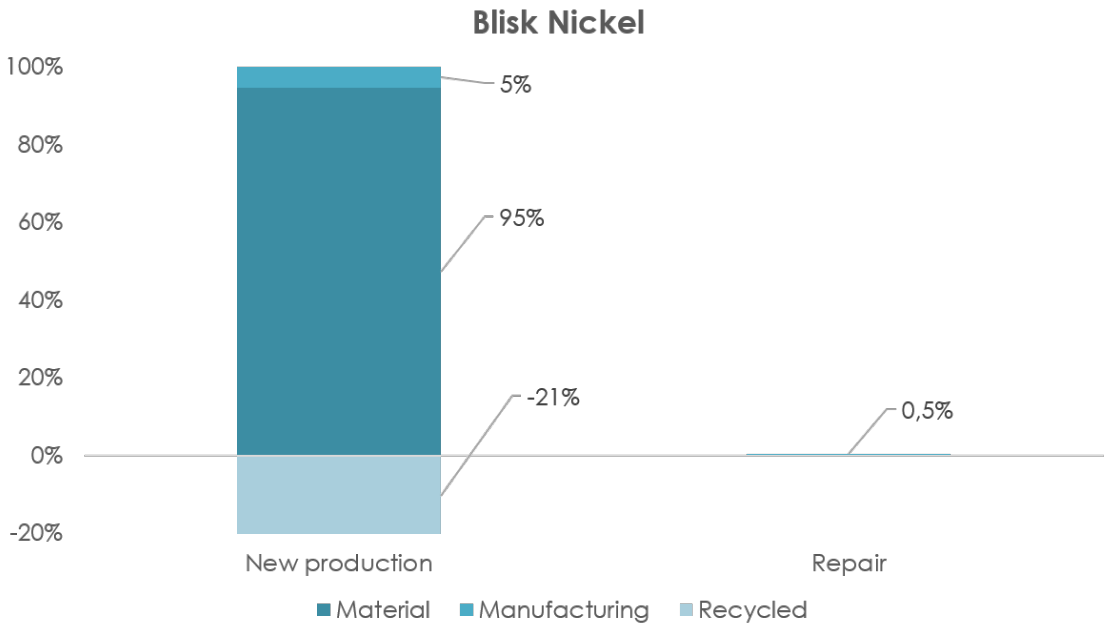


Figure 4.5: *The* CO_2*-eq of manufacturing and repairing a Ni-alloy blisk*

4.4 Comparison of environmental impact between components

The environmental impact of the components compared to each other are presented as follows, see Figure 4.6 and Figure 4.7 below. It is clear that the new production of heavier components, i. e., the fan disk and blisks, have a higher environmental footprint than the fan blades. However, the repair of fan blades, both metallic and composite, have a higher environmental impact than the repairs of the fan disk and blisks. This can be explained by the different repair methods used, where the conventional methods used for fan blade repair cause higher material consumption.

Noticeable is also the high impact of fan blade composite repair (see Figure 4.6). The whole leading edge is replaced, which requires a lot of material, is the main driver of CO_2-eq impact. Compared to repairing a metal fan blade, the process of replacing the leading edge requires more than 12 times the raw material needed for metal fan blade repair.

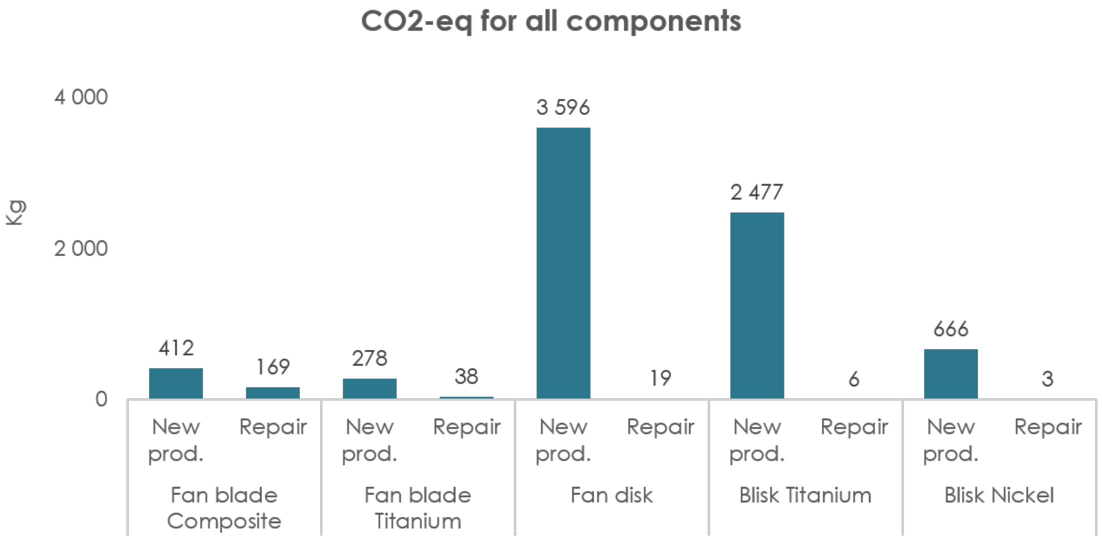


Figure 4.6: *The CO_2-eq for new production and repair of all the components of study.*

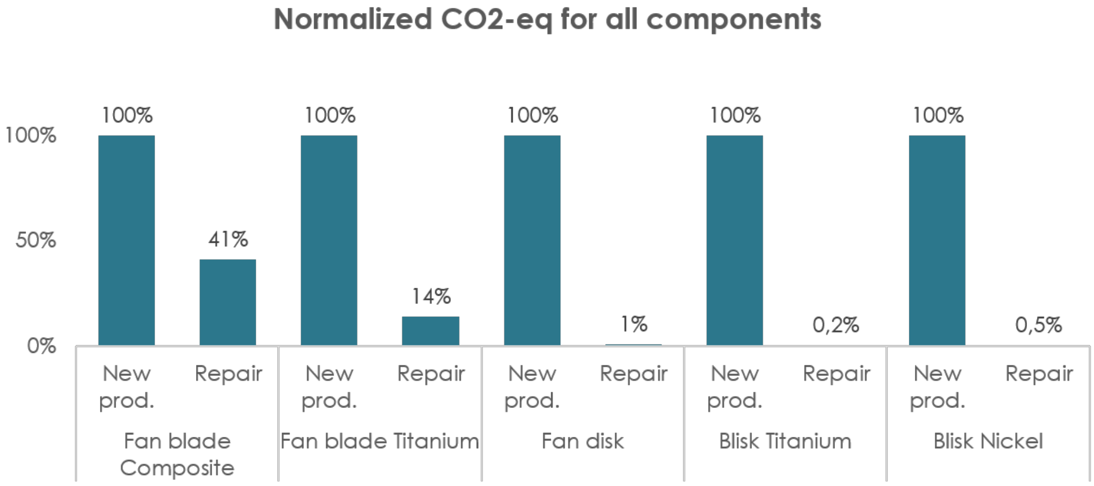


Figure 4.7: *The CO_2-eq for the components of study, normalized to percentage of the corresponding manufacturing process.*

It is clear from Figure 4.6 and Figure 4.7 that the environmental savings is the largest for repairing of titanium blisks and fan disks. However, the components appear in different quantities in an engine, from one disk to twenty-four titanium fan blades and the demand of repair will vary between them based on wear and tear and the quantity of the components. Therefore, Figure 4.8 illustrate the impact of the different components scaled to an engine shipset, i. e. their quantity in an engine, to give insight into how much CO_2-eq is saved by repairing instead of replacing all of the components with new spare parts.

As there is only one fan disk in each engine, the savings of CO_2-eq for repairing fan disks when scaled for an engine shipset is therefore only the fourth highest potential savings. The fan blades bring the second most savings after the titanium blisk with the highest savings.

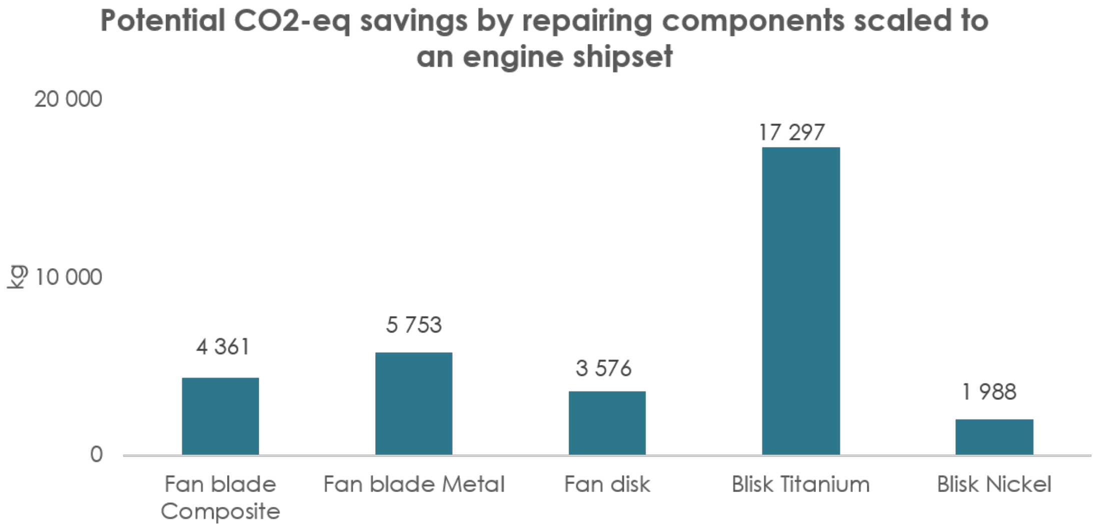


Figure 4.8: *The CO_2-eq savings of repair compared to new production of each component scaled to the engine shipset (quantity in an engine).*

4.5 Generation change and market prognosis

The environmental impact that can be gained by repairing components depend on how many components that need repair and would otherwise be exchanged by spare parts. As illustrated earlier in Figure 4.6 the saved CO_2-eq of repair varies between the different components, and this impact the CO_2-eq savings that the different generations can make. Figure 4.9 and Figure 4.10 illustrate the savings that can be done over time divided into generations. For the fan blades, the savings of repairing generation 1 pass generation 0 at first in 2034. Gen 1 has a steady incline, while Gen 0 has a very slow decline. Already in 2025 it is possible to save 60,000 tons of CO_2-eq through repair of fan blades, and the amount increases to 80,000 in 2040.

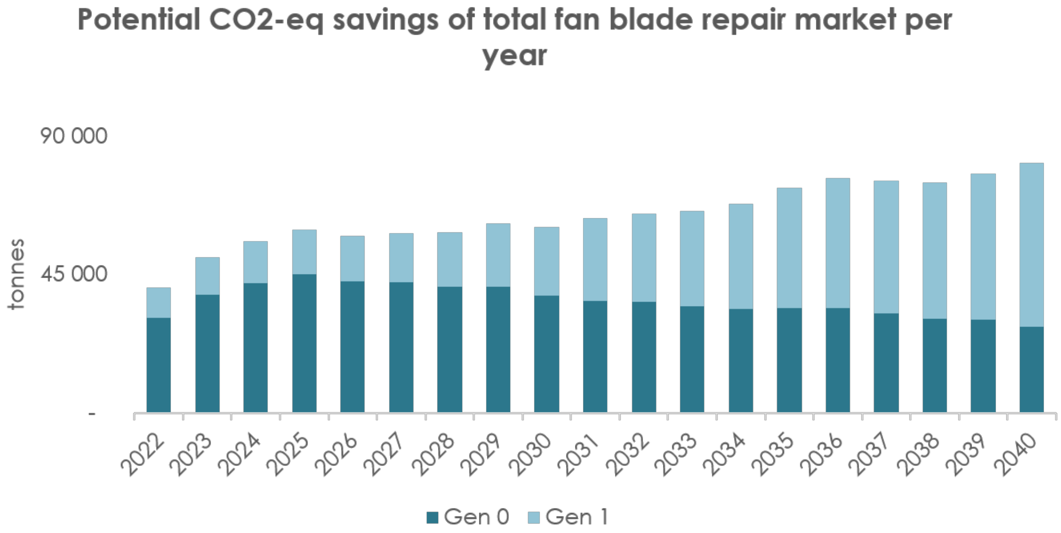


Figure 4.9: *The potential savings of CO_2-eq by meeting the total market demand of fan balde repairs per year, segmented by engine generation.*

It is visible in Figure 4.10 that generation 1 come up to more than 50 % of the potential savings in year 2028, and increase its share of possible saved CO_2-eq with time. It is possible to save 19,000 tons CO_2-eq through repair of fan disks in 2025, and the amount increases to 35,000 in 2040. This is less than half of potential savings through fan blade repair.

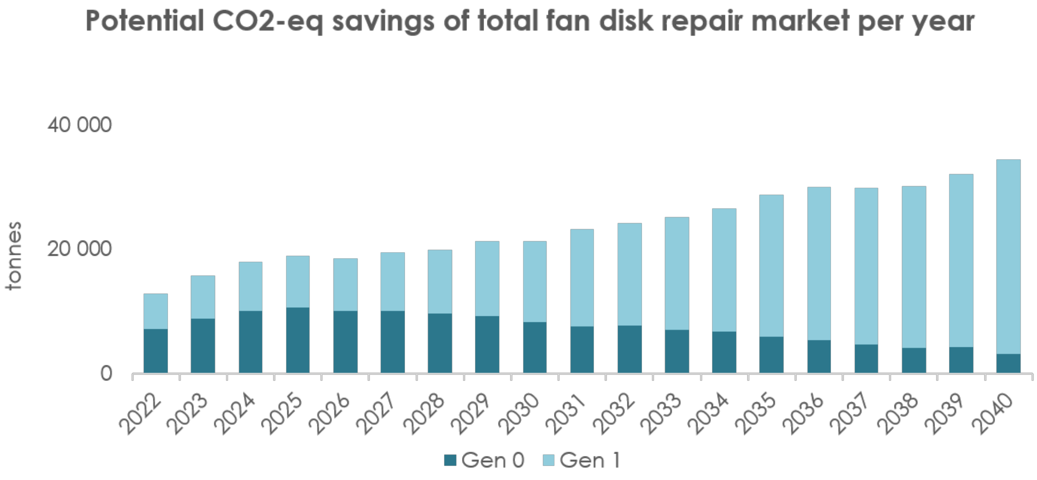


Figure 4.10: *The potential savings of CO_2-eq by meeting the total market demand of fan disk repairs per year, segmented by engine generation.*

Over time, it is saved more CO_2-eq through repair of titanium blisks than nickel, which is illustrated in Figure 4.11. This can be explained by the fact that there are more titanium blisks in an engine, and also because the titanium blisks are placed in front of the nickel blisks, exposing them to more wear and corrosion. Figure 4.11 below is the potential savings of CO_2-eq for the whole blisk market per year, if repair shops can meet the expected market demand.

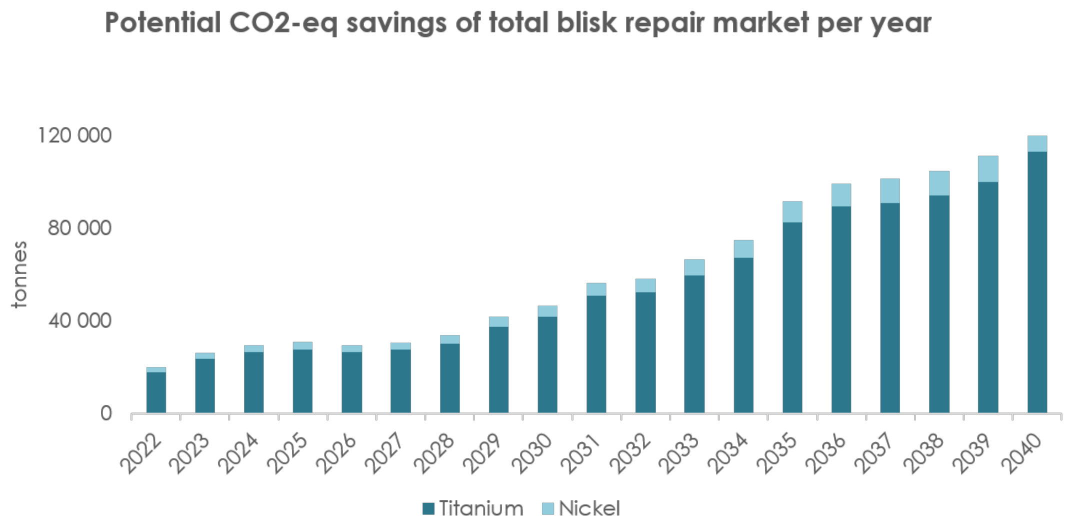


Figure 4.11: *The potential savings of CO_2-eq by meeting total market demand of blisk repairs per year, segmented by metal type.*

4.6 Financial results

The following section presents the results of the financial calculations of the study. All costs are presented as normalized in percentage in order to not disclose any confidential information of the case company.

Figure 4.12 illustrates the costs for repairing the components compared to the process of new production of each component.

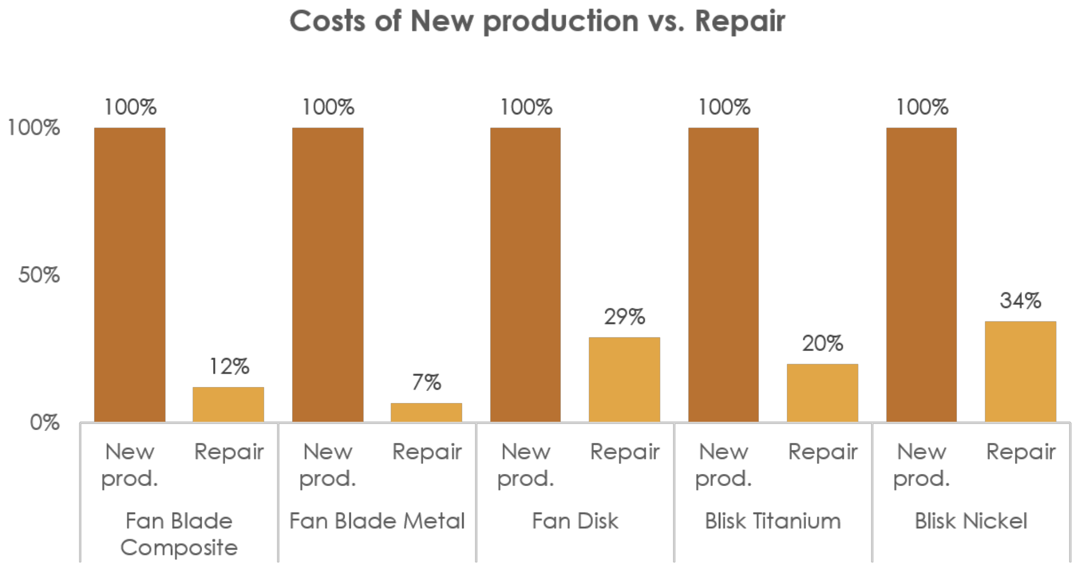


Figure 4.12: *Visualization of the comparison of repair with new production for each component.*

As seen in Figure 4.12, it is always cost saving with repair regardless of the component. For all the components, costs of the repair corresponds to less than 35 % of that of new production. The component showing the relatively most expensive repair compared to its new production process is the Ni-alloy blisk, while the repair being the most cost efficient compared to the new production is the metal fan blade.

However, Figure 4.12 only illustrates the comparison of new production and repair of each component separately. To get a more holistic view and understand how the costs are distributed between the components, Figure 4.13 illustrates the costs in relation to each other, normalized in percentage of the most expensive process, i. e. the fan disk new production.

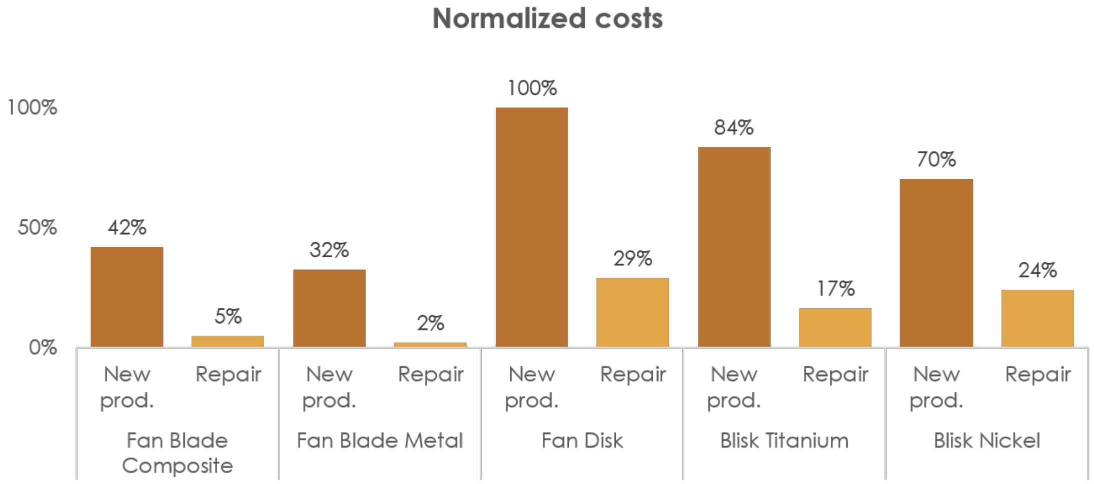


Figure 4.13: *The costs of producing and repairing each of the components, normalized to percentage of the most expensive measure, new production of fan disks.*

As Figure 4.13 illustrates the most expensive component is the fan disk with both highest costs for repair and new production. Despite this, the fan disk and the titanium blisk are the components with the highest cost savings of repair compared to new production. New production and repair process of both the metal and the composite fan blades are significantly cheaper than the other new production and repair processes.

As with CO_2-eq it is interesting to scale the costs to an engine shipset, which is visualised in Figure 4.14 below. The costs are re-distributed compared to Figure 4.12, showing that the most expensive engine shipset of the components are fan blade metal closely followed by fan blade composite. The titanium blisk are still one of the more costly components to produce also when scaled to an engine shipset. While the fan disk was the most expensive component to both produce and repair (see Figure 4.13), it has the least cost impact when scaled to an engine shipset, because there is only one fan disk in an engine.

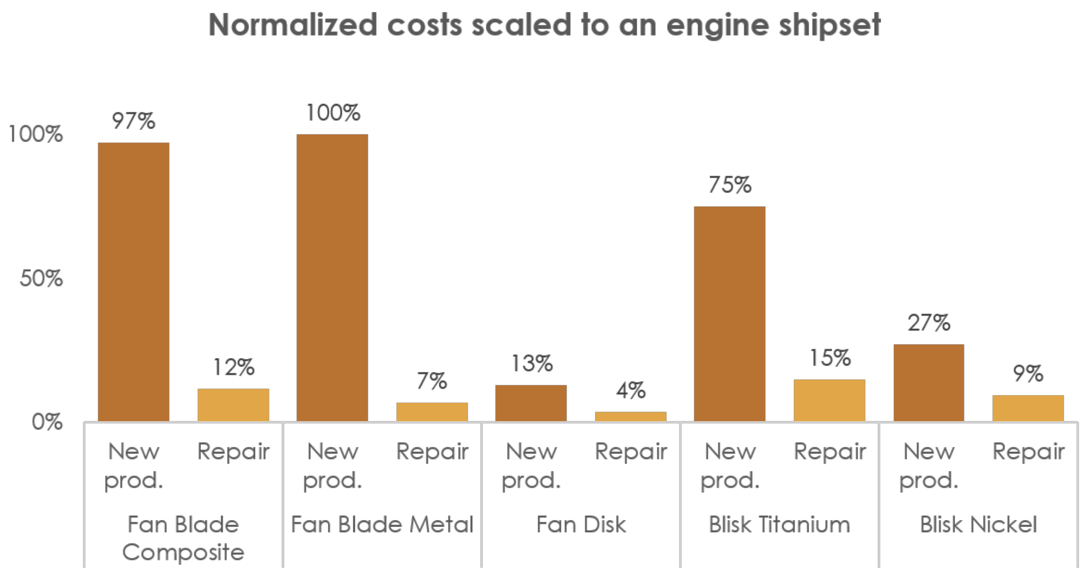


Figure 4.14: *The costs of new production and repair of the components normalized to percentage of the most expensive measure, new production of metallic fan blades.*

The results of the financial calculations show cost savings for all of the repair processes. However, the distribution of costs between the components differs between the single component and when scaled to an engine shipset. The financial results give valuable insights to the analysis in the following chapter.

5

Analysis

The global aircraft fleet is expected to grow continually in the coming years, and will be more than doubled in 2050 compared to now. Hence, the demand for repairing components to jet engines and the civil aftermarket will automatically grow. Following is a discussion on how the case company can develop its repair business in a sustainable way. The first research question, about structuring the portfolio, is mainly handled by the section 5.1, 5.2. and in 5.3. The second research question, regarding the business case structure, is mainly handled in 5.3 and 5.4, but also touched upon with regard to trade off between new and old technology in section 5.2.

5.1 Increased cost efficiency and reduced emissions

Both the results of the study and literature (Borland et al., 2019; Bocken et al., 2014) tells us that repair clearly is a way of doing sustainable business. Moreover, Figure 4.13, which show the cost savings of each component, illustrate how repair is beneficial for all components also from the financial perspective, implying that there is a connection between cost efficiency and reduced emissions in the repair portfolio. Reinhardt (1999) support this link between improved cost efficiency and reduced emissions, and propose that cost saving can be a strategy where the company simultaneously reduce emissions.

Boons et al. (2013) elaborate how this win-win situation can arise from turning sustainable innovation into new business models. Further, Bocken et al. (2014) elaborates on how building a business model revolving around increased resource efficiency through additive manufacturing is a way of creating a sustainable business. This particular technology is currently under research for application in the repair industry and may thus be an innovation that could be utilized to the maximum through business model innovation.

It is also important to discuss which repair process is chosen for the components. Repair will improve the environmental performance for all components, however, when analyzing the results on environmental impact in Figure 4.6 and 4.7, it is noticeable that the type of repair process have relatively large influence on the environmental impact. The repair of composite and metallic fan blades have significantly higher environmental impact compared to repair of the three other components, for which repair has almost negligible impact. Those three components are repaired not by conventional repair methods, but by using additive manufacturing or plasma spraying, which is in line with the resource efficiency described in literature (Ford and Despeisse, 2016; Bocken et al., 2014).

Further elaborating on the environmental impact of the different repair methods, and put in relation to market outlook and generation change, will give an interesting aspect of analysis. Repairing of composite fan blade represent the process with the clearly highest environmental impact among all components in the study (see Figure 4.6). Composite fan blades belong to Gen 1 and the environmental impact of repairing fan blades will thus increase as the repair demand of Gen 1 engines increases. This is an important aspect to consider for the case company when expanding the business.

The results from the environmental and financial impact assessment also give insight to how the repair portfolio can be structured regarding prioritization between the components. Many aspects argues for the importance of including repair of titanium blisks in the portfolio. According to Figure 4.8, repairing titanium blisks have the clearly highest potential savings of Co_2-eq when scaled to an engine shipset. Also when the potential savings of Co_2-eq is put in the perspective of market outlook, as in 4.11, the repair of blisk will contribute to the highest savings CO_2-eq among all components, of which titanium blisk will stand for a majority of the savings. In addition to this, a titanium blisk is the second most expensive component to manufacture (see Figure 4.7), thus repairing the component will help cut high costs of spare parts.

Based on the above discussion it is possible to determine that the repair business poses an exceptional opportunity for the case company to achieve sustainable growth in both the economic and environmental dimensions. However, it is important to also relate innovative processes to new business models in order to ensure both economic and environmental performance (Boons et al., 2013).

5.2 Environmental impacts in the life cycle and the technological cycle

There is an interesting contrast between the life cycle management perspective and the technological cycle perspective. The life cycle management perspective underlines the importance of reducing impact and managing the whole life cycle of the product including extending its life. The technology cycle on the other hand focuses more on the initial phases of a product's life cycle - the innovation, and competition for dominance, and not as much on extending life or end of life, and rather calls for continuous innovation and development than focus on old products. It is interesting to understand how these two aspects coexist and affect the choice of portfolio, and the business case, and is therefore analyzed thoroughly in this section.

Life cycle management stresses the importance of prolonging a product's life cycle

(Borland et al., 2019), which is performed in the engine industry through repairing the components. It is seen as important because of the reduced emissions and reduced extraction of material. For the jet engine, components repair provide both reductions which can be seen in any of figure 4.1, 4.2, 4.3, 4.4, and 4.5 by the significantly reduced material and reduced overall environmental impact from repair processes. Hence, applying the life cycle perspective would imply repairing the engines for as long as possible and keep them in the loop. Further, it is suggested to avoid unnecessary extraction of material from the environment and understand the restrictions of limited resources (Borland et al., 2019), which would speak against manufacturing new components, particularly from partly virgin material. Thus, a focus on components of gen 0, prolonging their lives, and not support or encourage a shift of engines producing waste and extracting new material.

On the other hand, literature on technology cycles focuses on the importance of technology development, and how continuous and sometimes disruptive innovation in technology increases product and technology efficiency (Anderson and Tushman, 1990). With increased efficiency comes reduced emissions, which become very visible comparing the traditional repair methods of the fan blades with respectively 169 and 38 kg of CO_2 per repair, to the repair utilizing the new technology of AM that contribute to only 6 and 3 kg of CO_2 (see figure 4.6. Further continuous innovation is emphasized as a way for firms to achieve competitive advantage through developing new products (Anderson and Tushman, 1990). Constantly developing and producing new products to win a technological race may make it challenging to integrate life cycle management. Further, the quest for increased efficiency and thus decreased operating emissions provides a weak excuse for a linear mindset, which may reduce the company's drive for life cycle management thinking.

Regarding the aerospace industry, there are shifts in engine design approximately every thirty years (Epstein, 2014) (personal communication, Dahlin, 2023.02.09), translating to technology cycles of thirty years. While the advancements in technology do improve environmental efficiency for the new engine generations (Anderson and Tushman, 1990) (personal communication, Nylander, 2023.02.02) a life cycle management perspective would still argue to prolong life and keep the material in the loop, prioritizing environmental business models like repair over individual innovations (Borland et al., 2019). This would suggest to serve the old market to prolong the life of the engines and contradicts the ideas behind the technological cycles. However, because of the long lifespan of engines, the use phase stand for more than 90% of the engines' emission (personal communication, Nylander, 2023.02.02). Increased engine efficiency may therefore surpass the benefit of extending the life of the old engines, and there are trade-off for how long one should keep the engine running or exchanging it for a new design.

Further, by excluding the new engine generation from the focus of the case company, a lot of potential early mover advantages are lost, particularly those that may arise from a technological leadership (Lieberman and Montgomery, 1988). Anyway, it is not in the case company's power to decide if the engine manufacturers or their customers endeavor to keep the old engines in the loop or to implement new technology. The issue is that while following the technological cycle would enable one to reap first-mover advantages, it would cut short the life cycle of previous generations. Therefore, from both business and life cycle perspectives, it is important to apply life cycle management as well as follow the technological trends, thus including both generations in the repair portfolio.

The market for repairing the engines will lag behind the new manufacturing market because the last sold engine of a particular design will operate for many years and need repair long after it is out of production, as well as it will take some years from the first sale till the new engines need repair (personal communication, Wallin). There will therefore be good opportunities to do research on repair methods on the new engines while also providing service to older engine types. This facilitate the need for balancing the portfolio between the old and the new engine generations.

By pursuing research on the repair methods of new generations, technological leadership may be achieved. As the repair business is highly regulated (Rolls Royce, 2015), there may also be opportunities to win patent races and standards for repair processes which may be reaped to earn economic benefits (Lieberman and Montgomery, 1988). Also, literature on life cycle management highlights the opportunities technology innovation provides (Bocken et al., 2014), however as a way to develop more sustainable business models and not the exploitation of individual technologies (Lüdeke-Freund et al., 2019; Borland et al., 2019). There should therefore be a holistic goal behind the research, and front both economic and environmental values. An example of such is the research on the additive manufacturing repair technology which would bring significant material savings (Ford and Despeisse, 2016), illustrated by the blisk repairs of the study, and potential technological leadership.

5.3 Life cycle management and increased repair's impact on social sustainability

As discussed earlier, the outcome of repairing components is positive both from an economic and environmental perspective. In addition, it can be determined that the repair business can help improve social sustainability as well.

The results implies that repair significantly improves resource efficiency by decreasing the need for input material, which is common for all repair processes included in the study. The improved resource efficiency will have both positive and negative impact on the sub-tier suppliers of the case company. Mancini and Sala (2018) states that the mining industry mainly has a negative social impact on the local population in the industry. Hence, as a majority of the material used in the components is extracted from mining, the reduced demand on raw material will have a positive impact on the local communities where the mining takes place. Negative impacts that may be mitigated with a lower demand is the unfair distribution of benefits and different types of controversial labor like child labor. However, according to

Mancini and Sala (2018) the locals being employed in the industry often enjoy the positive aspects coming from mining, implying that a reduced demand of the metals will have considerable negative impacts for those employed.

The contribution to keeping CRM materials in the industry loop for longer is another positive aspect from repairing components, further implying that repair also improves the social dimension of sustainability. With the repair of components, of which many contains metals listed on the EU's CRM list, the materials is kept in the industry loop and the high supply risk that comes with the materials are reduced due to a reduced demand (IEA, 2023).

Regardless of how resource efficient the repair operations of the case company can become, there will always be a need for virgin raw material in an increasing market. Integrating life cycle management to the strategy and goal of the company will help expanding the scope and help managing social sustainability also in the upstream activities (Rebitzer, 2015) when expanding the repair business. The actors included in the chain from raw material extraction to the sub-tier supplier providing the billets to the case company implies that the indirect approach proposed by Tachizawa and Wong (2014) may be a relevant approach to apply for managing the sub-tier suppliers. By putting pressure on the first tier suppliers to monitor their suppliers, the case company utilize cross-tier collaboration to manage compliance through the supply chain.

5.4 Stakeholders and strategies in an increased repair business

An important consideration when developing potential business models for the case company is the stakeholders (Dorobantu et al., 2018), and develop a plan for distribution of benefits and costs between the actors of the supply chain (Boons et al., 2013; Bocken et al., 2014). The results (see Figure 4.13) show that the repair bring increased cost efficiency, a benefit that mainly land on the owner of the engine who can enjoy the operating cost savings. It is of the owner's interest to keep the engine flying as cheap as possible, and as the results (see Figure 4.13) illustrate repair is the cheapest way to restore the quality.

By repairing components the case company compete with the engine OEMs who sell spare parts to the components, meanwhile these actors are also the customers of the case company as seen in Figure 2.4. While it is always important to distribute the benefits of an innovation between the stakeholders (Boons et al., 2013; Bocken et al., 2014) it becomes even more important in this situation, to not infringe on the close relation with the engine OEMs. Because the repair business proves to bring both CO_2-savings and cost savings there should be more benefits to share than losses to share, which should make it easier to please the stakeholders and achieve collaboration.

Another important aspect is that it takes many years before the sale of a jet engine becomes profitable because f high initial investments and that the aftermarket is the profitable stage of the engine's life cycle (Epstein, 2014), illustrated in figure 2.1. There is therefore an unbalance in costs connected to developing and selling engines vs repairing. In addition to this, the OEM has the power to decide who gets to repair the components (personal communication, Dahlin, 2023.05.05), meaning that they must be pleased and motivated to give this profitable task to any actor. A typical way to solve this is to partake in an engine innovation program, where every actor that provides a component, thus partaking in the costs, has a greater chance of being a part of the repair program (personal communication, Dahlin, 2023.05.05). There may therefore be motivation for taking some load of the innovation costs for the engine in order to be allowed to partake in the beneficial aftermarket.

With a change of ownership, a shift from selling a product to selling a service, and the servitization business model there are good opportunities to shift the benefit distribution, by delivering functionality instead of ownership (Bocken et al., 2014). This model is efficient for environmental business models because it breaks the linkage between production and profit (Bocken et al., 2014), and thus may make it more profitable to sell engines. Also, it creates incentives for the producing companies in the industry to provide the most cost efficient repairs. However, this business model requires the OEMs to initiate the business model change, since the case company is not the one selling engines to the end customer. This model already exists in the aerospace industry and is called flight hour agreements (personal communication, Dahlin, 2023.23.01), where the OEMs license out the engines and keep the ownership. If the OEMs own the engines it would be in their interest to keep them operating as cheaply as possible, which would motivate repair of all components where this process is cheaper.

6

Discussion

This chapter will discuss the strengths and weaknesses of different aspects of the study. Following, the reliability and credibility of the data will be discussed, as well as the validity of the study. Lastly, the study's contribution to the subject area is discussed, and how it aligns with existing theory.

6.1 Strengths and weaknesses

To understand how meaningful the study and the results are, one must understand the strengths and weaknesses of the methodology used. This has implications for how the results and conclusion can be interpreted. The following sections describe this.

6.1.1 Literature

The literature search was efficient in gaining insight in the industry and environmental strategic topics like life cycle management and social sustainability. A broad but rather shallow topic literature search was efficient in providing different views and aspects of the increased repair business. A more extensive search of the topics could have provided more nuanced views. However, the most interesting aspect was still the contradicts and similarities between the topics.

6.1.2 Method

The method of the study had a clear framework, with flowcharts to utilize for the data structuring, and interviews and literature search to understand the subjects. However, the means to gather the numerical data had a more problem-solving approach, utilizing the opportunities at hand. Since the method affect the result and conclusion it is important to evaluate the strengths and weaknesses of it.

The method used for the study is difficult to replicate to detail. While there was clear organization of the method and data handling, there was some information and data gathering that had more of a problem-solving approach, asking individuals for help with gathering the specific data in question. This data gathering method would have to be adapted to the object or organization of study. Even applying the same method with the same case company may result in asking different people and receiving slightly deviant numbers. However, the flowcharts and specified equations should ensure that the final results do not deviate much.

Further, an increase in the quantity of components of study would allow for more comprehensive and detailed results. Now, when the report analyse potential business models assumptions must be taken that any other component will have similar results, whereas a broader product scope would have confirm or reject this assumption.

The scope of processes included in the impact assessments could have been broadened to include all factors giving a more precise and detailed description of the impact sources. This would allow for a deeper analysis, however with the strategic focus of the study the 80% coverage of impact should be enough for a relevant analysis. The last 20% of the impact would significantly increase the time and labor needs for the study, beyond what was reasonable.

6.1.3 Limitations and assumptions

The limitation of only investigating one company's part repair business affect the generalisation, as one can not be sure it is equal for every jet engine parts repair business. However, since the results were clear and showed significant differences between repair and new production, and because the repair methods of the blades and disk are standardised, the study is relevant also for other actors within the aerospace engine parts repair business.

The limitation of only investigating processes within the gates of the production site and raw material production eliminate the opportunity to understand the source of the largest impact during the engines life cycle. However, this was not the aim of the study, and the included aspects is sufficient to make decisions upon which components that save the most CO_2-eq, and strategies on how to grow the repair business.

During the calculations and numerical data gathering some assumptions had to be done due to lack of exact numbers. This necessarily affect the validity as exact numbers would have been to prefer. Still, the assumptions were always discussed with industry experts, and have always been pursued with their approval, implying that they have been reasonable.

6.1.4 Reliability and credibility of the data

Credibility is how believable the study is (Bell et al., 2018). To ensure credibility industry experts have read the report to verify that any information gathered from the case company is correct, as well as investigate the credibility of any industry specific information. The results are also credible as they are aligned with repair being more environmentally friendly than new production, as well as the numbers are similar to results of the LCAs previously conducted at the case company.

In an effort to secure reliability, only reliable sources of information has been utilized: academical articles, books, aviation authorities web pages, industry reports, case company internal documents, and communication with industry experts. However, much of the information is gathered from the case company and have not been controlled against other sources, because it is not information typically found in public sources. The reliability of the company is therefore important for the reliability to the result. Because the report gives implication for how the case company may grow their repair business it is in their interest to give as correct information as possible, and the company representatives are therefore deemed reliable. Also, when any interviewee could not ensure that their answers were correct they would forward to another more reliable source in the company or industry.

6.1.5 The general validity

Validity is how logical and well the study correspond to the real world (Bell et al., 2018). Overall the study and result appear sound and reasonable in perspective of the industry knowledge gained through the study. The results show that repair is better for the environment than new manufacturing which correspond well with the generally accepted theory that repair reduce impact. The significance of material impact however may raise questions.

The material impact is the most significant impact driver, which also correspond to what has been found in the internal LCAs. However, the material impact of this study are higher, which is a result of including all processing outside the case company's gates into the material impact because of challenges with separating processes and raw material impact at these stages. This may therefore look suspicious, but taken into account the processes that are included they seem credible. Further, the very low repair impacts of the blisks may raise questions, however as the processes consume very little material and because the material is otherwise the main impact driver, it is a valid result. The additive manufacturing repair has also been proven to have very low impact in internal LCAs, which support the low impact of the blisk repairs.

6.2 Contribution to the subject area

The study has contributed with an empirical example of how an environmental business model can be strategically implemented in the aerospace industry. While there is abundant theory on the theoretic environmental benefits of the repair business, this study supply empirical evidence. The study has contributed with numerical data on environmental and economic performance of repair of jet engine components, providing quantitative evidence on the benefits of repair. Further, the study put the business case in context of other theoretical aspects of technological cycles, sustainable supply chain and stake holders providing a holistic analysis of the environmental business model.

The results of the study confirm much of the life cycle management theory regarding repair and material efficiency. In particular that a repair business model is a way to reduce environmental impact, and that AM is resource efficient and through that lower the impact or the repair process. However, while this point is not stressed as a conclusion, our findings did question if prolonging of the life cycle always is the best for the environment. There are implications that following the efficiency improvements of the technical cycles may lead to better environmental performance due to the engines high impact during the use phase. Anyways, this was not the focus of the study and should be investigated further in order to draw any conclusions.

7

Conclusion

This report aimed to investigate the sustainability of a part repair business within the aerospace industry. Further, the aim was to assess the balance between economic and environmental aspects of sustainability in order to build a strategic business portfolio. To conclude, the repair portfolio is advantageous from all three dimensions of sustainability; economic, environmental and social. All components demonstrated savings of 59% or more in CO_2-eq compared to new production. Repair also showed significant cost savings as the most expensive repair still corresponded to only 34% of that of new production. The reduced demand for raw materials related to repair will also improve the social impact at low tiers in the mining sector.

In order to structure the repair portfolio, it can be concluded that it is important to have a diversified portfolio, in terms of included components and research. This is because the total market will include both Gen 0 and Gen 1 for several years in the future, and provides the opportunity to reap from both. However, the combination demands different capabilities, and the company must balance an operative focus and a research focus. Moreover, additive manufacturing proved to be very resource efficient and possesses opportunities for sustainable expansion and growth for the case company.

Lastly, it can be concluded that it is important to link innovative repair processes to a new business model for optimizing the structuring of the business case. A proposed business model is a servitization model, which combines sustainability and capturing the economic value. Due to the complex stakeholder situation, this is argued to be the most suitable and responsible business model for maintaining good relations for the case company.

In short, by demonstrating that repair is advantageous and an opportunity for sustainable growth, this study has contributed with a practical view to research in the field of managing sustainability within the aerospace industry. However, future research is needed to fully evaluate and understand the impact of the repair activities as well as understand the stakeholder network. Recommendations for future work could be to:

- Perform a complete life cycle assessment of the whole repair portfolio, which also includes the use phase to get a full understanding of benefits and challenges with the repair since a majority of the emissions are said to come from the use phase.
- Stakeholder analysis, to understand their view on supplier innovation poten-

tially competing with their products.

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