



# **Life cycle assessment comparing manufacturing and repair operations of aerospace fan blades with conventional and additive manufacturing**

Master's thesis in Industrial Ecology

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Gothenburg, Sweden 2022

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[GKN JET ENGINE]

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## ABSTRACT

The aviation sector has made it possible for people to explore the world in just a matter of hours but the industry is facing large challenges. To prevent further environmental changes, actions must be taken. This report investigates the sustainability impacts of new manufacturing Fan blade, compared to two repair methods, one based on conventional manufacturing and one based on Additive Manufacturing (AM) with Laser Metal Deposition with powder (LMD-p). Literature search and interviews were performed to understand and map the different processes. A Life cycle assessment (LCA) was made to assess the environmental impacts associated with the three cases to validate potential hotspots. Lastly a social assessment was made to understand the social impacts. The LCA showed that the AM repair significantly reduces the environmental impacts, resulting in 6 kg CO<sub>2</sub> equivalents, compared to new manufacturing, 184 kg CO<sub>2</sub> equivalents, and conventional repair, 80 kg CO<sub>2</sub> equivalents. The social assessment displays several positive aspects, firstly less toxic exposure to workers and less impact on natural capital. This study concludes that the AM repair significantly reduces the environmental and social impacts compared to both new manufacturing and conventional repair.

Keywords: sustainability, aerospace, life cycle assessment, environment, repair, circular economy, additive manufacturing, conventional manufacturing



## **Acknowledgments**

We would like to thank GKN aerospace for our chance to do our master thesis in a nourishing and high tech industry. We truly appreciate all interviewees and experts at GKNA for making our work possible, letting us be a part of your work and giving us new knowledge. A special thanks to our supervisors at the company, Johanna Nylander and Pauline Leonard, for their support and encouragement to expand our work and perspective towards the greater. We would also want to acknowledge and thank our supervisor and examiner at Chalmers University, Mélanie Despeisse, for her help and guidance along the way.

Cecilia Magnusson & Linus Einarsson, June 2022



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## Abbreviations

**ADP:** Abiotic Depletion Potential

**Al:** Aluminium

**AM:** Additive Manufacturing

**AP:** Acidification Potential

**Ar:** Argon

**CAD:** Computer Aided Design

**CLCA:** Consequential Life Cycle Assessment

**CM:** Conventional Manufacturing

**CNC:** Computer Numerical Control

**CRM:** Critical Raw Material

**CO<sub>2</sub>:** Carbon dioxide

**DED:** Direct Energy Deposition

**EBFFF:** Electron Beam Free Form Fabrication

**EP:** Eutrophication Potential

**EPO:** European Patent Office

**ESA:** Environmental System Assessment

**FAETP:** Freshwater Aquatic Ecotoxicity Potential

**Fe:** Iron

**GHG:** Greenhouse Gas

**GKNA:** Guest, Keen, and Nettlefold - Aerospace

**GWP:** Global Warming Potential

**He:** Helium

**WT:** Weight Percent

**HTP:** Human Toxicity Potential

**LCA:** Life Cycle Assessment

**LMD:** Laser Metal Depositioning

**LMD-P:** Laser Metal Depositioning - Powder

**LMD-W:** Laser Metal Depositioning - Wire

**MAETP:** Marine Aquatic Eco Toxicity Potential

**MAM:** Metal Additive Manufacturing

**MRR:** Material Removal Rate

**NO<sub>x</sub>:** Nitrous oxide

**O:** Oxygen

**ODP:** Ozone Depletion Potential

**PAN:** Polyacrylonitrile

**PBF:** Powder Bed Fusion

**POCP:** Photochemical Ozone Creation Potential

**RTM:** Resin Transfer Molding

**SDG's:** Sustainable Development Goals

**SIA:** Social Impact Assessment

**SLM:** Selective Laser Melting

**SLS:** Selective Laser Sintering

**TETP:** Terrestrial Ecotoxicity Potential

**Ti:** Titanium

**TIG:** Tungsten Inert Gas

**V:** Vanadium

**WAAM:** Wire Arc Additive Manufacturing

**WLAM:** Wire Laser Additive Manufacturing

**CFP:** Carbon Fiber Part

# 1 Introduction

The aviation sector has made it possible for people to explore the world. One can travel from one country to another within just a few hours. Although the aviation sector has made life simpler for many, it has also contributed to a row of sustainability issues. The aviation sector is the second biggest contributor to greenhouse gas (GHG) emissions related to transport, where road transport is the biggest contributor and aviation stands for around 14 percent. The aviation sector was responsible for 3.8 percent of the global CO<sub>2</sub> emissions in 2017 and is expected to rise in the near future (European Commission, 2022).

Efficiency improvements have been made to reduce the emissions released but the number of flights and passengers travelling have risen faster and thus neglected the reduction of emissions (European Union Aviation Safety Agency, 2019). Analysis shows an expected increase of Carbon dioxide (CO<sub>2</sub>) and Nitrogen oxide (NO<sub>x</sub>) from the aviation sector by 21 and 16 percent respectively in 2040 from 2019 values. Aviation release GHG in the upper troposphere and causes contrail clouds which cause a greater impact on global warming than if GHG were released on the ground (European Union Aviation Safety Agency, 2019). To meet the Paris agreement and keep the global average temperature below 1.5C, improvements in all sectors are needed including the aviation sector.

Actions can be made to reduce the environmental impacts of the aviation sector, both in use and in the production of its components. Efficiency improvements and circular measures could be implemented to prolong the lifetime of products and reduce emissions. Some examples could be repairing engine components, re-manufacture, recycling and circulating valuable materials in a closed-loop system to prevent the need for additional materials input and excess energy usage, thus creating a circular economy (Ellen Macarthur Foundation, 2019). Although environmental sustainability is only one of the pillars needed to be taken into consideration (Elkington, 1998). To reach sustainability, all three dimensions, environment, social and economic need to be considered, also called the triple bottom line, see Figure 1.

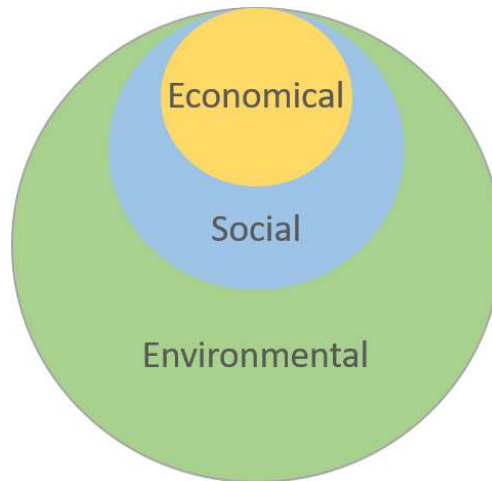


Figure 1: A schematic view illustrating the three dimensions of sustainability where sustainability is achieved within the boundaries of the environment (Gibson, 2006; Pryn et al., 2015)

To fulfil our needs as humans, now and in the future, all three dimensions of sustainability need to be satisfied. Some of the social sustainability's core aspects are human health, human rights and a fair distribution of the earth's resources. Economical sustainability is to meet human needs in form of finite natural resources and human-made goods. Lastly, the environmental sustainability includes the natural systems products and services provided (Hedenus et al., 2018).

## 1.1 Background

This master thesis is made in association with GKN Aerospace Sweden which strives to reduce its environmental impact. Previous improvements have focused on reducing fuel consumption through lightweight design and efficient manufacturing processes. This study focuses on alternative solutions to conventional linear consumption, with circular strategies, thus extending the use phase of composite and metal fan blades with repair methods based on Conventional Manufacturing (CM) and Additive Manufacturing (AM). The environmental impacts will be assessed by a Life Cycle Assessment (LCA) and potential business opportunities, as well as social impacts related to repairment, will be analysed qualitatively. Numerous previous environmental assessments of AM have been made, for example an comparison of CM and AM usage in mold manufacturing, where AM manufacturing has a lower environmental impact for complex molds with a low solid-to-cavity volume ratio (Morrow et al., 2007). The study also reflects on the opportunities for AM to be used as a repair method to reduce the environmental burden and manufacturing costs.

A fan blade is the first rotating part of an aerospace jet engine which supplies the engine with air. This component is prone to mechanical wear like abrasion, erosion and fatigue, and is occasionally hit by flying objects like birds. Repairing components is one way to prolong the life cycle of a product (circular measures) instead of replacing it with a new one. Currently, damaged composite fan blades are replaced with new ones during service instead of repairing them. There are different methods to repair aerospace components, and one method is using additive manufacturing which may be suitable since it is a technology with high efficiency and low waste (Monteiro et al., 2022). Fan blades can be made fully out of metals such as titanium alloy, or as in this study a part made of both composite and titanium alloy to reduce weight. The fan blade is currently manufactured with conventional manufacturing methods.

GKN as a company started in 1759 and the name is formed from the initials of the three founders, Guest, Keen, and Nettlefold (GKN Aerospace, Nd). GKN's Aerospace sector includes both aeroplanes and space rockets and focuses on three core markets, Civil, Engines, and Defence, all three equally divided. GKN aerospace has over 15 000 employees across 41 manufacturing locations in 12 countries. When flying there is a big probability that GKN has made the flight possible since they serve over 90% of the world's aircraft and engine manufacturers (GKN Aerospace, Nd). GKNA develops and manufactures advanced engine components, cabin windows, aircraft structures, and much more, including engine maintenance.

GKN Aerospace (GKNA) is working towards all three aspects of sustainability, social, economic, and environmental. The aerospace industry has a great challenge when it comes to environmental sustainability, which is to manifest the benefit of flight but in a truly sustainable way. Specific targets and policies have been set to become a business with net-zero greenhouse gas emissions before 2050 (GKN Aerospace, Nd).

GKNA is striving to support the Sustainable Development Goals (SDGs) that the United Nations has set to reach by 2030. In total 17 SDGs include the biggest issues facing the planet and people which businesses and organisations are going to act on to increase the wellbeing of the life on earth (United Nations, nd). GKNA Aerospace and its core business of manufacturing aerospace parts contribute directly to six of the goals (GKN Aerospace, 2022). The six SDGs that GKNA contributes directly to are presented in Figure 2 where this thesis aims to contribute to mainly goal 3, 9 and 13.



Figure 2: The six SDGs that GKNA work directly towards.

## 1.2 Aerospace engine and its components

To understand the need for repair within the aerospace industry, basic knowledge about the Jet Engine and its components is necessary. A jet engine relays on Newton's third law of motion "For every force acting on a body, there is an equal opposite reaction" in this case the engine's thrust (Rolls Royce, 2005). See Figure 3 for a schematic view of a Gas Turbine Jet Engine.

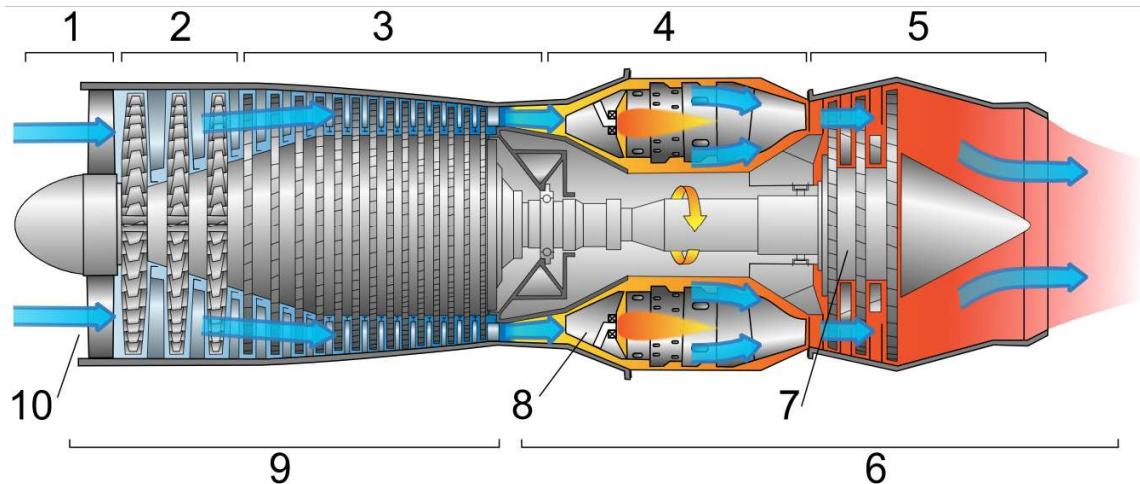


Figure 3: A schematic view of an Gas Turbine Jet Engine (Dahl, 2008). Creative Commons Licence.

A jet engine works by pulling in the air at the front of the engine (10) and compressing it (9). The air is then mixed with fuel and igniting thus starting to burn (4). The hot air moves its way towards the rear of the engine where the energy in the hot air is taken advantage of by the turbine blades (5) to continue combustion and thrust production via turning the fan blades (2) at the front of the engine. The hot air is therefore leaving the engine on the backside as thrust.

There are various types of jet engines depending on the application and thus specifications such as fuel economy, size and thrust produced (Rolls Royce, 2005). Figure 4 shows a generic view of a Turbofan Jet Engine commonly used in civil aeroplanes. The turbofan engine works on the same principles as the Gas Turbine Jet Engine shown in Figure 3 but instead has a large part of the air passing by the outside of the engine at a slower velocity.

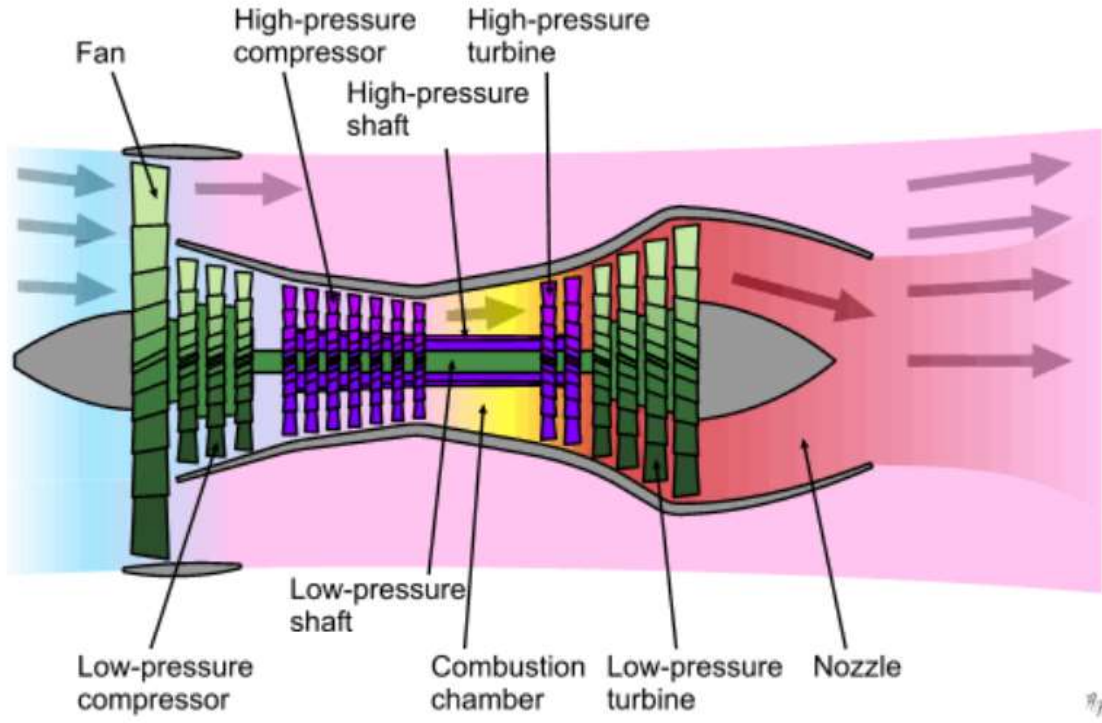


Figure 4: A schematic view of an Turbofan Jet Engine during operation (Emoscoptes, 2005). Creative Commons Licence.

As seen in Figure 3 and 4 a Jet Engine has parts that operate in higher and lower temperatures and can thus be divided into mainly two parts: a hot part (6) and a cold part (9). For this report, the focus is on a Turbofan Engine and the fan blades that are located in the front part/colder side of the engine.

Components in the Jet Engine get worn and damaged due to heat, strain and particles in the air passing through it. When a Jet Engine is designed the potential service hours of the engine itself and components within are taken into consideration. Between flights, the engine is inspected with a predesignated service/inspection time interval. Damaged or worn parts, like fan blades, could therefore be detected and repaired if needed.

To the left, in Figure 5, fan blades made of carbon composite and Ti64 are assembled to the engine rotor and to the right the complete fan blade, including the dovetail for attaching the blade to the rotating assembly, is illustrated. The dovetail is made of carbon composite and is integrated into the main composite part of the blade. To prevent wear on the composite part of the fan blade when the engine is rotating, wear strips are mounted on both sides of the dovetail. Wear strips is a thin rectangular plate made of Ti64.

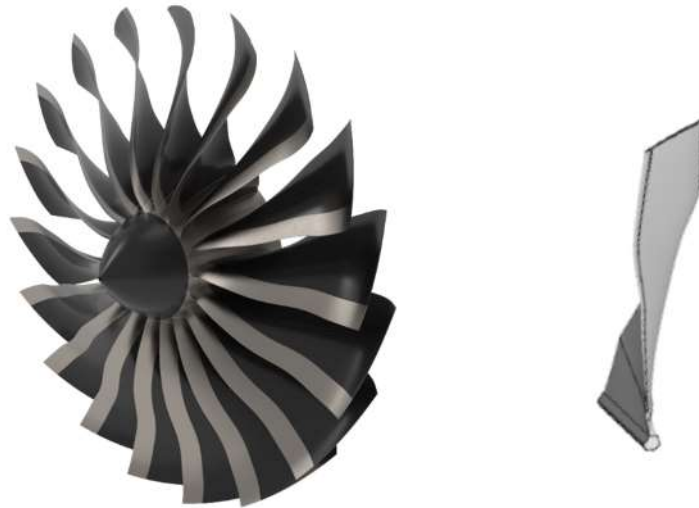


Figure 5: Fan blades assembled on the rotational assembly of the Jet Engine.

The composite is the structural and the main part of the fan blade and Ti64 is only used on the blades leading edge. This metal edge protects the composite part of the blade from Foreign Object Damage (FOD) and erosion. The studied fan blade is around 700 millilitres long, 300 millimetres wide and only a few millimetres thick. Table 1 shows a technical description of the main material and composition of the fan blade .

Table 1: Listing of materials included in the studied composite fan blade (in weight percentage, wt%).

Material	wt%
Ti64	14.5
Carbon fibre	40.2
Glassfibre	3.4
Epoxy	23.5
Polyurethane	17.2

The titanium alloy part is assembled to the composite part with an epoxy-based adhesive. To secure the assembly the leading edge is shaped to grip around the composite part of the blade both mechanically and through a permanent bond with adhesives. Figure 6 shows the cross-section of how the leading edge is attached to the composite part.

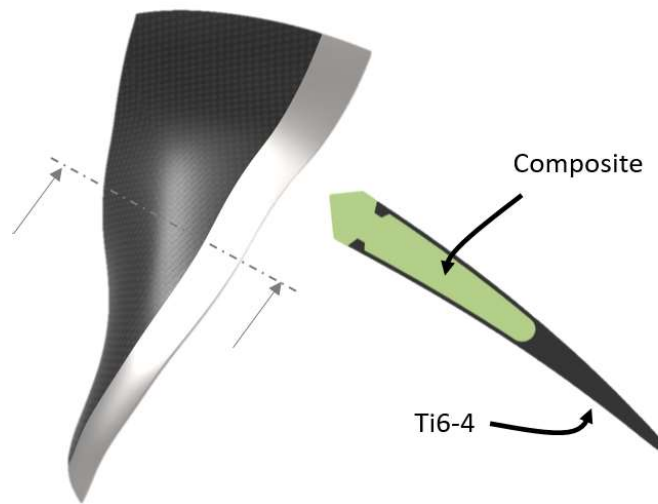


Figure 6: Figure that illustrates the composite and Ti64 part of a fan blade (without the dovetail). To the left, a cross-section of the leading edge shows how the part is mounted on the composite part.

### 1.3 Aims and Objectives

This study aims to contribute toward a greener aviation industry by analysing new repair methods for extending the life cycle of aerospace components. This is made by analysing the current linear flow of components that are produced, used and discarded towards a more circular flow with repair, which is one of the circular measures.

To meet the reports aim the following research question have been formulated:

- *What is the social and environmental sustainability impact of manufacturing a new fan blade compared to repairing it?*

The objective is to analyse the environmental and social impacts associated with manufacturing a new fan blade and two different repair methods, AM and CM. The environmental analysis is made with a consequential LCA. A qualitative assessment of social aspects such as work environment, material sourcing etc., is be based on interviews and complementing literature.

This report's objectives are:

- *Assess the sustainability impact of manufacturing a new fan blade.*
- *Assess the sustainability impact of repairing an old fan blade with AM or CM.*
- *Map the different processes to assess the benefits and challenges with each case.*

### 1.4 Limitations

The life span of a fan blade is hard to assume since the quality of the materials correlates to the environment it is exposed to. Engines are flying in different climates meaning a large variety in humidity, air particles and other foreign objects. Factors like this affect the longevity of the component because of uneven erosion and wear. Since carbon composite fan blades are a relatively new concept in the aviation sector, since limited experience from flight time, the lifetime is hard to specify. Engines are inspected at regular intervals between flights which means that parts are exchanged if the damage is detected or if the wear is too large.

Since the fan blade is a rotating part of the engine there are higher demands on safe operation. There could be a maximum set amount of flight hours a blade is allowed to be used and afterwards should be replaced. However, this is not taken into account in the study since no such demands could be enforced and defined, therefore the blades are assumed to have the same lifetime as the rest of the engine. The study also assumes that repaired fan blades have the same quality and performance as a new fan blade. It is, however, important to acknowledge that more research and experience within the area will be done and a more specific lifetime could be defined in the future. To get an idea of how long a fan blade needs to be operational, and thus how long a jet engine is in use the CFM56 engine is used as an example. The CFM56, developed by CFM International, is a jet engine used in the aviation sector since the 80s (CFM International, 2016). The CFM56 engine has around 30 000 flight hours before its first engine service/overhaul in ideal conditions. This means that the engine if used 24/7 every day, could fly for almost three and a half years if only accounting for the hours of flight and not cycles. The biggest forces, and thus wear, on engine components are from takeoffs and landings since the engines are then used to their full capabilities. This means that long-distance flights and short distance flights might not vary much in wear on the components since much of it is from the takeoff/landing. This means that there are specifications on both maximum flight hours and cycles an engine is allowed before maintenance/part changes. The maximum approved lifetime of a fan blade is estimated to be the full length of an airplane's life where the average is around 50 000 flight hours (Fernandez, 2020).

The following limitations are set:

- Some company-specific details might be confidential and is therefore left out of the published report.
- Only recycling of Ti64 is considered other material wastes are left outside the studies scope since they are considered neglectable small and to simplify modeling of the system.
- Described product in the study is a generic product due to confidentiality.
- Processes only contributing to less than 5 percent of the environmental impact are discarded to simplify the modeling of the system.
- Cut of criteria for the technical system are set to exclude impacts caused by workers, production of equipment/machines.
- No economical part of sustainability is assessed since it is already considered a viable market to repair airplane products like engine parts.

Table 2 present the assumptions and simplifications that were made in the report.

Table 2: Assumption and simplification in the report.

<b>Type</b>	<b>Assumption/simplification</b>
Average life time of a repaired blade is the same as for a new.	50 000 flight hours
The material content and weight of the composite part.	60 % Carbon fibre 35 % Epoxy resin 5 % Glass fibre Total weight 4,04 kg
The weight of the leading edge	Total weight 0,85 kg
Cutting fluid content	35 % Petroleum, the rest is not accounted for
The adhesive bonding has the same environmental impact as epoxy resin.	Environmental impact of epoxy resin
Waste that are left outside the scope.	Carbon composite, epoxy resin cotton textile and cutting fluid
Value of titanium scrap.	Recycling fraction is 60 %
The same type of transportation is used for all transports.	Truck euro 6, 32t gross weight Rail cargo, electric Cargo plane, 113t payload

## 2 Manufacturing process and material review

In this chapter information of aerospace engine and its component, conventional manufacturing, additive manufacturing and material knowledge of titanium alloys and composites are described.

### 2.1 Conventional Manufacturing

Conventional manufacturing of materials could be divided into five different manufacturing processes as defined by (Scallan, 2003) and seen in Figure 7.

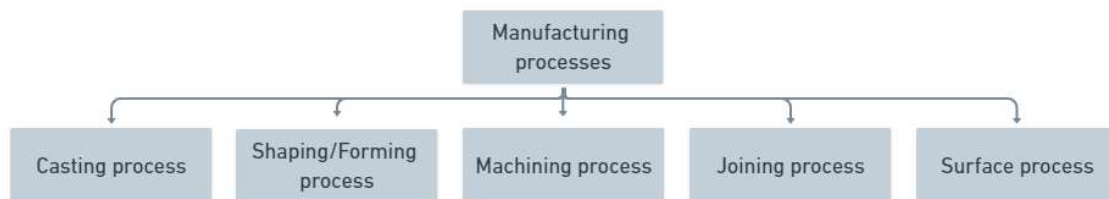


Figure 7: Manufacturing processes in CM reproduced based on (Scallan, 2003).

#### 2.1.1 Casting process

Castings of metals can be made in different ways, with an expandable or permanent mould. An expandable mould can be made of for example sand or ceramics while a permanent mould is often made out of metal (Scallan, 2003). Casting is done in an expandable mould at low pressures while those in permanent moulds can withstand pressurization. One commonly used casting process in the aviation sector is investment casting which falls under the expandable mould category. This means that the mould is destroyed after its use to release the part. The main principle of moulding is that metal is heated up to melting temperature and then formed by a dye or mould to the desired shape. Figure 8 shows some different casting processes.

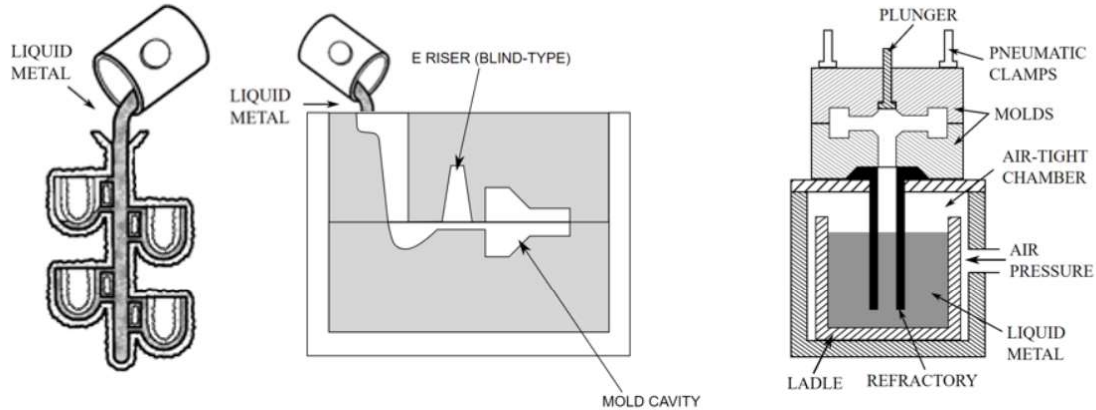


Figure 8: Different casting processes. From left to right: Investment casting (Groover, 2008), permanent mould casting (Wizard191, 2009a) and low pressure casting (Wizard191, 2009b). Creative Commons Licence (Reworked).

### 2.1.2 Forming and shaping processes

Forming is a mechanical method where solid material is shaped by implementations of forces to reach the desired geometry and material properties without removing any material (Corrosionpedia, 2018). When using suitable stresses such as tension, compression and shear, the material will undergo plastic deformation which changes the microstructure of the material. This can improve the mechanical properties and for example, increase the material's strength. Materials suited for this process are metals since other material often lack desired properties like ductility (Arcella & Froes, 2000). One example of a forming approach in the aviation industry is forging, used to produce engine components with high material specifications.

Shaping is another method that often involves moulding of a material at an elevated temperature, which in many ways is similar to casting but could also be performed on materials like plastics (Scallan, 2003). Moulding is when a material is shaped through a matrix or mould (Malkin & Isayev, 2017). The most common materials for moulding processes are polymers which are melted and pressured into a mould. This method can also be used for manufacturing composite materials where resin is pulled into the form by vacuum also called Resin Transfer Moulding (RTM). Figure 9 shows the processes mentioned above.

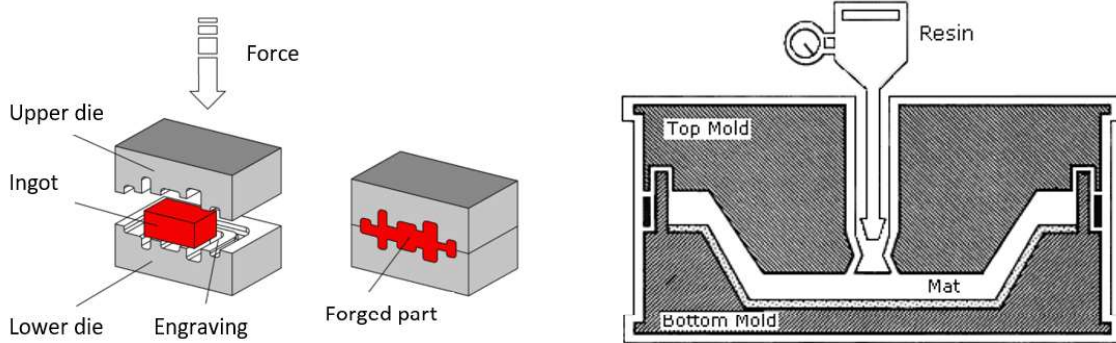


Figure 9: Different casting processes. From left to right: Forging (F.Broer, 2006) and RTM (Administration, 1999). Creative Commons Licence (Reworked).

### 2.1.3 Machining process

Machining processes are commonly used to reach desired geometry, tolerances and surface finish of components (Scallan, 2003). Machining can be divided into mainly three subcategories which are: cutting, abrasion and non-traditional machining. Cutting is when material leaves the part in a chip form, and can for example be milling, drilling and turning. In milling, the part is stationed and the tool rotates around the part while in turning the part rotates and the tool is stationary. Abrasive machining is methods like grinding, honing and polishing where less material is removed. Non-traditional methods are for example laser cutting and spark erosion cutting. Figure 10 shows some of the processes mentioned above.

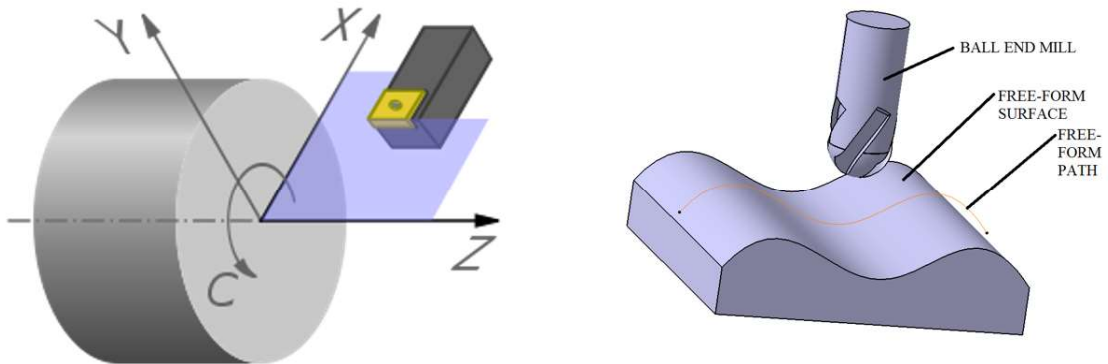


Figure 10: Different machining processes. From left to right: turning (MatthiasDD, 2019) and milling (Abhishekmep2014, 2015). Creative Commons Licence (Re-worked).

#### 2.1.4 Joining process

Joining is when one or several parts are put together to form a desirable product (Scallan, 2003). There are different types of joining and these can be categorised into three categories: welding processes, adhesive bonding and mechanical fastening. These processes work either by fusing the parts together with or without additives, glues, or pressing the parts together with a great force to form a joint. Figure 11 shows some of the joining processes.

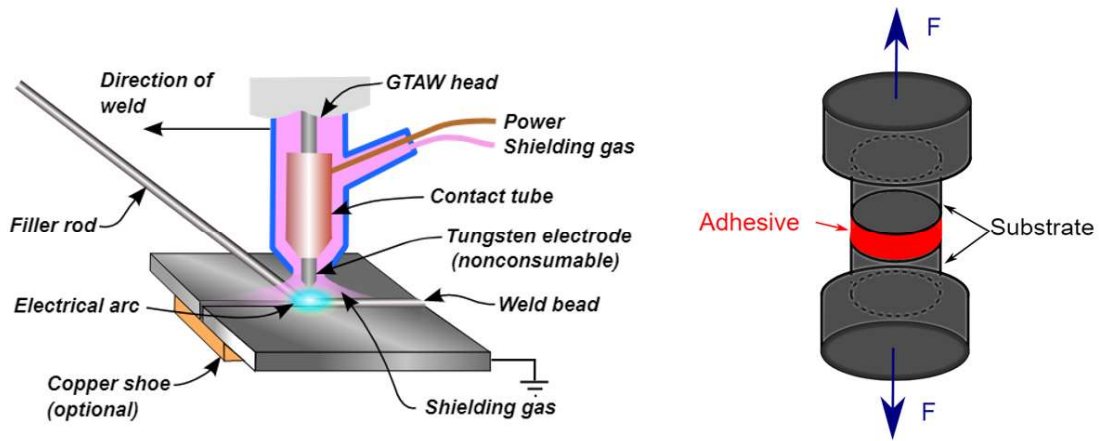


Figure 11: Different joining processes. From left to right: TIG Welding process (Duk, 2006) and adhesive bonding (Clemintime, 2021). Creative Commons Licence (Reworked).

### 2.1.5 Surface process

The surface process is often the last in the manufacturing, with exception of heat treatments (Scallan, 2003). There are different surface processes such as bulk treatments, surface treatments, surface coatings and cleaning processes. These processes are also called finishing processes and can for example change the microstructure, and thus enhance the properties of the materials, like improving corrosion resistance and act as a thermal barrier. Finishing can also be used to remove surface contaminants. Figure 12 shows some of the processes mentioned above.

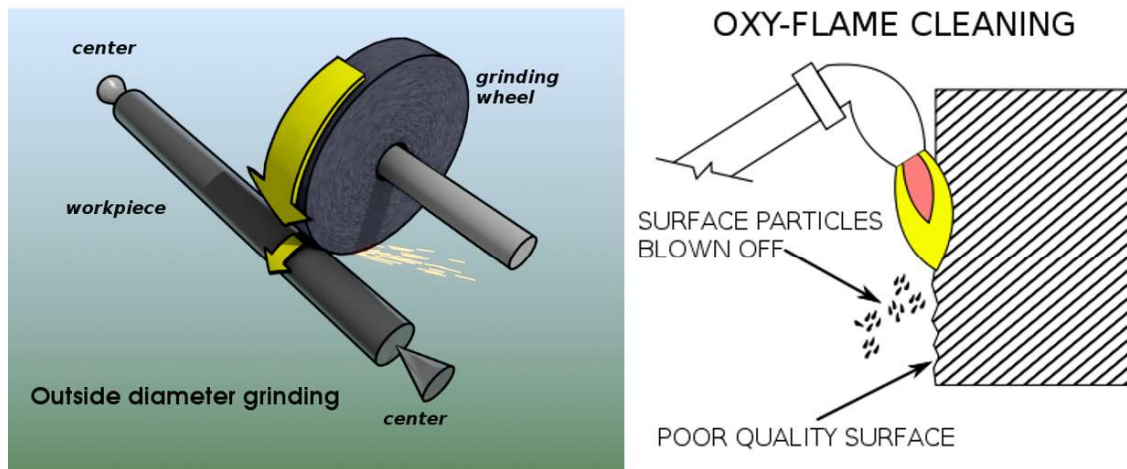


Figure 12: Different surface processes. From left to right: Grinding (InfraYellow, 2015) which are a surface treatment and Cleaning (Hall, 2009) which are a cleaning process. Creative Commons Licence (Reworked).

## 2.2 Additive manufacturing

AM is, compared to CM which is a subtracting manufacturing process an additive manufacturing process. AM is based on Computer Aided Design (CAD) where the file is used to build the component from the "bottom-up" on a layer by layer basis (Ford & Despeisse, 2015). AM can be used to produce several different products with a large span of different materials including, polymers, composites and metals. AM consists in many different forms depending on how materials are fused and added together. Acronyms for the same AM method may differ depending on the manufacturer of the machines used.

Additive manufacturing is nothing new to the industry, but a shift towards final component production has been made rather than just conceptualized prototypes used in rapid prototyping (Ford & Despeisse, 2015). One of the early patents on AM where established in 1977 by Wyn Kelly Swainson who described how a laser was used to fuse materials and the material was lowered one step at a time (Swainson, 1977). Patents made within the field of AM have had exponential growth since the early 2000s according to statistics from the European Patent Office (EPO) (Pose-Rodriguez et al., 2020) and can be seen in Figure 13.

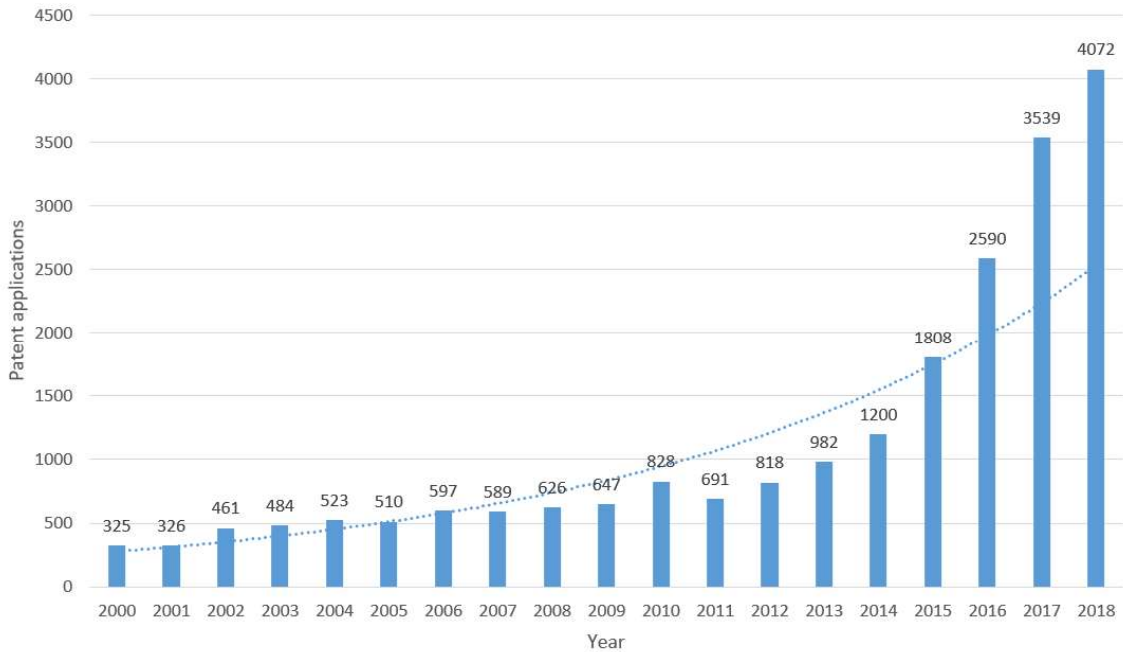


Figure 13: Graph illustrating AM Patent applications to the European Patent Office. Compiled from data 2000-2018 (Pose-Rodriguez et al., 2020).

AM of metal components has wide use in the industry with the example such of Caterpillar’s engine re-manufacturing (Ford & Despeisse, 2015). In the re-manufacturing process, AM is used to repair engine components such as engine blocks, crankshafts etc., to as a new or better condition to prolong the life cycle of engines. AM is also commonly used in the aviation sector for repairing Jet Engine components such as bladed disks, also called blisk, used in Optomec’s Leans Process (Optomec, 2020).

### 2.2.1 AM technologies for metals

Additive technologies for metals, also called Metal Additive Manufacturing (MAM), is especially attractive to those sectors with high-quality standards, such as the aviation industry (Monteiro et al., 2022). There are four current available MAM processes, Powder Bed Fusion (PBF), Direct Energy Deposition (DED), binder jetting and sheet lamination. For the aerospace industry, the most commonly used are PBF and DED (Garcia-Colomo et al., 2020).

Powder bed fusion (PBF) processes have a power source in the form of a laser or electron beam (Garcia-Colomo et al., 2020). This power source is used to locally melt a layer of metal powder which are previously spread, layer by layer. The powder bed fusion process has the advantage that the fabrication time does not depend on parts complexity, but is instead dependent on the part volume (Gisario et al., 2019). PBF includes three main types, Selective Laser Melting (SLM), Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) (Monteiro et al., 2022). PBF can construct complex structures in one operation that otherwise would be impossible to make in any other way, see Figure 14.

Direct Energy Deposition (DED) processes build the component by depositing and melting the powder or wire simultaneously (Monteiro et al., 2022). DED includes four main types, Laser Metal Deposition (LMD) and Electron Beam Free Form Fabrication (EBFFF), Wire Laser AM (WLAM), and Wire Arc AM (WAAM) processes. LMD and EBFFF are both Direct Metal Deposition (DMD) processes. See Figure 14 for examples of components that were made by DED.



Figure 14: The two left components is made by PBF and the right by DED.

### 2.2.2 Laser Metal Deposition (LMD)

The AM method considered for the repair of fan blades, in this study, was Laser Metal Depositing (LMD). LMD uses a laser beam as its heat source and additive material can either be added by powder (LMD-P) or as wire (LMD-W) in different nozzle configurations (Gisario et al., 2019). The heat source is guided by a robotic arm which allows flexibility and, since it is distributed by a laser, the given heat amount is focused in a small area. However, if the peak power is too high which results in reaching the evaporation temperature of the material it can generate bubbles and cracks (Song et al., 2012). To protect the chemical and mechanical properties of the material, the process needs to either be assisted by a shielding gas, usually argon or helium (He), or in an anaerobic atmosphere (vacuum) (Ming et al., 2007).

The use of LMD technologies is most suitable for building up or repairing high-value components and is, therefore, an appropriate AM method to use in the aerospace industry (Yu et al., 2012). LMD can for example be used to build up titanium rudders or repair turbine blades.

## 2.3 Comparing CM with AM

The manufacturing review on CM and AM covers the potential challenges and advantages of implementing AM in the production and repair of components. In this chapter, the potential advantages and challenges are stated from a production view.

Some of the clear advantages of AM is the availability to produce and repair components with complex geometries, for example, producing internal cavities in a component. Something that would be impossible to achieve with CM on a component made out of one solid piece. The advantages and challenges with AM differ based on what AM method is used. Wire based methods can have a high deposition rate, faster production, and powder based methods can offer more detail and part complexity. AM opens new potentials in design to enable products to be both lighter and stronger, thus reducing the material needed for production and improving the efficiency of the product during its life cycle. Assemblies of components could be redesigned into one single piece instead of several, reducing the time and complexity of assembly and thus reducing unnecessary supply chains. The capabilities of AM show that components with a high buy to fly ratio, and high material use per equivalent product output, are good candidates for AM and thus enable a reduction of waste from the production process (Monteiro et al., 2022). Less capital is bound in stock, tools and fixtures with the capabilities to produce on-demand.

Challenges connected to implementing AM to a higher degree in the industry are the uncertainties of the sustainability benefits connected to the method. Parts produced with AM still need to be future investigated and certified for some uses for example in the aviation sector (Ford & Despeisse, 2015). There are potential challenges with the incorporation of AM into CM manufacturing lines for post-processing. Machine development within AM is still new and investment costs are large. Some challenges may, by the time AM matures as a method, be less relevant. One of those challenges is that AM is most applicable to small volume production and components with a high buy to fly ratio.

## 2.4 Titanium alloy: Ti64

Titanium alloys are a widely used metal in the aerospace industry where high standards are put on components (Gialanella & Malandruccolo, 2020). Titanium has a low density (4.51 g/cm<sup>3</sup>) and a high tensile strength, i.e low density to strength ratio and Young’s module of 120 Gpa. Titanium has good corrosion resistance and is stable up to 882 °C and reaches its melting point at 1670 °C. Titanium can be processed by a variety of production processes including most CM methods like welding, forging, rolling, casting, and milling and by powder and wire technologies such as AM.

The development of titanium-based alloys were driven by the increased aviation activities in the early 1950s (Gialanella & Malandruccolo, 2020). One of the most used titanium alloys, and the one investigated in the study, is Ti64 also called Ti-6Al-4V. This alloy consists of 90 percent Titanium (Ti), 6 percent Aluminium (Al) and 4 percent Vanadium (V) except for a small amount Oxygen (O) and Iron (Fe). See Table 3 for more key properties and a comparison of Ti64 and an aluminium alloy that also is commonly used in the aviation sector, Al 8091 T6.

Table 3: Comparison between to commonly used materials in the aviation sector, based on Granta Selector (Ansys, 2021).

<b>Key properties</b>	<b>Ti64</b>	<b>Al 8091 T6</b>
Density [g/cm <sup>3</sup> ]	4.42-4.43	2.56-2.61
Melting range [C]	1610-1660	510-680
Tensile strength [MPa]	1100-1127	505-595
Young’s Module [GPa]	111-119	77-81

Some of the metals used to produce Ti64 is unevenly distributed over the world and in small concentration. Titanium and vanadium are on the EU's Critical Raw Material (CRM) list and are mainly mined and produced by a few leading suppliers/countries (Latunussa et al., 2020). This means that the EU is reliant on other countries outside the EU for raw materials. The EU's CMR list describes materials that are of great interest and concern for the EU's economic development where supply risk and economic developments are put into correlation. The list includes materials that are important for cleaner and more efficient technologies such as windmills, batteries and lightweight materials that could be used to enhance the efficiency of aeroplanes. It is therefore important to keep these metals in the technosphere by methods such as recycling. Currently, the recycling fraction of Ti64 used in the world is around 60 % (Ansys, 2021). However, the aluminium used in the alloy is an abundant chemical element found all over the globe in the form of aluminium oxide and is neither regarded as scars nor as a critical material. Figure 15 shows were the main global suppliers of titanium and vanadium.

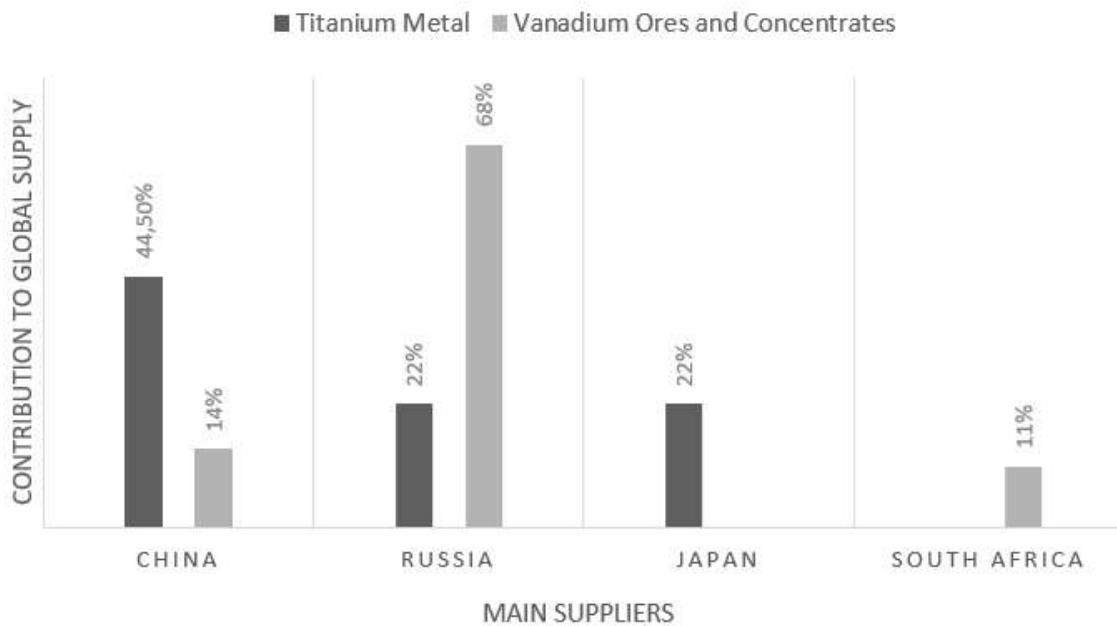


Figure 15: Global suppliers of titanium metal and vanadium (ores and concentrates) compiled from data 2012-2016 (Latunussa et al., 2020).

### 2.4.1 Production of Ti64 powder for AM

For repairing the fan blade with LMD-P, the input of titanium alloy needs to be pulverized. This process is energy-intensive due to it, first of all, includes the production of Ti64 which on its own is energy intense, and also includes a large argon usage. The titanium alloy is fed into an atomiser in the form of an ingot that is melted by an induction coil and then directly enters the atomisation chamber (Sphera, 2022). Argon jets disintegrate the metal which becomes falling solidified metal droplets. The gas atomisation process in argon leads to an increased solidification time which results in more spherical powder particles compared to, for example, water atomisation.

Since the production of Ti64 powder consumes a high amount of argon the production of argon itself needs to be considered. Argon is the third most abundant atmospheric gas, after nitrogen and oxygen, and constitutes around 1 % of the atmosphere (Ansys, 2021). Argon is a tintless, colourless and odourless gas that is non-toxic. One of its usual applications is to be used as an inert gas and should therefore be handled with care in closed areas due to argon characteristics to displace oxygen in the atmosphere. To extract argon, air needs to be liquefied by compression and cooling and then fractionated by distillation (Sphera, 2021). The main energy source for the process is the electricity grid mix.

## 2.5 Carbon fibre based composites

Composites are structural materials used in the aviation sector due to their mechanical properties and low density. Composite is made of two or multiple different phases to create desired properties that one material lacks. The most used composite in the aerospace industry is carbon, glass or aramid fibres in a matrix of epoxy resin. The epoxy matrix distributes the load between the fibres in the composite structure and the direction of the fibre directly correlates to the properties and strength of the part. Figure 16 illustrates some examples of how fibres can be arranged in the layup phase.

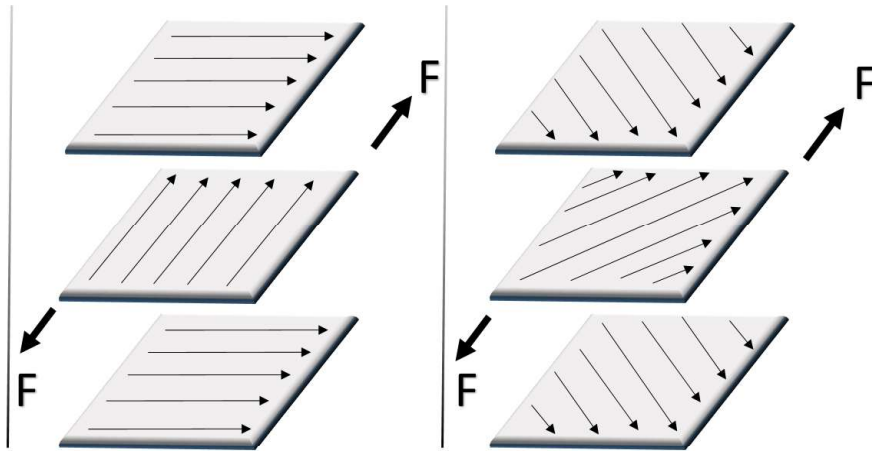


Figure 16: Illustration of fibre direction in composite structures where material properties differ depending on layup direction.

The epoxy matrix can be applied directly into the fibres by so-called prepreg fibres/mesh where the material is already filled with epoxy or by using RTM as discussed in Chapter 2.1.2. With RTM the fibres are exposed to a vacuum in a sealed container and the vacuum is used as media to pull and distribute the epoxy into the mould as well as forcing the fibres together during the curing process. Prepregged fibres/mesh can also be used in a vacuum to cure and force the materials together. To fully cure the epoxy matrix additional heat treatment processes may be needed.

Properties that characterize composites are low thermal expansion and low density. In aerospace, light structures are an important measure to reduce fuel consumption and increase the payload or passengers. On the other side, composite material such as glass and carbon, does not display a fatigue limit and has low toughness and therefore cannot withstand sudden impacts like birds and lightning. However, these impacts can be avoided by incorporating metals into the composite which are more ductile and prevent cracking in the component. Since composites are made out of polymers which makes them great insulators, the problem of galvanic corrosion is close to non. But other issues arise regards to the use within aviation where lightning is a concern. Metal like conductive mesh or similar is needed in the composite to act as a conductor to distribute energy from a lightning strike. However, composite may need a protective layer to stop water from intruding into the material and delaminate the fibres.

One commonly used composite is carbon fibre composite which consists of carbon fibre and epoxy. Carbon fibre is made of carbon atoms arranged in a specific molecular stable structure called ladder structures. These fibres are woven together to a mesh with epoxy. The composition and methods for producing carbon fibres are different between suppliers and are often regarded as a trade secret. Carbon as a chemical compound is abundant in nature and is therefore not a critical resource according to the EU's CRM list. Epoxy is an adhesive material and is made of an oxygen atom bonded to two carbon atoms (Park & Seo, 2011). To produce epoxy resin it is important to have a correct mix ratio between resin and hardener to avoid unreacted resin or hardener will remain within the matrix. The hardener, called amine, is a basic nitrogen atom with a lone pair. When the mixing is made correctly, the epoxy resin has good water-resistant, stiffness, toughness and heat resistant properties. The most common epoxy-based composites can be used at temperatures up to 93 - 121 °C without degrading material properties, but some epoxy resins can perform well up to 204 °C. There are two types of plastics, thermoplastics and thermosets (Recycled Plastic, 2014). Thermoplastic has a low melting temperature and can be repeatedly melted, that is 100 % recyclable. On the contrary, the thermosets are permanent once melted and can withstand high temperatures without losing shape and strength, and therefore this plastic cannot be recycled, only reused. Epoxy resin is a thermoset and since a lot of aerospace materials need properties that are heat resistant and retain their strength, thermosets are often used in this sector.

## 3 Method

This chapter covers the different methods used in the study with motivations to why they are used. The different methods used are Strategic literature search, interviews, Life Cycle Assessment and Social Impact Assessment.

First, a strategic literature search and interviews were made to gain knowledge about materials and processes used to produce/repair a composite fan blade. Then a life cycle assessment is used to assess the different cases' environmental impact and analyse where and why some processes have a larger impact than others, in other words, identify hotspots. Lastly, a social impact assessment was performed to include and assess the social aspects of the three cases.

### 3.1 Strategic literature search

The Strategic Literature Search Method was used to gain knowledge on Additive Manufacturing technologies. To start, keywords were identified from the GKN thesis proposal. The keywords were divided into blocks with Boolean operators to create a search string. Boolean operators where: AND and OR (Livoreil et al., 2017). The operator *AND* was used to combine different blocks and the operator *OR* to distinguish between different search terms in the block, thus building many different potential configurations of materials searched for. The asterisk \* symbol was used as a wildcard for synonyms, double quotation marks "" for adjacent search terms and curly brackets { } for exact terms (Elsevier, Nda). Subject pearl growing technique (Lunds Universitet, 2019) was used on the identified keywords.

First search string :

- {Laser metal deposition} OR {LMD} OR {Additive manufacturing} OR {DED} OR {direct energy deposition}

The bibliographic source used for the search was Scopus (Elsevier, Ndb). A quality assessment was made on the sources used based on the number of citations, source credibility and the age of content. Type of sources used were primary and secondary sources, academia, and in some cases grey literature. Primary sources are the raw information which is first-hand evidence and secondary sources are the second-hand information (Streefkerk, 2018). Academia is the literature related to education and scholarship (Encyclopedia, 2018). Grey literature is all kinds of literature, with sufficient quality, produced outside conventional means (Livoreil et al., 2017).

The first search strings gave good results but could be widened more towards manufacturing technologies and be more specific towards aerospace to reach more suitable results connected to the study. The final search string can be seen in Figure 17.

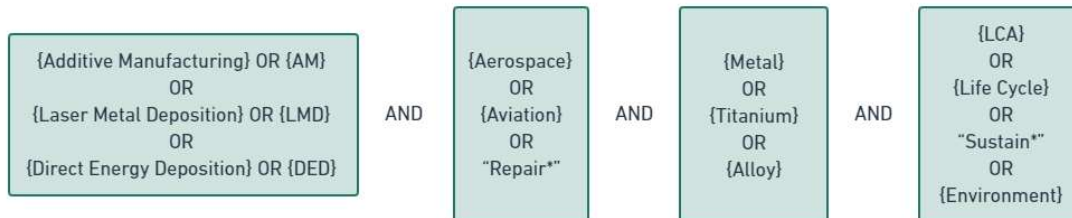


Figure 17: Search string for AM with Boolean operators.

The string was used to search for articles in the bibliographic source, Scopus. The search string in Figure 17 gave initially 175 articles as a result. With filtering regarding subject area, language and by year published, the result was 29 articles. The articles were thereafter screened manually for relevant areas resulting in 12 articles.

For further search, two articles were retrieved from an expert which has extensive knowledge within the field of Additive Manufacturing. The method used was the Citation pearl growing technique, also called Snowballing Strategy, (Lunds Universitet, 2019) on the two articles received: *Additive manufacturing and sustainability: An exploratory study of the advantages and challenges* (Ford & Despeisse, 2015) and *Energy and material efficiency strategies enabled by metal additive manufacturing – a review for the aeronautic and aerospace sectors* (Monteiro et al., 2022). Citations used in the two articles given and on those from the subject Pearl growing technique were used to find other suitable sources for the master thesis. The articles made way for further understanding of the subject's applications and implications.

## 3.2 Interviews, observations and documentation

To capture qualitative data the method semi-structured interviews were used. The choice of method was based on open-ended and closed questions with the participant to capture both precise answers like features, mass etc., and data regarding problems/paths to investigate further. Data searched for was not easily retrieved from documentation within the company, since it is based on a future business case, and therefore gathered from experts working closely in the project. Qualitative and numerical data were also put into context and verified with the interviewee to see acceptable ranges. Semi-structured interviews are suitable when follow-up questions are required (Newcomer et al., 2015). Follow up questions could be for example *why is that?*. The interviews were held with experts and team members on the AM repair team of GKNA, both individual participants as well as in some cases in a group to gain first-hand data from people engaged in repair projects at GKNA. Data was also gathered through observation in form of guided tours through GKNA's production facilities. The tour included looking into similar products and processes to the projects, that already been implemented or tested at the company.

Preconditions to the preformed semi-structured interview were for example to gain fundamental knowledge in the area, drafting the questions, set up the interviews and choosing participants etc. Questions were altered, erased or added to capture appropriate information before each interview to get the right information from that expert's area, but the main structure for the interviews was the following:

- Present ourselves and what our project is about.
- Ask what they are working with and their latest successful project.
- Ask them the prepared questions for the project that are suitable for their professions. Questions that were asked was for example:
  - What materials do a fan blade consist of?
  - What is the composition of each material?
  - Why do damages occur on fan blades and how do they look like?
  - What processes are involved when manufacturing a new fan blade?
  - What processes are involved when repairing an used fan blade?
  - What are the wastes from the processes?
  - What is the life extension of AM repair of the fan blade?

Each interview had a planned duration of roughly one hour to keep the interviewer and participants from fatigue. One hour was also sufficient to collect the information needed for one session. Some of the interviews were held in Swedish and afterwards translated into English for use in the report.

The interviews were conducted by a two-person team and divided so that one person was asking the questions to ensure that every topic was covered, and the other person was taking notes to ensure that all information was remembered correctly. Immediately after each interview, the written notes were clarified and extra information where potentially added while the discussion was fresh. Keywords from the interviews were then identified between the different notes to highlight areas of importance. The interviews set the ground for information about the component and its specifications as well as social aspects related to the production process which is described later in the following chapters.

Data was also gathered and documented through mail contact with the GKN purchaser department and machine suppliers. In total 15 different experts were interviewed and Table 4 presents the interviewees, their professions, data gathered and the duration.

Table 4: The table shows the data collected through interviews and observations. The time presented includes, in some interviews, multiple interview sessions.

Titel/Profesion	Field of expertise	Method for data collection, total duration [h]	Type of data
Senior engineer - Design	Manufacturing processes in GKN using AM	Semi-structured interview [1]	Qualitative
Manufacturing Engineer - Product & Planning	Supporting manufacturing processes for AM	Workshop tour based interview [2]	Qualitative
Senior Engineer - Design	Potential of repair	Presentation and semi-structured interview [0.5]	Qualitative
Research Engineer/Specialist - Process Development	Process steps manufacturing and repairing a fan blade	Semi-structured interview [3]	Qualitative, numerical and validation
Research Engineer/Specialist - Process Development	Repairing with AM	Workshop tour based interview [2]	Qualitative
Associate Research - Engineer/Specialist	Manufacturing carbon composite	Semi-structured interview [1]	Qualitative and numerical
Research Engineer/Specialist - Materials & Processes	Manufacturing carbon composite	Semi-structured group interview [1]	Qualitative and numerical
Associate Research Engineer - Process Development			
Senior Research Engineer - Process Development	Manufacturing energy usage and waste	Semi-structured interview [2]	Qualitative and numerical
Senior Research Engineer - Digital Engineer	Process steps manufacturing and repairing a fan blade	Semi-structured interview [1]	Qualitative
Senior Research Engineer - Process Development	Energy consumption of LMD and local heat treatment	Workshop tour based interview [2]	Qualitative
Principal Engineer - Materials & Processes	Forging process	Semi-structured interview [1]	Qualitative and validation
Maintenance multi skilled - Mech/Electric.	Heat treatment	Observation [1.5]	Numerical
Research engineer -system engineering	Sustainability	Workshop [1]	Qualitative
Senior research engineer -system engineering			

### 3.3 Life Cycle Assessment

The following chapters describe how the life cycle assessment was conducted. Data regarding the fan blade and processes were gathered through semistructured/in-depth interviews with experts in the production of jet engine components. A literature study was conducted to assess current research and solutions in the field as well as data regarding machine specifications and equations for energy calculations.

A Life Cycle Assessment (LCA) was made, in the software GaBi, to analyse the environmental impacts associated with current and new methods for repair (Sphera, 2022). An LCA is an analytical tool within the field of Environmental System Assessment (ESA) and can be used to analyse the potential environmental impacts associated with a product or process. The assessment is made by analysing the input and output flows throughout the life cycle and can be used to support decision making processes such as policy making or production decisions. The LCA results of this thesis study will provide data on the environmental impacts of fan blade repair compared to fan blade production, from a cradle to gate perspective. The LCA is done in accordance with the standard ISO 14040 (International Organization for Standardization, 2006) that describes how an LCA should be employed to be published, the basic procedure can be seen in Figure 18 and the steps are described in the following chapters.

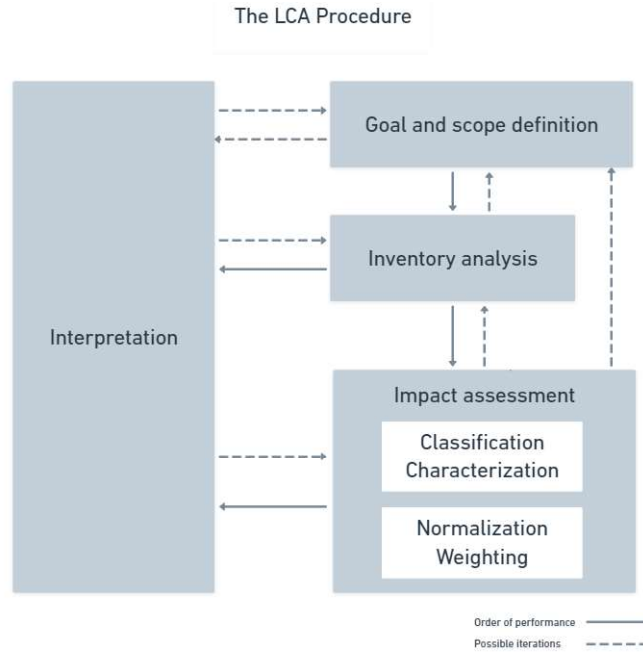


Figure 18: The LCA procedure based on ISO 14040 Standard (International Organization for Standardization, 2006).

### 3.3.1 Goal and scope

The LCA was performed as decision support for GKNA's future business opportunities and communicated to the company by a formal report. To ensure compliance with the ISO standard, specific questions have been formulated to guide the purpose of the study (International Organization for Standardization, 2006) and were set in Chapter 1.3.

An initial flowchart was made at an early stage to get an overview of what processes were included. The three systems are presented in Figure 19. The flowchart to the left represents the system manufacturing a new fan blade, the flowchart in the middle is the repair with CM and the flowchart to the right is the repair of a fan blade with AM.

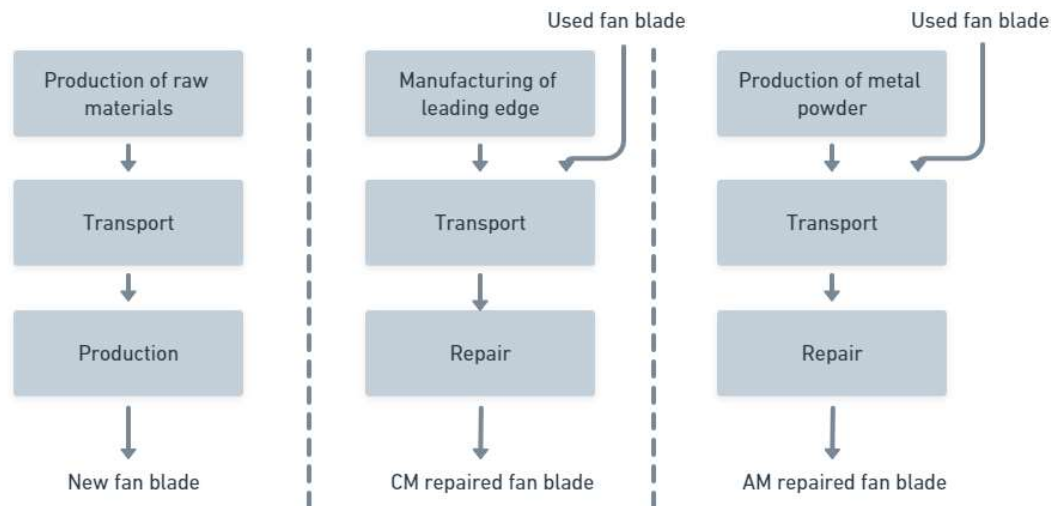


Figure 19: To the left: Initial flowchart describing the production of a new fan blade. The middle: repairing an used fan blade with CM and to the right: repairing an used fan blade AM.

The functional unit should reflect and express the function of the system and was set to *50 000 flight hours* to represent the function of the system, since it is assumed to be the average lifetime of a fan blade. To perform the LCA, the system’s environmental impacts need to be considered (International Organization for Standardization, 2006). Impacts can be divided into three main impact categories: resource use, ecological consequences and human health. Thereafter, these impact categories can be interpreted into operational impact categories to measure impacts caused. In this report the impact categories have been categorised according to CML, an impact assessment method developed by the Center for Environmental Sciences in the Netherlands which is based on European regional conditions (Dassault Systèmes, 2017). CML methodology is the most commonly used set of environmental indicators for LCA performed outside of North America and is therefore used in this study. Considered impact categories are presented in Table 5.

Table 5: Main categories and the considered operational impact categories used in the GaBi Software with CML 2001 -Jan 2016.

<b>Ecological Consequences</b>	<b>Resources</b>	<b>Human Health</b>
Global warming Pot. (GWP) [kg CO2 eq.]	Abiotic Depletion Pot. elements (ADP) [kg Sb eq.]	Human Toxicity Pot. (HTP) [kg DCB eq.]
Ozone Depletion Pot. (ODP) [kg R11 eq.]		
Acidification Pot. (AP) [kg SO2 eq.]		
Eutrophication Pot. (EP) [kg Phosphate eq.]		
Photochemical Ozone Creation Pot. (POCP) [kg Ethene eq.]		
Marine Aquatic Eco Toxicity Pot. (MAETP) [kg DCB eq.]		
Freshwater Aquatic Ecotoxicity Pot. (FAETP) [kg DCB eq.]		
Terrestrial Ecotoxicity Pot. (TETP) [kg DCB eq.]		

A change-oriented LCA (CLCA), was used since it is a comparison of three different systems. A CLCA puts specific specifications on the work procedure and data used: using marginal data that are site-specific, and use of system enlargement since partitioning should be avoided, see Table 6 (Baumann & Tillman, 2004). The time horizon is set to represent a probable future since the LCA is done to analyse a future business case.

Table 6: The two different types of LCA, Table from (Baumann & Tillman, 2004).

<b>Characteristic</b>	<b>Accounting</b>	<b>Change-oriented</b>
System boundaries	Additivity Completeness	Parts of system affected
Allocation procedure	Reflecting causes of system Partitioning	Reflecting effects of change System enlargement
Choice of data	Average	Marginal (at least in part)
System subdivision	-	Foreground & background

An LCA can cover different parts of a product's life cycle, from cradle to grave where the cradle describes the extraction of material to the grave where the life cycle ends (Baumann & Tillman, 2004). The LCA scope is set to cover cradle to gate, where the cradle is the extraction of the material in different countries and the gate is when the blade leaves the production plant in Sweden. Boundaries are put between the technical and natural system, where the natural system is defined as where humans lack control over the input and output resources for example the ocean. The opposite applies to a technical system, where humans have control over resources, for example when land is used for open pit mining of minerals.

For the study, the spatial boundaries are set to include countries for extraction of raw materials and the countries of the production sites. The temporal boundary is set to the average lifetime of a civil aeroplane which is 50 000 flight hours. Cut of criteria for the technical system is set to exclude impacts caused by workers and production capital. Weighting of the impact categories is left out of the study since it is not compulsory by ISO 14044 standard since it lacks a scientific base. Weighting is based on values which can differ between all humans.

### 3.3.2 Inventory analysis

The inventory part of the LCA describes materials and energy sources used as inputs to the processes as well as outputs such as wastes. The results are normalized to what is needed and discarded to produce one fan blade and thus fulfill the functional unit. Transports like trucks, planes and rails are described in tonnes\*km transported. Energy and energy carriers such as natural gas in MJ. Material usage and waste in kg. The data is later used to model the different cases in GaBi.

The inventory analysis was divided into three steps as suggested by Baumann & Tillman (2004), as described below:

As a first step in the inventory analysis phase a detailed flowchart was constructed representing all steps in the systems. Information about the system's composition was retrieved from interviews of employees at GKNA, suppliers/producers, literature studies and measurements like analysing a CAD model of the component. Numerical data were used to describe the input and output flows from each process, whereas qualitative data described the processes, their geographical location, etc. Missing data or data deemed too time-consuming to find and gather were replaced with assumptions shown in Table 2. Boundaries were set between the modelled systems and other surrounding systems according to the goal and scope definition defined in the previous chapter. The data collected and assumptions were checked to ensure validity by mass balances and comparison to other sources.

### **3.3.3 Impact assessment**

The next step, suggested by Baumann & Tillman (2004), was to calculate each process. This was made by using the LCA software, GaBi. In the software, flows were linked between the processes in the system and the numerical data was normalized to the functional unit. The LCA software was used to simplify the calculation process since a large amount of data can be time-consuming to calculate.

The impact assessment phase of the LCA aims to describe the environmental loads caused by the system into relevant environmental impacts. Each process emits different types of emissions and these emissions are classified into their respective impact category. Then a characterisation was made by multiplying each type of emission with a factor corresponding to an impact category reference value. One example is the impact category of Global warming, which converts every Greenhouse gas to CO<sub>2</sub> equivalents with a specific conversion factor. The CO<sub>2</sub> equivalent for methane is 28 since methane contributes 28 times more than CO<sub>2</sub> to the radioactive forcing in the atmosphere under a 100-year period (U.S. Environmental Protection Agency, 2021).

Other examples are the impact categories Marine Aquatic Eco Toxicity Potential (MAETP) and Human Toxicity Potential (HTP). These toxicity potentials aim to measure negative impacts on the marine water or on humans (GaBi sphaera, 2018). The damaging effects depend on the duration and frequency of an impact and toxicity is based on several parameters. The potential toxicity of a substance is for example a chemical composition, point source of emission, physical properties, etc. This was then characterised according to its effect on the environment. This is calculated in a similar manner as global warming, in other words, converting a potentially toxic substance into a specific equivalent. These impact categories are measured in kg 1,4-Dichlorobenzene (kg DCB eq.) which is a substance that may be a carcinogen in humans since it has been indicated by animal studies and therefore also toxic to water organisms (New Jersey government, 1998).

### **3.3.4 Interpretation**

To analyse the robustness of data used as inputs to the LCA modeling, an uncertainty analysis has been made. The uncertainty analysis is based on varying the input values in a range from -10% to +10% to get a worst-case and best case interval. Only uncertain data and processes with a large environmental impact based on GWP have been analysed. Uncertainty of data was based on the its source, where primary data preferred for a CLCA, is ranked with the highest credibility and secondary data has the lowest. Table 10 in Chapter 4.3 shows the result of the weighting of data for each case and process. Some data is also tested and validated through a comparison of values found in the literature regarding the specific process. Input data that has been changed and tested can be seen in Table 11.

## **3.4 Social impact assessment**

The Social Impact Assessment (SIA) was performed by following the principles and guidelines proposed by the US Interorganizational Committee (The Interorganizational Committee on Guidelines and Principles for Social Impact Assessment, 2003). These principles were made by experts in different fields to ensure scientific practices when doing a social impact assessment.

To analyse the effects of a change the stakeholders of the system needs to be considered. When manufacturing a new blade, or repairing an used blade people in the nearby area or in the process chain are affected. Different social aspects related to the production and sourcing of materials will be assessed quantitatively by statistical data on equality, healthcare, suicide mortality, education, etc. Data was gathered by different methods including interviews, workshops, and literature searches. The affected stakeholders and processes have been identified through workshops and interviews.

For a company such as GKN to be in business in the long run its stakeholders' interests need to be taken into account (Dashwood, 2013). Stakeholders have different powers, legitimacy, and urgency (Mitchell et al., 1997). A change from producing new products to repairing used products brings along a change in the entire production chain and thus concerns stakeholders of GKN. To identify how potential stakeholders influence and are affected by a change a stakeholders analysis was made. A stakeholder can possess one, two, or all three of the attributes whereas one who possesses all three is considered a key player.

A stakeholder is considered to have:

- power when they are in the position of affecting a choice.
- legitimacy when they have gained reliance in a specific area, for example, a research institute.
- urgency when they claim that they need to have urgent change.

A stakeholder analysis is used to analyse how different types of stakeholders are affected by a change of operation and thus how to improve the relationship between stakeholders and the company itself. The stakeholders can be divided into different categories called primary and secondary stakeholders (Waddock, 2013). Where primary stakeholders have a direct influence on the company's activities and are for example the company's owners, employees, suppliers, customers, and investors. The secondary stakeholders are more distant stakeholders for activities concerning the company and can for example be the nearby communities, municipalities, or on a national level NGO's.

The social consequences (beneficial or costly) related to the manufacturing and repairing fan blades have been identified by analysing the processes included in each case and the benefits that may arise with the implementation. Social aspects connected to the product's life cycle are assessed by tracking the different materials used, their corresponding origin, and their properties. Health and safety sheets on chemicals and materials are found in an Environmental tool, Chemsoft (Chemsoft, 2022).

## 4 Results

This chapter presents the inventory used for modeling the systems and it is corresponding environmental and social impact. An uncertainty analysis is also shown based on the data used.

### 4.1 Inventory analysis

This subchapter present the full flowchart and describes all the processes and flows involved in each case. The equations and the quantitative inputs and outputs are also presented.

#### 4.1.1 Inventory analysis of transports

When manufacturing a new fan blade virgin material must be shipped to Trollhättan, Sweden. The Ti64 forgings, as well as Ti64 powder, are transported from the US to Gothenburg, Sweden with air cargo a distance estimated to be around 7700 kilometres (Globefeed, 2022). The goods are thereafter reloaded and transported 76 kilometres (Maps, 2022b) to GKNA in Trollhättan with a medium-duty truck.

Argon is bought in liquid form from Germany, where it is produced and is sent by electric train to Malmö and redistributed by a medium-duty truck to Surahammar for analysis where it is then sent to the facility in Trollhättan with a similar truck. The total distance with a truck is estimated to be 900 km and with train, 660 km (Maps, 2022c).

Carbon fibre, glass fibre, epoxy, polyurethane coating and used fan blades are bought/-shipped from manufacturers in Germany and are transported to Trollhättan, Sweden by a medium-duty truck driven on diesel and the distance is estimated to be 1048 km (Maps, 2022a). The transport also includes a ferry but is neglected due to the small distance.

Cutting fluid, acetone, titanium scrap as well as other products/wastes used/discarded are assumed to have a neglectable transport attribution due to a short transport distance and is therefore left out of the study's scope.

Figure 20 shows the transportation of materials and products used.



Figure 20: A graphical view (Zhiren, 2015) of where materials and components are sourced from (not including globally sourced titanium). Creative Commons Licence (Reworked)

#### 4.1.2 Inventory analysis of manufacturing a new fan blade

To manufacture a new fan blade different processes are needed, ten processes for manufacturing the leading edge, six for the wear strips and eight processes for manufacturing the carbon fibre part. These parts are manufactured separately and then assembled in four different processes, see Figure 21 which illustrates the processes needed. The following paragraphs describe each of them qualitatively. Equations for material and energy usage in each process are described.

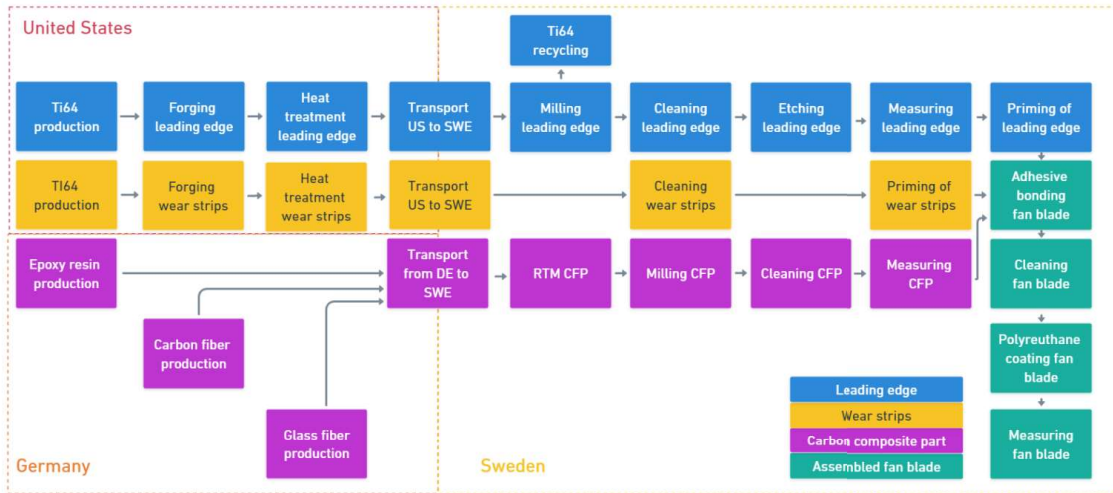


Figure 21: Flowchart illustrating the processes to manufacture a new fan blade.

### Forging Leading edge

A forged part made of Ti64 is bought from the US, where the materials are sourced globally and then cast, forged and finally heat-treated before transport to Sweden. The alloying elements (titanium, aluminium and vanadium) are tipple melted which means they are heated up to above 1670 °C and remelted at least three times to enhance the purity. After the remelting process, the metals are poured into a mould to create ingots for the forging process. The remelting and melting process occurs in an inert atmosphere, or vacuum, to protect the material from oxidation and impurities. The part is forged from a cylindrical bar, with the same cross-section area and formed to a shape closer to the final product, as can be seen in Figure 22. The final ingot size is around 6.25kg. The energy usage as well as other inputs and outputs from the process are modelled with data from the GaBi software.

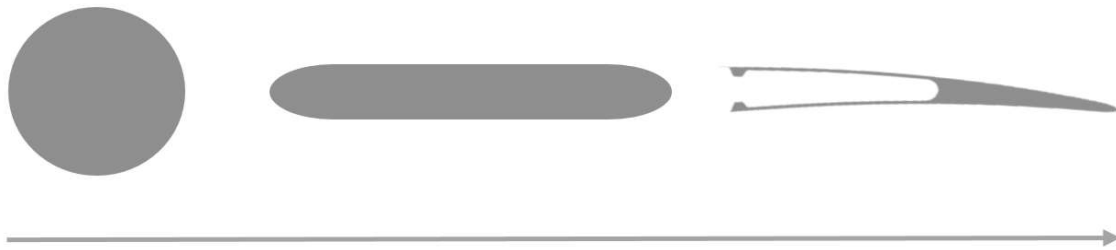


Figure 22: From the left: Ingot's geometry, forged blank and finally a machined leading edge.

The forging process is performed to enhance the material properties of the part and is done at an elevated temperature due to Ti64 poor cold shaping properties. The heat source for the oven is natural gas and the forging press is driven by electricity. The forged part has an additional 3 mm added around its entire circumference for the ability to be machined to correct dimensions later. Data was gathered from internal company reports given by a supplier of forged Ti64 ingot products. Electricity used for the forging hammer was estimated by the supplier to be 2,18 kWh/kg during 2020. Electricity used for the leading edge could be estimated with Equation 1 where  $e_{el,for\text{ging}}$  is the energy needed per kg forging and  $m_{for\text{ging}}$  is the mass of the forging.

$$E_{el,for\text{ging}} = e_{el,for\text{ging}} * m_{for\text{ging}} \quad (1)$$

The forging company also reported the energy used for heating the ingot for the forging process. The amount of natural gas used was estimated to be 0,427 m<sup>3</sup>/kg. The total amount of natural gas used for the forging process was estimated with Equation 2 where  $v_{ng,for\text{ging}}$  is the volume of natural gas per kg forging and  $m_{for\text{ging}}$  is the mass of the forging. The environmental load of producing and burning natural gas is thereafter calculated with a predefined process in the software GaBi. The equation is based upon the same company as the equation above.

$$V_{ng,for\text{ging}} = v_{ng,for\text{ging}} * m_{for\text{ging}} \quad (2)$$

### Heat treatment Leading edge

The final forging component is afterward heat-treated according to the SAE AMS4928 standard (SEA International, 2007). The standard specifies a solution heat treatment where the material is heated to a temperature just below beta transus phase which is 954C. To reach a homogeneous temperature of the part a soaking time is set based on the thickness of the part and is specified and calculated according to the AMS2801 (SEA International, 2014). The duration of the heat treatment at a constant temperature, with soaking, was calculated to be 1 hour and 20 minutes. Afterward the part is cooled down to room temperature by cooling fans built into the oven. The following heat treatment called annealing is recommended and is done at a temperature of 704C. Soaking time was calculated to be 6 hours and 20 minutes. An illustration of the heat treatment process can be seen in Figure 23. Solution heat treatments are done in an inert atmosphere created by argon as a shield gas and annealing is done in vacuum.

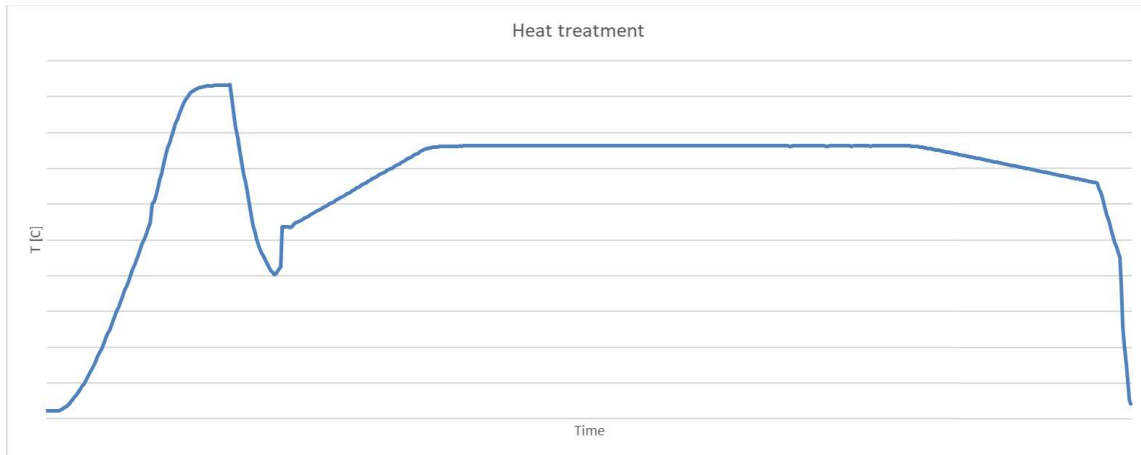


Figure 23: Illustration of the heat treatment process including solution heat treatment and annealing of the forging for the leading edge.

The energy and argon usage for the heat treatment process was estimated by analysing the energy withdrawn for heat treatment of a component already manufactured at GKNA. The product had a similar temperature interval and duration of the heat treatment the heating, cooling, and usage of argon were registered in the ovens management system. In total 26 leading edges, along with the same amount of wear strips, were estimated to fit into the oven and undergo the heat treatment at the same time (to match the weight of the measured heat-treated product). Energy and argon usage from the process was allocated by the physical attribute mass and multiplied by the mass of the components to get the component's attribution.

### **Milling Leading edge**

Once the leading edge forging has arrived at the production facility it is put into a CNC milling machine. The leading edge is machined all around since an alpha case is introduced to the surface of the part from the forging and heat-treatment process. Removing the alpha case from the component is crucial since it compromises the part's resistance to crack growth. Three millimeters of the outer surface are removed by rough milling and one millimeter is removed by fine milling to reach desired surface and tolerances. The machine used is a GROB 350 (GROB-WERKE GmbH Co. KG, nd). The time for the operation and the different removal rates of material (MRR) were estimated by machining equations from the tooling supplier Sandvik (Sandvik, nd) and in consultation with a machining expert at GKNA. Total time for rough milling and fine milling was estimated to be 1 respectively 8.2 hours.

Power used, during material removal, in the milling process was estimated by using an equation created by Mohamad Farizal RAJEMI (RAJEMI, 2010). The equation is based on power measurements from machining different materials with different MRR. The variable K is a specific value for Ti64 and is 2.9 Ws/mm<sup>3</sup>, and MRR is in mm<sup>3</sup>/s which varies depending on fine or rough machining, see Equation 3.

$$W_{\text{milling}} = k_{Ti64} * MRR_{\text{milling}} + 2082.4 \quad (3)$$

Data on the power of the milling machine during standby, also called idling, as well as the compressed air consumption are borrowed from measurements performed by Alaitz Gonzalez (Gonzalez, 2007). Idle power is when the machine is powered up but not in cutting operation. The set time was estimated to be 45 minutes and included time to install tools and the component and remove it from the machine. Idle power is assumed to be 1660W and 76 l of compressed air is used each minute (Gonzalez, 2007). Equation 4 describes the energy used for the milling process where  $W_{\text{fine-milling}}$  is the power during fine milling,  $t_{\text{fine-milling}}$  is the time for the fin milling, and so on.

$$E_{\text{mill}} = W_{\text{fine-mill}} * t_{\text{fine-mill}} + W_{\text{rough-mill}} * t_{\text{rough-mill}} + W_{\text{idle}} * t_{\text{idle}} \quad (4)$$

Cutting fluid is used during the process to cool and lubricate the tools used. To simplify the case, only the cutting oil's major ingredient is accounted for which is petroleum, which roughly is estimated to 37.5 % (Castrol, 2022). The cutting oil is mixed with fresh water from the tap to form an emulsion. The amount of cutting fluid used by the machines is estimated by what is lost from vaporisation and other processes during a day. To reach the desired level and percentage of cutting oil in the fluid 50 liters are added each day including 2 percent of cutting oil. To get an hourly usage of cutting fluid the total amount refilled each day is divided by the hours per day (24h) resulting in roughly 2 l/h. Cutting fluid per process/part is thereafter estimated with Equation 5 where  $Flow_{\text{fluid}}$  is the flow of the cutting fluid and  $t_{\text{fluid}}$  is the operation hours.

$$V_{\text{fluid}} = Flow_{\text{fluid}} * t_{\text{fluid}} \quad (5)$$

The milling process uses compressed air which was calculated with Equation 6 where  $Flow_{\text{air}}$  is the flow of compressed air per minute and  $t$  is the milling process time. The environmental load of producing compressed air is thereafter calculated with a predefined process in the software GaBi.

$$V_{\text{air}} = Flow_{\text{air}} * t_{\text{milling}} \quad (6)$$

The Ti64 scrap is transported to a nearby recycling facility to be recycled. The recycling of cutting fluid is not considered in this report.

### **Cleaning Leading edge**

After the milling process, the leading edge is cleaned with acetone to remove any oil residues on the surface. Cleaning is done manually with cotton wipes and acetone. A test was made to estimate the material used during cleaning by wiping a similar area as the product. The material used for cleaning is estimated to weigh 34 grams of cotton fabric and 15 ml of acetone.

### **Etching**

To remove Alpha case from the Ti64 alloy and promote adhesion when assembled to other parts, an etching process is done. The etching process include different solutions bath that remove the top layer. This process is left out of the LCA´s scope since data is limited, only the social aspects are considered later in the report.

### **Measuring Leading edge Ti64**

To secure that specified dimensions of the part are achieved in the production processes a measuring operation is done in a measuring machine. The machine used is a ZEISS CONTURA (Zeiss, nd) which is rated at 200 W in use and uses 80 NI/min of compressed air. The time to measure the component is estimated to be 15 min. The electricity used is estimated with Equation 7 where  $P_{machine}$  is the power drawn by the machine in use and  $t$  is the time for the measuring operation. The compressed air used in operation is estimated with Equation 6.

$$E_{measure} = P_{machine} * t \quad (7)$$

### **Priming Leading edge**

To promote adhesion to the Ti64 alloy a primer is used. The primer is applied manually with a spray gun to the interface of the leading edge. This process is left out of the LCA´s scope since data is limited, only the social aspects are considered later in the report.

### **Forging wear strips**

Wear strips are used on the blades dovetail to act as a barrier between the composite and jet engines interface. The plates are forged to NNT in the US and the energy and natural gas used are calculated in the same manner as described in Equation 1 and 2.

### **Heat treatment wear strips**

To reach the desired material properties the wear strips are heat-treated in the same manner as described for the leading edge. The time for the solution heat treatment was estimated to be 1 hour and 15 minutes and the time for annealing was 6 hours, very similar to the leading edge. The heat treatment of the wear strips was assumed to be done in the same oven as the leading edge during the same time, resulting in 26 pairs of wear strips (to match the batch size of blades). Energy and argon usage from the process were allocated by the physical attribute mass.

### **Cleaning wear strips**

The wear strips are cleaned in the same manner as the leading edge, using 34 grams of cotton fabric and 15 ml of acetone.

### **Priming wear strips**

The wear strips are primed in the same manner as described earlier for the leading edge manufacturing.

### **Production of Carbon fibre, Epoxy Resin and Glass fibre for carbon composite part**

Carbon fibre is produced from the two materials acrylonitrile and methacrylate, which first are processed to polyacrylonitrile fibre (PAN) (Sphera, 2022). PAN fibre then undergoes a stabilisation treatment, carbonisation, and a final treatment to produce carbon fibre. Some of these processes need for instance high temperatures (1300-1500 C), nitrogen atmosphere, and epoxy resin. Glass fibres are mainly made from silica sand which needs to be melted at a high temperature which is energy-intensive (Sphera, 2022). Epoxy is mainly made from the conversion of Bisphenol A with epichlorohydrin, which undergoes a chemical reaction that creates thermoset epoxy (Sphera, 2022). Processes for producing materials like these have been modeled with a predefined process in GaBi. The materials are produced in Germany and transported to Sweden.

### RTM carbon composite part

Carbon fibre and glass fibre are put into a mould where epoxy resin is injected under pressure. The mould in the resin transfer moulding process is made of tool steel and is heated to an elevated temperature with induction heating. The temperature is specified by the epoxy manufacturer Solvay (Solvay, 2022) and is 100 °C for injection of resin and 2 hours at 180 °C for curing. The required energy for heating the mould can be estimated with the Equation 8 based on (Zhang et al., 2021) with some modifications.  $m_{steel}$  is the mass of the mould,  $C_{steel}$  is the specific heat capacity of the steel,  $\Delta T$  is the temperature difference,  $n_{capacity}$  is the batch size and  $\eta_{mould}$  is the thermal efficiency of the moulding tool that is based on tests performed of UltraFlex Power Technologies of induction heating reaching 90% efficiency (UltraFlex Power Technology, nd).

$$E_{Heat-mould} = \frac{m_{steel} * C_{steel} * \Delta T_{1,steel}}{\eta_{mould} * n_{cap}} + \frac{m_{steel} * C_{steel} * \Delta T_{2,steel}}{\eta_{mould}} \quad (8)$$

When the mould is at an elevated temperature the thermoset epoxy is injected into the mix of carbon fibre and glass fibre. This process gives the blade an NNT shape. The ingoing material is in total around 4.6 kg and the energy intensity of the injection is estimated to be 12800 kJ/kg (U.S. Department of energy, 2017). The electricity usage is estimated with Equation 9 where  $m_{RTM}$  is the ingoing mass to the RTM and  $e_{RTM}$  is the energy intensity of the process.

$$E_{injection} = m_{RTM} * e_{RTM} \quad (9)$$

To cure the epoxy resin the mould needs to hold the temperature of 180 °C for two hours. The electricity required for this process can be estimated with calculation 10, based on the second law of Thermodynamics (Gesellschaft, 2010) where  $E_{cure}$  is the energy used,  $t_{cure}$  is the time of the heating process,  $\Delta T$  is the temperature difference between the mould and room temperature,  $A_{mould}$  is the surface area of the mould,  $u_{steel}$  is the convection coefficient for steel to air (23,3 W/m<sup>2</sup>\*k) (Yener et al., 2019) and  $\eta_{mould}$  is the thermal efficiency of the moulding tools heat source.

$$E_{cure} = \frac{t_{cure} * \Delta T * A_{mould} * u_{steel}}{\eta_{mould}} \quad (10)$$

### **Milling carbon composite part**

After the RTM process, the interface to the leading edge and the dovetail of the composite part are machined in a GROB 350 to reach desired dimensions and surface finish. Roughly 10 % of the outer surface is milled away. The time, less than 2 minutes, for the milling process was neglectable small due to the high MRR and low material volume removed. The energy used during the milling process was therefore calculated by the set time that was assumed to be 45 minutes and can be seen in the last part of Equation 4 described before. The process uses compressed air and is calculated as described in Equation 6, no cutting fluid is used.

### **Measuring carbon composite part**

The component is measured in the ZEISS CONTURA measuring machine and the time of the operation is estimated to be 25 minutes, see Equation 7 and 6.

### **Cleaning carbon composite part**

To get the surface free from any contaminants a cleaning process is needed. This is usually done by wiping the leading edge with acetone. The amount of acetone used is 15 ml and the wipe is made of cotton fibre, weights 34g.

### **Adhesive bonding process; Leading edge, CF part and wear strips**

An epoxy based glue is used to bond the parts together, both the leading edge and the wear strips. The glue is for simplification assumed to have the same environmental impact as the epoxy based resin used in the composite production. The amount of epoxy used is estimated, by the area covered and the thickness needed, to be 7 grams and it is applied manually.

### **Cleaning of fan blade**

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

### **Polyurethane coating process**

The blade is thereafter covered by a polyurethane coating to protect the composite part of the blade from foreign object damage and erosion. The amount of coating used is estimated to be around 1000 grams. The energy for applying the coating as well as any waste from overspray is neglected.

### **Measuring assembled component**

The components geometry is measured one final time in the ZEISS CONTURA measuring machine and the time of the operation is estimated to be 30 minutes, see Equation 7 and 6.

The inventory data used in the manufacturing of a fan blade is presented in the forms of inputs and outputs to and from the processes to produce a fan blade, see Table 7.

Table 7: Inventory table describing the inputs and outputs from the production of a new carbon composite fan blade.

<b>Product:</b>		
CF Fan blade	1	pc
<b>Inputs:</b>		
Ti64	6.27	kg
Carbon fibre	2.93	kg
Glass fibre	0.34	kg
Epoxy resin	1.37	kg
Polyurethane	1.03	kg
Cutting fluid/petroleum	0.16	l
Fresh water, tap	20.88	l
Compressed air	51.78	m <sup>3</sup> n
Argon	0.32	m <sup>3</sup> n
Cotton textile	0.14	kg
Acetone	60	ml
Natural gas	102.61	MJ
Electricity for processes, grid	391.36	MJ
Truck euro 6, 32t gross weight	5.5	tkm
Cargo plane, 113t payload	48.28	tkm
<b>Output:</b>		
Ti64 shavings, waste for recycling	5.4	kg
CFP shavings, waste	0.4	kg
Acetone, EVP to atmosphere	60	ml
Cotton textile waste	0.14	kg
Cutting fluid, waste	0.16	l
Water, waste	20.88	l
Argon, to atmosphere	0.32	m <sup>3</sup> n
Epoxy resin, cured, waste	0.12	kg

### 4.1.3 Inventory analysis of CM repair

To repair a used fan blade with conventional methods there are several processes used that are the same as for new manufacturing seen in Chapter 4.1.2. See Figure 24 for an illustrative flowchart including the processes. The following paragraphs describe each of them qualitatively. Equations for material and energy usage in each process are described.



Figure 24: Flowchart illustrating the processes of CM repair.

The CM method analysed is based on removing the damaged part, the leading edge, and replacing it with a new one. This repair only focuses on the replacement of leading edge and the main fan blade body is untouched.

#### Disassembly from engine, CM repair

The used fan blade is disassembled from the engine at the service center in Germany and prepared to be shipped to Trollhättan.

#### Cleaning prior to inspection, CM repair

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

#### Inspection measuring, CM repair

The incoming component is measured in the ZEISS CONTURA measuring machine to identify any discrepancies from the usage phase. The time of the operation is estimated to be 30 min, see Equation 7 and 6.

### Milling leading edge, CM repair

Machining is done to remove the leading edge from the composite part as illustrated in Figure 25. The removal is done by milling away the leading edge and epoxy adhesive in a GROB 350. The power used for this milling process can be estimated with Equation 3 and the energy with Equation 4, in the same manner as described earlier. Total time for rough milling and fine milling was estimated to be 20 minutes respectively 1 hour. The process uses cutting fluid and compressed air and is estimated with Equation 5 respectively 6.

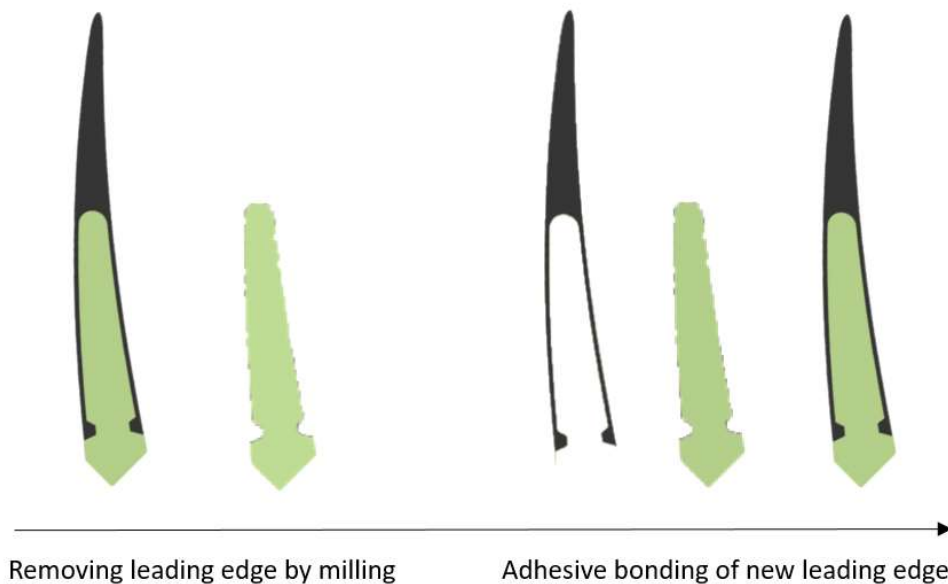


Figure 25: Illustration of the basic plan for CM repair, the removal, and replacement of the leading edge.

### Manufacturing of leading edge, CM repair

Manufacturing a new leading edge is done in the same manner as described in Chapter 4.1.2 above.

### Cleaning prior to assembly of leading edge, CM repair

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

**Adhesive bonding process; Leading edge to CF part, CM repair**

An epoxy-based glue is used to bond the parts together much as described in the previous chapter. The amount of epoxy used is estimated by the area covered and the thickness needed, to be 7 grams and it is applied manually.

**Cleaning final product, CM repair**

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

**Measuring final product, CM repair**

The component is measured one final time in the ZEISS CONTURA measuring machine and the time of the operation is estimated to be 30 min, see Equation 7 and 6.

The inventory data used in the CM repair is presented in the forms of inputs and outputs to and from the processes to repair a fan blade, see Table 8.

Table 8: Inventory table describing the inputs and outputs from CM repair.

<b>Product:</b>		
CF Fan blade, CM repair	1	pc
<b>Inputs:</b>		
Used CF Fan blade	1	pc
Ti64	6.25	kg
Epoxy resin	0.07	kg
Cutting fluid/petroleum	0.19	l
Fresh water, tap	24.85	l
Compressed air	63.29	m <sup>3</sup> n
Argon	0.32	m <sup>3</sup> n
Cotton textile	0.1	kg
Acetone	45	ml
Natural gas	102.26	MJ
Electricity for processes, grid	308.8	MJ
Truck euro 6, 32t gross weight	6.87	tkm
Cargo plane, 113t payload	48.13	tkm
<b>Output:</b>		
Ti64 shavings, waste for recycling	6.25	kg
Cotton textile, waste	0.1	kg
Acetone, EVP to atmosphere	45	ml
Cutting fluid, waste	0.19	l
Water, waste	24.85	l
Argon, to atmosphere	0.32	m <sup>3</sup> n
Epoxy resin, cured, waste	0.07	kg

#### 4.1.4 Inventory analysis of AM repair

To repair a used fan blade with additive manufacturing there are in general seven processes needed, see Figure 26 which illustrates the flowchart including the processes. The following paragraphs describe each of them qualitatively. Equations for material and energy usage in each process are described.

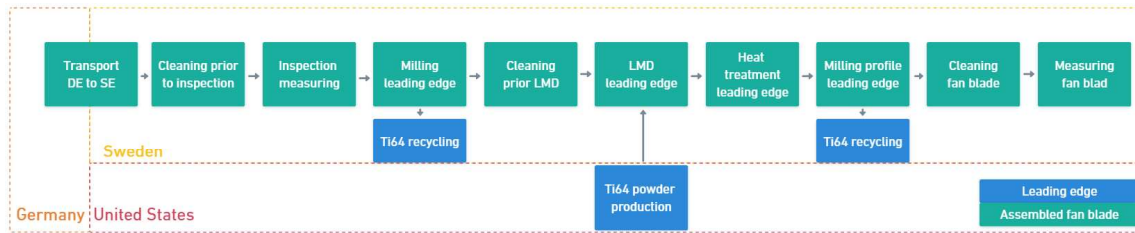


Figure 26: Flowchart illustrating the processes of AM repair.

### Disassembly from engine, AM repair

The used fan blade is disassembled from the engine at the service center in Germany and prepared to be shipped to Trollhättan.

### Cleaning prior to inspection, AM repair

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

### Inspection measuring, AM repair

The incoming component is measured in the ZEISS CONTURA measuring machine to identify any discrepancies from the usage phase. The time of the operation is estimated to be 30 min, see Equation 7 and 6.

### Milling leading edge, AM repair

Machining is done to remove the damaged part of the leading edge. This is done by milling away a rectangular shape on the leading edge in a GROB 350. The amount of material removed is standardised and is the same for every blade, unrelated to the extent of the damage, to make the processing time-efficient and repeatable. The rectangle that is removed is estimated to be 3 mm x 400 mm furthest to the top where most of the erosion/damage occurs and can be seen in Figure 27. This results in 10 grams of Ti64 scrap. The time, less than 1 minute, for the milling process was neglectably small due to the low material volume removed. The energy used during the milling process was therefore calculated by the set time that was assumed to be 45 minutes and can be seen in the last part of Equation 4. The process uses cutting fluid and compressed air and is estimated with Equation 5 respectively 6.

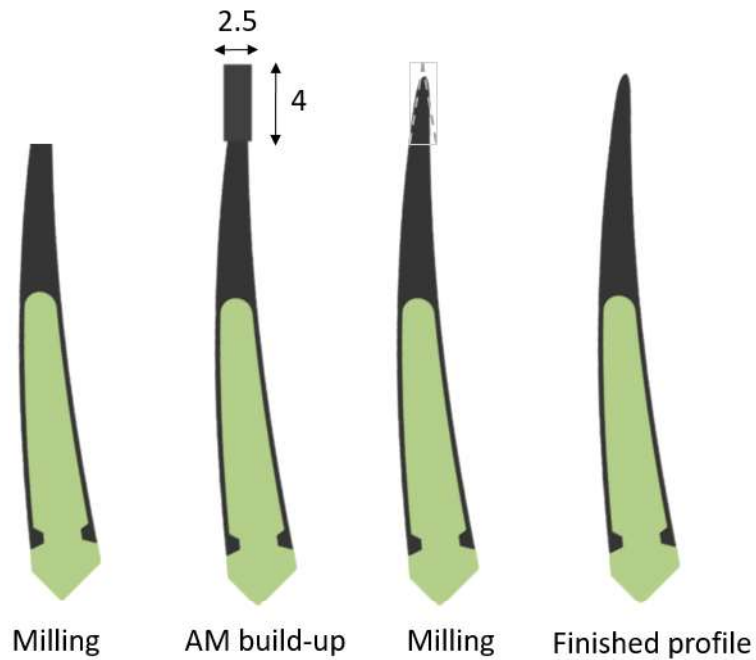


Figure 27: Illustration of the basic plan for AM repair.

#### **Cleaning prior to LMD-P, AM repair**

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

#### **LMD-P process, AM repair**

The next process is the Laser Metal Deposition with Powder (LMD-P). This process builds up the leading edge layer by layer with a Ti64 powder. A rectangular shape is built upon the leading edge to allow for machining in the final shape in a later process. The deposited volume is in total 4000 mm<sup>3</sup> (20 grams).

The time for the process is calculated based on the deposition rate and the efficiency of powder being melted in the deposition. Argon is used as a shielding gas and for transportation of powder to the melting pool. The total energy used for the process is based on data previously measured on test pieces at GKNA. The recorded data was altered to fit the case of repairing a fan blade, like the one presented in the report, with different operation times. Energy for the LMD's machine operation  $E_{LMD-p}$  was calculated based on the energy from depositing material  $E_{depositing}$ , energy usage during waiting between layers  $E_{wait/cool}$  and the standby power  $E_{standby}$  for the set time (mount part to the machine) and the time needed for air cooling. Equation 11 shows how different parts of the operation are added up to total energy usage.

$$E_{LMD-Total} = E_{depositing} + E_{wait/cool} + E_{standby} \quad (11)$$

The argon usage  $V_{argon}$  in the process is estimated by the flow of argon  $Flow_{argon}$  and the deposition time  $t_{depositing}$  and can be seen in 12.

$$V_{argon} = Flow_{argon} * t_{depositing} \quad (12)$$

### **Local heat treatment, AM repair**

Due to the difference in material properties between the material added by the LMD process and the material built upon a heat treatment process is needed. The heat treatment releases the stresses within the material and makes it more uniform. A laser is used as a heating source to heat the parts repaired area. The local heat treatment reaches 700-1000 °C on the top layer of the part and is performed in an inert atmosphere caused by argon. The machine and part need to be cooled down during the heat treatment process. The total electricity used is estimated with Equation 13, where  $P_{laser}$  is the power of the laser,  $\eta_{machine}$  the machines efficiency,  $P_{Cooler}$  is the operation power drawn by the cooler and  $t_{operation}$  is the time of the operation.

$$E_{localheat} = \left( \frac{P_{laser}}{\eta_{machine}} + P_{cooler} \right) * t_{operation} \quad (13)$$

To estimate the argon used for the local heat treatment process the volume of the oven containing the leading edge forging was calculated. The chamber was estimated to be 1.2 x 1 x 1 m filled with argon for an anaerobic atmosphere. To reach anaerobic conditions the oxygen needs to be pushed out which was assumed to be done by using double the amount of argon compared to just filling the chamber. Argon usage was estimated with Equation 14 where W, H, and L defines the chambers size and  $n_{cap}$  defines the maximum capacity of parts in the machine. An environmental load of producing and releasing argon to the atmosphere is thereafter calculated with a predefined process in the software GaBi.

$$V_{\text{argon}} = \frac{2 * W * H * L}{n_{cap}} \quad (14)$$

#### **Milling profile, AM repair**

Milling is then used to remove the additional material and to get the final shape. The material removed is estimated with an isosceles triangle, as can be seen in Figure 27. The time for rough milling and fine milling was estimated to be 5 respectively 22 minutes with an additional set time of 45 minutes. The process uses cutting fluid and compressed air and is estimated with Equation 5 respectively 6.

#### **Cleaning final product, AM repair**

The fan blade is cleaned in the same manner as described previously, using 34 grams of cotton fabric and 15 ml of acetone.

#### **Measuring final product, AM repair**

The component is measured one final time in the ZEISS CONTURA measuring machine and the time of the operation is estimated to be 30 min, see Equation 7 and 6.

The inventory data used in the AM repair is presented in the forms of inputs and outputs to and from the processes to repair a fan blade, see Table 9.

Table 9: Inventory table describing the inputs and outputs from AM repair.

<b>Product:</b>		
CF Fan blade, AM repair	1	pc
<b>Inputs:</b>		
Used CF Fan blade	1	pc
Ti64 powder	0.02	kg
Cutting fluid/petroleum	0.03	l
Fresh water, tap	4	l
Compressed air	13.85	m3n
Argon	4.96	m3n
Cotton textile	0.1	kg
Acetone	45	ml
Electricity for processes, grid	103.94	MJ
Truck euro 6, 32t gross weight	10.15	tkm
Cargo plane, 113t payload	0.15	tkm
Rail cargo, electric	2.81	tkm
<b>Output:</b>		
Ti64 shavings, waste for recycling	0.02	kg
Cotton textile, waste	0.1	kg
Acetone, EVP to atmosphere	45	ml
Cutting fluid, waste	0.03	l
Water, waste	4	l
Argon, to atmosphere	4.96	m3n

## 4.2 Impact assessment

The inputs and output flows that are presented in Chapter 4.1 contribute, indirectly or directly, to different environmental impacts and were characterised according to CML 2001-2016. A contribution analysis was made to identify where the different cases have their major environmental impacts. These impacts are shown in Figure 28, in a base 10 logarithmic scale. The stacks that are on the top side of the red line indicate emissions higher than 1 kg of respective impact equivalent, the lower the stack is the less is emitted. It is important to note that all impact categories do not have the same equivalent and affect the environment differently. It is clear that the most affected impact category is Marine Aquatic Eco Toxicity Potential (MAETP) and the second most affected is the impact category Global Warming Potential in 100 years (GWP 100). Since impact within these categories is recognised as a major, a more into depth analyse has been made.

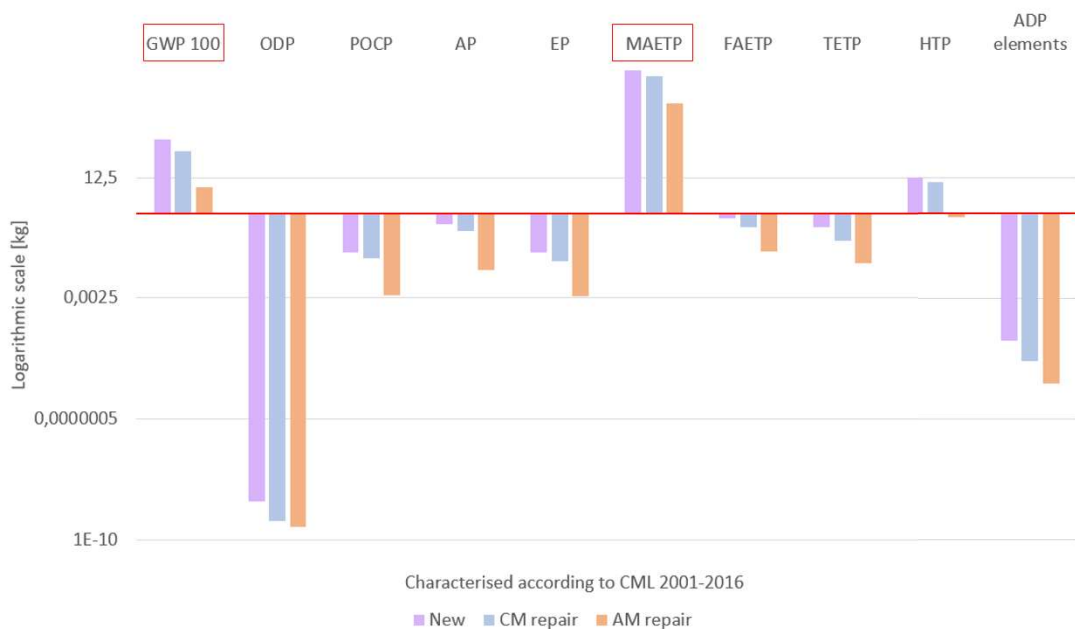


Figure 28: Contribution analysis of the three cases in a base 10 logarithmic scale. The two impacts that contribute the most, in kg, are marked with red boxes.

To be able to compare the different impact categories to the three different cases, a normalisation was made. The CM repair case was set to 100 % to compare the other cases, see Figure 29. It can be seen that manufacturing a new fan blade contribute the most to every environmental impacts, next is the CM repair and AM repair has the lowest impacts.

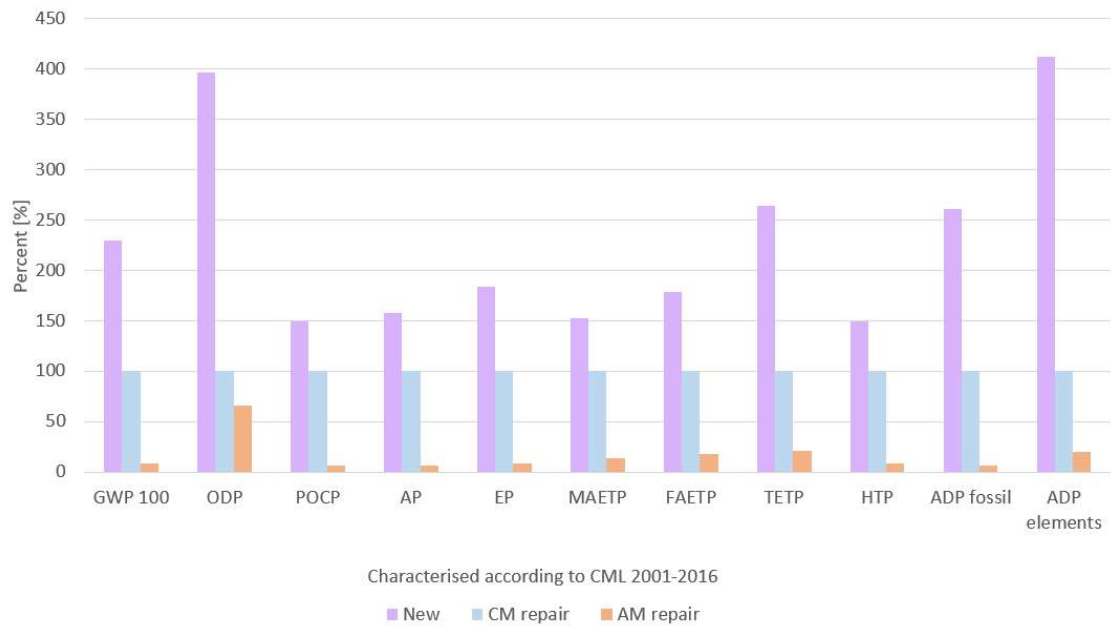


Figure 29: Bar chart shows the different impacts where the CM repair case has been normalised.

To understand what is causing the impacts in each case, one impact category at a time was investigated. The total contribution to global warming is shown in Figure 30 for all three cases. The blue staple in the barchart diagram represents the manufacturing of the leading edge, which has the greatest impact, resulting in 140 kg CO<sub>2</sub> eq. The process that has the next greatest impact is the manufacturing of the carbon fibre part, resulting in 92.6 kg CO<sub>2</sub> eq. The green coloured bar represents the Ti64 shavings which are sent for recycling and therefore lessen global warming. It can also be seen that manufacturing a new fan blade accounts for 184 kg CO<sub>2</sub> eq and has a higher impact compared to CM repair which accounts for 80.1 kg CO<sub>2</sub> eq., and AM repair at 6.4 kg CO<sub>2</sub> eq. To understand what parts and processes of a fan blade give rise to the greatest environmental impact a dominance analysis was made. The dominance analysis investigates what processes have the highest impact and which of the processes are hotspots and needs to be looked more closely at.

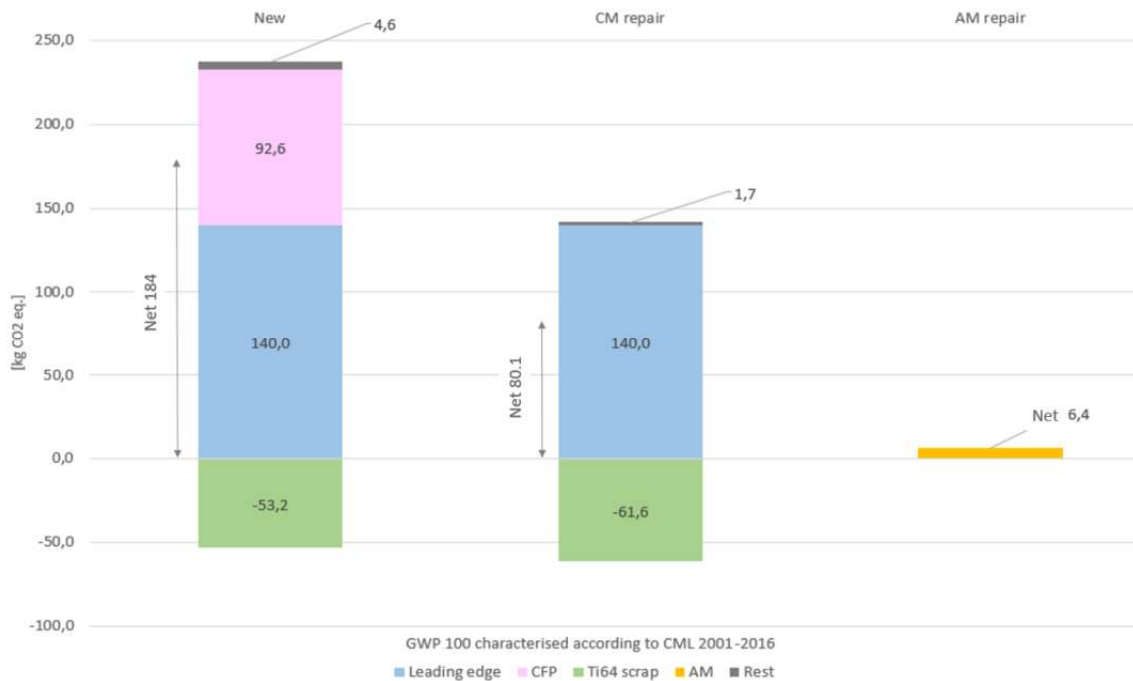


Figure 30: Stacked barchart shows the total and net global warming potential of each case.

In Figure 31 the GWP of manufacturing the leading edge is shown. The barchart shows that the production of the material Ti64 itself has the absolute greatest impact, followed by transport, heat treatment, and rest. The category "Rest" includes cleaning, measuring, and milling of the leading edge.

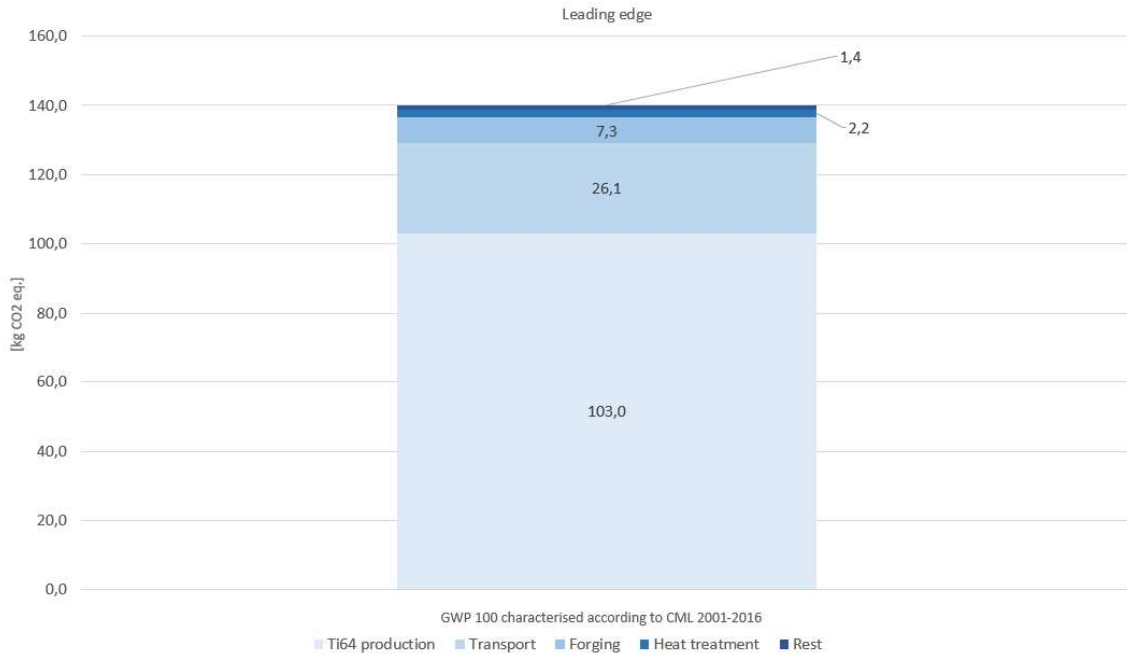


Figure 31: Stacked barchart shows the global warming potential of manufacturing the leading edge.

As previously seen in Figure 30 the next greatest contributor to GWP, for manufacturing a new fan blade, is the production of the Carbon Fiber Part (CFP) where the material production has the highest impact, especially in this case carbon fibre and epoxy production, see Figure 32. Glass fibre production is included in the group "Rest" since only a small amount is used in the CFP, 0,34 kg glass fibre, and therefore do not contribute as much to the impact category.

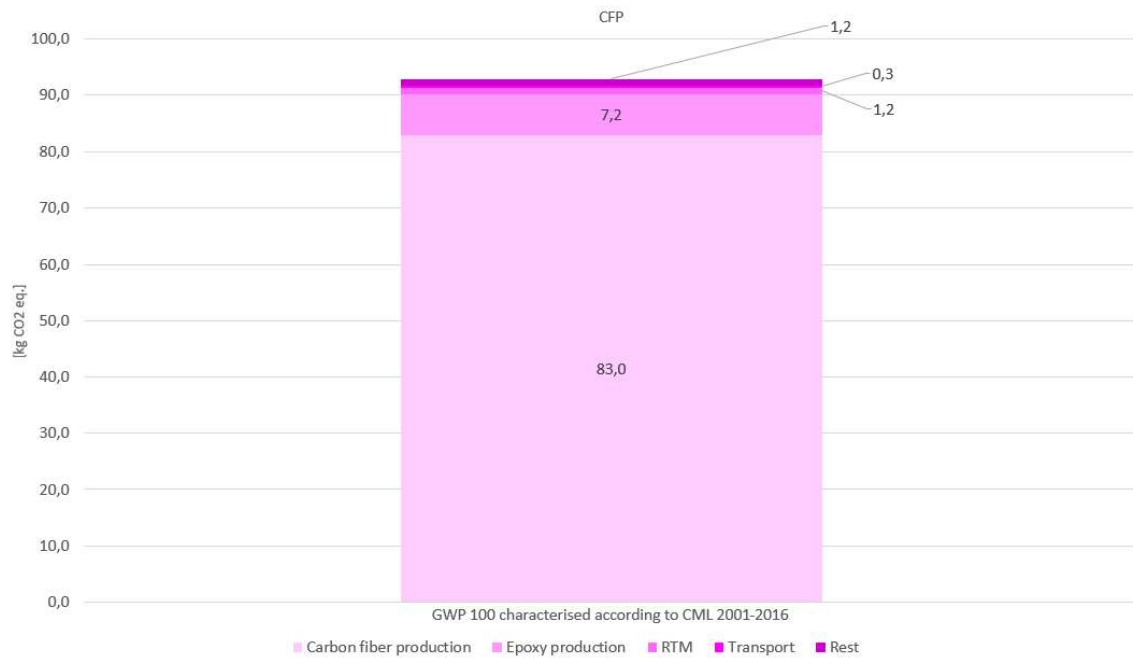


Figure 32: Stacked bar chart shows the global warming potential of manufacturing the carbon fibre part.

For the AM repair case, which is relatively small compared with the other cases, a separate bar chart has been made and can be seen in Figure 33. The major contributor to the AM repair case impact is the processes of LMD-P and Heat treatment where the argon production closely followed by the electricity grid mix used is the biggest parts. A side note is that the cleaning process is in the same order of magnitude as other processes in the AM repair and is now visible to be a major contributor to the total impact, compared to new manufacturing and CM repair.



Figure 33: Barchart shows the global warming impact of AM repair.

To investigate the most affected impact category, Marine Aquatic Eco Toxicity Potential (MAETP), a dominance analysis was performed in the same manner as before, see Figure 34. A switch from looking at GWP compared to MAETP shows that the leading edge is the even larger contributor. Figure 35 and 37 clarify that the production of Ti64 and carbon fibre has the largest impact. Another aspect is that the electricity grid mix contributes more to MAETP compared to GWP, while the transportation contributes less, see Figure 36. The relative order of impact between the different parts and processes within stays somewhat unchanged compared to previous bars on GWP.

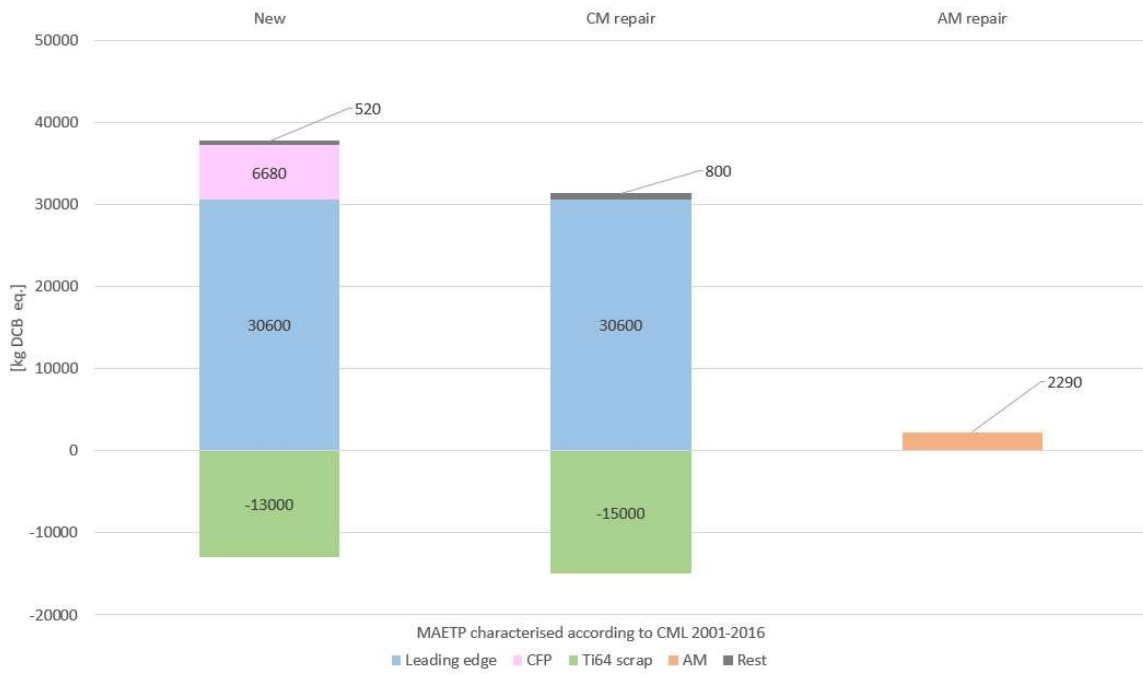


Figure 34: Barchart shows the marine aquatic ecotoxicity potential of each case.

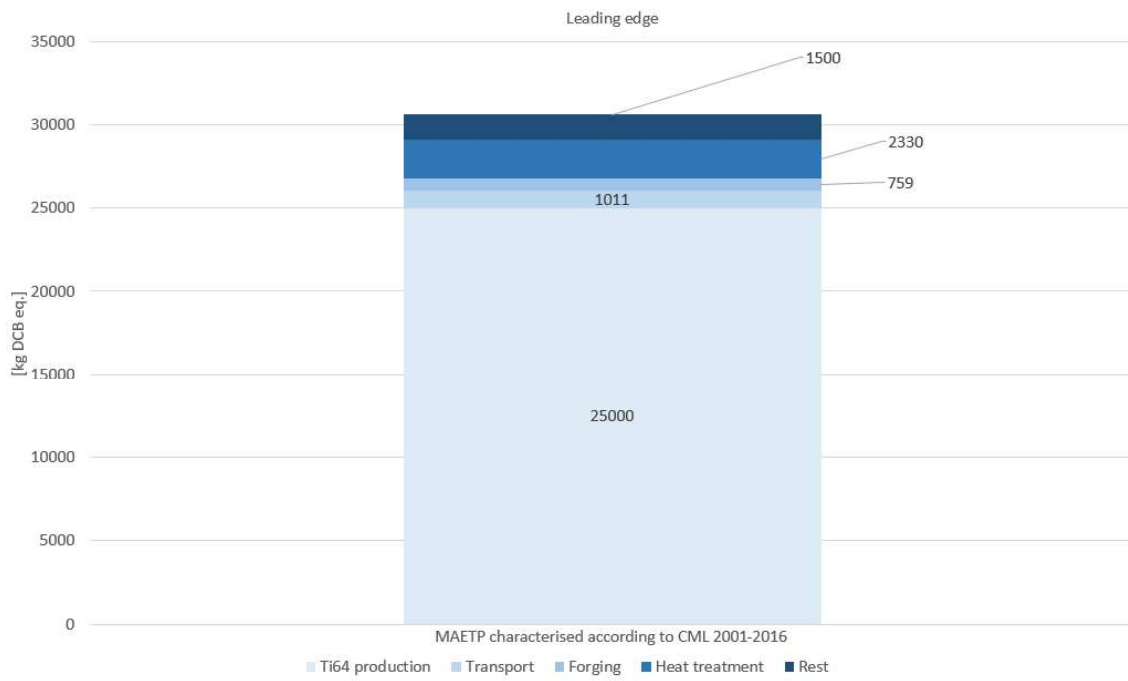


Figure 35: Barchart shows the marine aquatic ecotoxicity potential of manufacturing the leading edge.

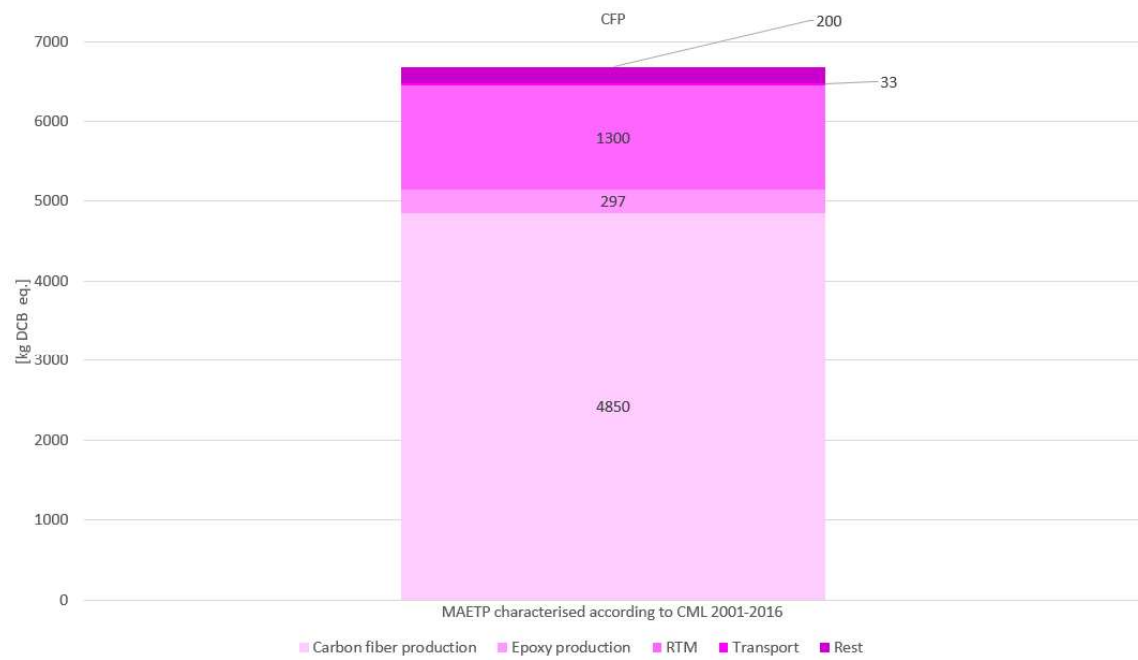


Figure 36: Barchart shows the marine aquatic ecotoxicity potential of manufacturing the carbon fibre part.

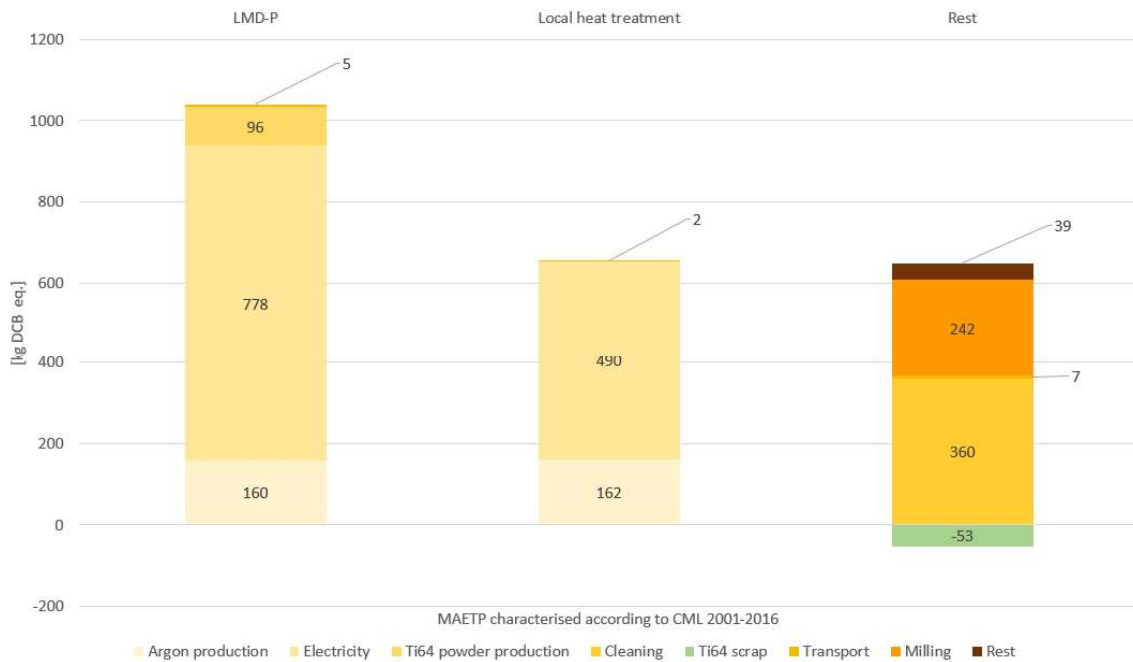


Figure 37: Barchart shows the marine aquatic ecotoxicity potential of the LMD-P build-up process when repairing a fan blade.

### 4.3 Validation of results

Table 10 shows the different kinds of data used for the three cases. Data sources have been weighted according to their robustness and reliability. CLCA should preferably be based on primary data, and such data has therefore received the highest values of reliability. Primary data from measurements is valued as highly robust and is given the value 5, while primary data such as estimates from experts have been ranked lower and given the value 3. Secondary data from GaBi and from literature has been valued even lower, at 2. The column "data value" shows the value of the data source. It can be seen that the average value doesn't differ much but shows larger robustness for CM- and AM repair.

Table 10: The table represents the weighted value for each process and which cases the process is included. Primary data, measured (5), Primary data, expert (3), Secondary data, GaBi (3), Secondary data, and literature (2). An x in the column represents that the process is used in that specific case.

Main Process	Data value	New Manufacturing	CM Repair	AM Repair
Ti64 Production	3	x	x	-
Ti64 Powder Production	3	-	-	x
Epoxy resin production	3	x	x	-
Carbon fibre Production	3		-	-
Glass fibre Production	3	x	-	-
RTM	2	x	-	-
Heat Treatment	5	x	x	-
Cleaning	5	x	x	x
Automated Measuring	3	x	x	x
Milling	3	x	x	x
LMD-P	5	-	-	x
Local Heat Treatment	3	-	-	x
Adhesiv Bonding	3	x	x	-
Polyreuthane Coating	3	x	-	-
Transport	3	x	x	x
<b>Avrage (Max =5, Min=2)</b>		3.27	3.5	3.57

Since some of the data used have low credibility and are uncertain since the production method is still under development, a validation of the data has been made. To validate the result a best and worst-case scenario was made. Data validation is done on the LMD-p process as well as for the local heat treatment. Literature values for LMD, or as its also called DED, presents a range of energy usage between 1000-8000 MJ/kg deposited material (Liu et al., 2018). As the measured value for the LMD-p used in this study is around 2700 MJ/kg the data is within the range and could be assumed to be rather correct. Energy for local heat treatment and cooling is based on expert estimates and is therefore uncertain and tested against literature. In the literature data measurements from an LMD machine are shown, where the laser’s energy withdrawal is measured separately (Liu et al., 2018). To reach an output power of 100 W the laser consumed 2.24 kW, with recalculation to match this study’s case would be roughly 75 MJ more than estimated and is therefore added in the worst-case scenario.

The uncertainty analysis, performed on non robust processes that are shown in Table 10, is the basis for which processes are analysed. The values that have been changed can be seen in Table 11.

Table 11: Table describing data varied for the uncertainty analysis.

Main Process	Varied data	Variation
Ti64 Production	Input material [kg]	+-10%
Ti64 Powder Production		
Epoxy resin production		
Carbon fibre Production		
RTM	Input Electricity [MJ]	+ -10
Local Heat Treatment	Input Argon [nm3]	+ -10
	Input Electricity [MJ]	+75

The change of input values affecting the GWP contribution can be seen in Figure 38. It is clear that the change in input values doesn't affect the overall order of the cases' contribution. Even with the best (smallest) contribution to GWP on the CM repair case, it is still far larger than the AM repair case in its worst scenario.

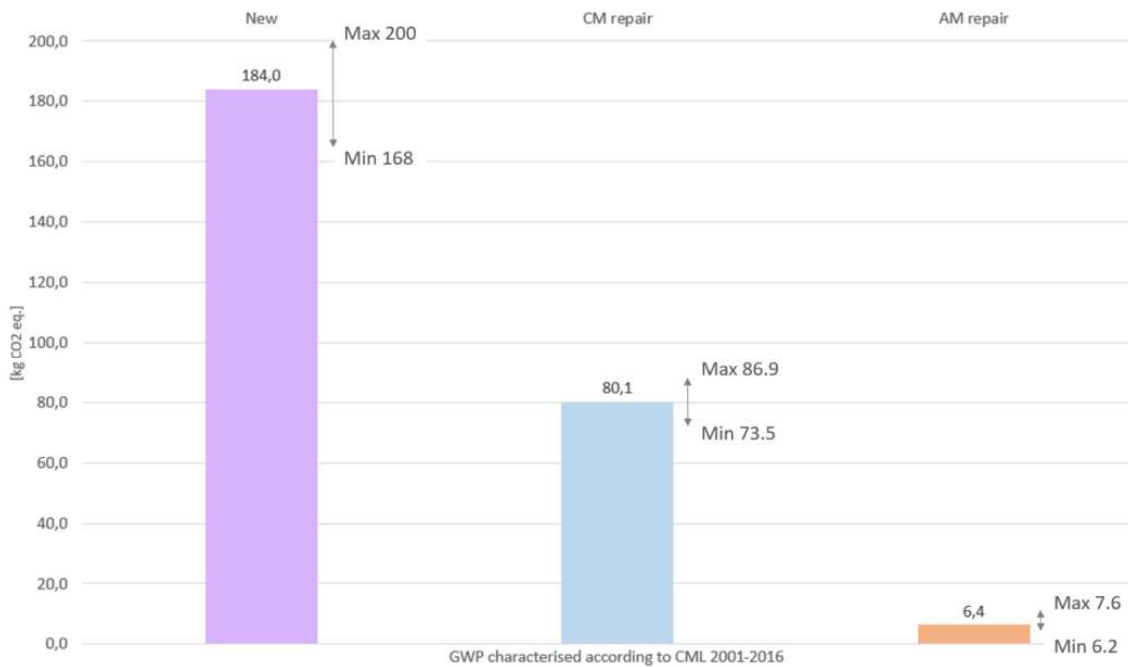


Figure 38: Barchart shows the variation in net GWP contribution from the uncertainty analysis.

## 4.4 Social Impact Assessment















The social impact assessment includes a variety of aspects, including the working conditions in the countries where the raw material is extracted to the hazards the workers are exposed to in the processes to manufacture and repair a fan blade. Most of the processes used when manufacturing a fan blade are still manual but are heading towards a more automated production.

When manufacturing and repairing a fan blade some of the processes include toxic chemicals and can risk danger to the human health and well being. Some of the most critical processes are presented below:

- **Milling** the leading edge in Ti64 involves loud sounds and rumblings in the production area. Being exposed to noise pollution like this can in some cases cause health issues and result in hearing losses (CDC, 2020). Another hazard in the milling process is the handling of cutting fluid (Cimtech A32) which can irritate the skin and cause serious eye irritation. Milling or blending of carbon fibre materials, like carbon composites, may cause particles in the air that are harmful/toxic to inhale and need to be ventilated properly.
- **Etching** is a process where strong acids are used, for example, sulfuric acid, and can cause severe burns to skin and eyes.
- **Polyurethane coating** is a process using polyurethane which is a flammable liquid and vapour that can cause serious eye- and respiratory irritation.
- **Priming** is made by applying an epoxy-based material that is harmful if inhaled and can cause an allergic skin reaction and respiratory irritation among other health concerns.
- **Cleaning process** use acetone which can cause skin dryness or cracks with repeated exposure. The liquid is also highly flammable, can cause serious eye irritation and in gas form may cause drowsiness and dizziness.
- **RTM** process uses a resin that contains formaldehyde which is a toxic substance that causes irritating to skin and may cause an allergic skin reaction. Placing the fibre material in the RTM process is done manually and handling of fibreglass may cause skin irritation and cuts.
- **Adhesive bonding** use an epoxy-based adhesive which can cause severe burns to skin and eyes among others.

- **Local heat treatment** is done by a laser machine and is an automated process, which makes it safer due to it being an enclosed process. The heat treatment is made in a protective atmosphere with argon. The argon used is initially bought as a refrigerated gas and can cause severe cold injuries if exposed to it. Since argon is an invisible and odor-free gas it can cause suffocation, if leakage occurs. To prevent and secure from leaks an oxygen sensor is used that measures the oxygen content in the atmosphere.
- **LMD-P** is a process alike local heat treatment, in terms of that it is mostly automated, using argon and done in a protected area. LMD-P also distributes particles in the air from the process that can be harmful to the operator if not ventilated correctly. The handling of titanium powder also includes explosion risk.

Figure 39 displays pictograms associated with all processes that are included in manufacturing a new fan blade and for CM- and AM repair.

Processes		New blade	CM repair	AM repair
Milling Leading edge		✓	✓	✓
LMD-P				✓
Local heat treatment				✓
Etching		✓	✓	
Cleaning	 	✓	✓	✓
Priming	   	✓	✓	
RTM		✓		
Adhesive bonding	 	✓	✓	
Polyurethane coating	 	✓		

 Harmful    
  Corrosive    
  Compressed Gas    
  Health Hazard    
  Flammable

Figure 39: An illustrative figure of hazard pictograms associated with the different cases.

The Human Toxicity Potential (HTP) is the potential harm of a chemical released in the environment and this impact can be seen in Figure 40 for the three cases. The results are received from the LCA and show that the largest contributor is the new manufacturing followed by CM- and AM repair.

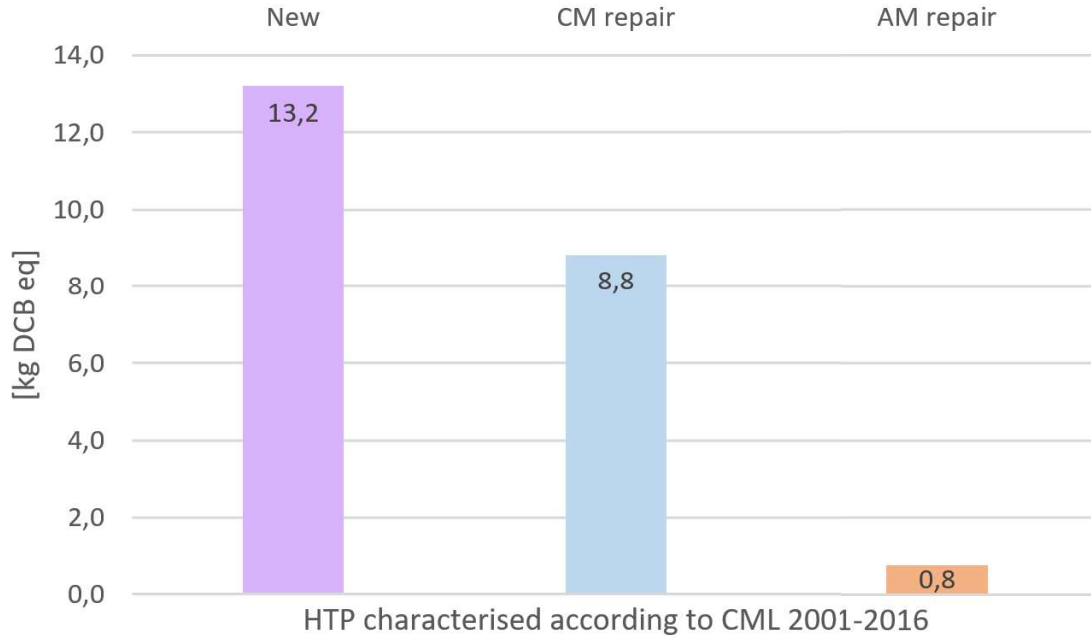


Figure 40: Human toxicity potential is associated with the different cases' life cycles.

Materials for the production of a fan blade are sourced globally and much of them consists of minerals extracted from mining operations. As shown previously in Figure 15, the main global suppliers of minerals included in the Ti64 alloy are China, Russia, Japan, and South Africa. From a global perspective, the mining business is one of the key players to reach some of the SDG goals developed by the United Nations (United Nations, nd). For example, the mining business supplies industries and engineers the opportunity to develop and produce cleaner and more efficient solutions for clean and affordable energy (SDG 7). Key impacts related to the mining industry are analyzed in (Mancini & Sala, 2018) review *Social impact assessment in the mining sector: Review and comparison of indicators frameworks*. The review presents both positive and negative impacts related to the industry, including:

Positive:

- Boosting employment, education and economic security
- Improved infrastructure making it easier to live
- Population growth

Negative:

- Social tension, economic and gender inequalities
- Theft and addiction
- Exploration, limited access to land, and poverty from loss of supporting means (for example indigenous people living on the land)
- Water usage
- Health impacts, physical and mental
- Human rights issues concerning child labor and working conditions

One common thing between the impacts mentioned above is that a net positive impact seems to occur for them who are employed in the industry while people not employed in the industry have negative impacts (Mancini & Sala, 2018).

Since the geographical origin of the Ti64 is uncertain, and that other materials also are sourced globally, the inherited social dilemmas associated with production in the countries have been analysed. Table 12, shows different indicators that are used to assess each countries social welfare. Social issues like these should therefore be considered by stakeholders such as GKN aerospace, their suppliers and customers since these stakeholders poses the legitimacy and power to make a change.

Table 12: Data on social welfare indicators associated with each country connected to producing materials or components used, data compiled from the period 2019 to 2020.

Indicator/country	China	Russia	Japan	South Africa	Sweden	Germany	United States	Source
Population [Million]	1411	144	125.8	59.5	10.3	83.2	329.5	(The World Bank, 2020a)
Education enrolment [Primary % gross]	103	104.7	97.6	98.4	126	102.5	101	(The World Bank, 2020a)
Unemployment [% of total labor force]	5.2	5.6	2.8	29	8.3	3.8	8	(The World Bank, 2020b)
Income inequality [0=equality, 1=unequally]	-	0.32	0.33	0.62	0.28	0.29	0.4	(OECD, 2020c)
Hours worked [Year/Worker]	-	1874	1598	-	1424	1332	1767	(OECD, 2020b)
Healthcare [Beds/1 000 Inhabitant]	4.8	8	12.8	2.3	2.1	7.9	2.8	(OECD, 2020a)
Life expectancy [Years]	77	73.2	84.7	64.2	82.5	81.1	77.3	(OECD, 2020d)
Suicide mortality rate [Death/100 000 Inhabitants]	8.1	25.1	15.3	23.5	14.7	12.3	16.1	(The World Bank, 2019)

## 5 Discussion

In this chapter, the results of the study are discussed. The chapter is divided into two different parts, one where the environmental aspects are discussed and the other the social aspects, both related to the different cases.

### 5.1 Discussion of methodology

The methodology that was used in this study has an affect on how the results turned out, and therefore it is important to evaluate the strength and weaknesses of each method. The strength with the strategic literature search makes it possible for other to track and make searches with similar results. There are however improvements that could be implemented, like broadening the search to intercept more valuable strategies for repair of aerospace components. A broadened search would help the comparison of current work in the industry and to evaluate the environmental impact of these repair methods.

The performed interviews gave a great insight of the aerospace industry and was a good method to provide first hand knowledge within the developing field. There could be some weaknesses though, since people have their own perceptions and perspectives that might be biased and angled. To avoid this problem, the interviewed should be based on a large variety of experts, preferably from multiple industries since it often leads to wider perspectives and ideas. The people interviewed in this thesis was experts within the GKNA company in Sweden, that currently not produce fan blades, and the result could be improved by interviewing people from other companies, preferably experts working with manufacturing of fan blades.

The life cycle assessment is a great tool for comparison between different product and services, and is widely used for quantitative values on environmental impacts. However assumptions and simplifications can affect the results credibility and their description of the reality, since modeled systems are simplifications of the real world. With that in mind it can be costly and time consuming to perform a detailed LCA. Other aspects to consider is that some environmental impacts are not analysed in a life cycle assessment, such as biodiversity

The social impact assessment gives an overview of the potential social impacts that the three cases have. There is a lack of quantitative values though, which makes it difficult to compare. The guidelines proposed by the US Interorganizational Committee is also kind of vague which can make the result differ if the study is performed by others. The thesis evaluate a future change from new manufacturing to repair which also makes it difficult to actually measure any differences in social sustainability since no changes have been made in reality.

## 5.2 Discussion of the environmental aspects

Manufacturing of a leading edge which is a high buy-to-flight ratio product, resulted in the final weight of 0.85 kg from 6.25 kg forged material, hence has a large amount of input material. This means that only around 14 % of the Ti64 is actually used in the final product and the rest is sent to a recycling facility for recycling. This is especially interesting since the titanium production has the absolute highest impact, as seen in Table 30 and Table 34, and therefore a major hotspot in the production of a new fan blade. The Ti64 should be handled with care since the extraction and production of the material has a great environmental impact and since it is made of titanium and vanadium which is on the EU critical raw material list. Therefore it is critical to investigate if the Ti64 could be used more efficiently to reduce the raw material extraction. One way to use the material more effectively and to circulate it in the technosphere longer is through recycling. Currently, the global recycling fraction for Ti64 is 60 % based on what is economically favorable to recycle, therefore 40 % is lost. In order to increase the recycling fraction, it must be more economically favorably to invest in recycled Ti64 than to produce new Ti64. The management of Ti64 is most critical for the new manufacturing case and the CM repair case, both of these cases have a large amount of titanium alloy wastes, see Table 7 and 8. This highlights one of the benefits of the AM repair case since it circulates aerospace-grade titanium within the aerospace industry and therefore not contributing to the large recycling losses. However in larger scale of repair or manufacturing with AM the loss of Ti64 powder in the LMD process should be circulated and recycled direct into the machine again to reduce losses, which was not considered in this report. Another waste, mainly from manufacturing a new fan blade and CM repair, is water which in total results in over 20-liter freshwater waste. The water is mixed with cutting fluid and becomes emulsion which needs to be separated and recycled accordingly.

Other quantities of wastes are considered rather small compared to Ti64 and water but are nonetheless important to investigate to decrease the environmental impact. Carbon fibre composite is for example a material that is difficult to recycle since it is a thermoset and cannot be remelted to a new product, unlike thermoplastics. Although carbon fibre could be reused, either as granulate input to new plastic parts or incinerated in the waste management to retrieve embodied energy. Incineration could on the other hand contribute to large emissions in relation to Sweden's current energy mix, resulting in non-clean energy.

Figure 28 shows that the GWP 100 and MAETP are the two impact categories that the three cases contribute most to. For both of the impact categories, it can be seen that the production of the raw materials, Ti64, carbon fibre, and epoxy, contributes the most. This enforces the importance to reuse or recycle material. Another high contributor to global warming is the transportation and argon production, while in the marine aquatic ecotoxicity the electricity is the major contributor as can be seen in Figure 37 and 33. The reason for electricity having a higher effect on MAETP compared to GWP 100 can be that the grid mix in Sweden is to a large extent produced from hydropower which can damage the marine ecosystem. Argon on the other hand, which is an energy-intensive gas to produce, is produced in Germany and uses the local grid mix where not as much hydropower is used, but on the other hand causes more emissions to the air from other energy sources like coal power plants. This can be the main disparity of why the two impact category is affected differently.

In the report, a repaired fan blade is assumed to have the same lifetime and performance as a new fan blade, which might not be the case. Aerodynamic parts like fan blades are sensitive to a change in geometry leading to a change in the engine's efficiency and therefore its environmental impact while in usage. Though, it is clear that a major reduction in environmental impact can be made at least within the LCA's scope of manufacturing/repair.

The results in this study show that AM repair is the preferable alternative when comparing the three cases, but to evaluate the real sustainability gain of repairing fan blades, the use phase of the engine needs to be considered. Historically the emissions from jet engines have been continuously reduced for each new engine generation, which makes it important from a climate perspective to exchange old engines to new more fuel-efficient engines. This development will probably continue with even more fuel-efficient engines or even climate-neutral engines in the future. With that in mind, it should be evaluated if repairing really is more beneficial from an environmental point of view, or if it is better to discard the engine and replace it with a newer one. So from a material scarcity perspective repairing is always good, because it reduces the use of new, often virgin material, but from a climate perspective, a repair can extend a lifetime of a product with high climate impact during use.

### **5.3 Discussion of the social aspects**

There are several positive aspects relevant to the repair cases compared to new manufacturing from a social point of view. Since the repair methods are automatized to a higher degree the employees are less prone to injuries like wear to joints in the body and chemical exposure. It also increases the precision of work done and excludes most of the human errors that can occur. This in turn can increase the quality of aerospace components and lower the risk of aviation accidents caused by malfunctions, thus lowering the social costs. Another aspect related to the working conditions on-site in Sweden is that the repair method excludes many processes otherwise used in new manufacturing like the carbon composite and epoxy handling in the RTM process. This in turn means that workers are less exposed to hazards when repairing a fan blade, see Figure 40.

The material extraction and refining market will be affected by a change from large usage of input materials, with less need for a high buy to fly ratio. Repair cases such as AM have a high potential to lessen the need for increased extraction of raw materials and therefore also affect the ones working within the mining sector. As previously presented in Chapter 4.4 the mining industry can contribute to a lot of positive social impacts, but mostly a net positive impact if one is working within that sector. Recycling or cycling of old products in the technosphere also lessen the burden and area used for final disposal of unused assets by methods such as landfill which will decrease the social benefit from the natural environment.

Since some of the material that GKNA uses for its components is on the EU:s critical raw material list a shortage or unavailability of these CRM can result in big implications for a company such as GKNA. Lack of materials for products could stop the manufacturing process and halt the aviation industry's growth and in turn cause stagnation of transport through air. An implication like this could result in a global social dismantling, lower people's life quality, and possibly loss of their source of income. When dealing with CRM such as vanadium and titanium standards and requirements should be set on the suppliers extracting the material to minimise social sustainability impacts such as child labor, inequality, etc., and help boost the employee's social welfare.

It is clear from the discussion with GKNA's sustainability team lead that many stakeholders are affected by a change from new manufacturing to repair but also that many of the stakeholders possess the attribute to make a change. The analyse of stakeholder showed that most of the stakeholders affected or effecting GKNA possesses two attributes, either Urgency, and Power or Urgency and Legitimacy, and that some possesses all three and are therefore considered key players. These key players, such as the municipal of Trollättan and customers, could make a transition to lessen the social impact easier by supporting clear directives on what is expected by GKNA and their associated social impact.

Although repairing old blades and prolonging their usage time seems to be benefited from an environmental view it is important to discuss what the implications may be of a long lifetime of products. Repairment of old and potentially inefficient products will increase their environmental impact along the life cycle that could be avoided by being replaced with newer solutions and more efficient products. There is also the risk evolving around flight safety which is a major social concern. High standards are put upon aviation components regardless if they are new or repaired. This means that every product repaired should have as high or higher standard than a new one.

## 6 Conclusion

In conclusion, repair cases such as CM and specifically AM have some major benefits and could reduce stresses put on the environmental and social sustainability. This report aimed to contribute toward a greener aviation industry and investigate the environmental and social impacts associated with manufacture and repair a fan blade. The life cycle assessment showed that two major environmental impact was affected, global warming and marine aquatic ecotoxicity, which should be acknowledged and researched more to minimize these in the future. For example, the global warming resulted in 184 kg CO<sub>2</sub> equivalents, CM repair 60 kg CO<sub>2</sub> equivalents and AM repair 6 kg CO<sub>2</sub> equivalents. This shows the benefits of repair, where AM repair significantly reduces stresses on the environment by reducing the extraction of virgin material, which is contributing the most to the environmental impacts. The social impact assessment displays several positive aspects with repair, firstly less toxic exposure to workers and less impact on natural capital. AM also repair puts less stress on the social environment in form of unchanged natural capital and less exposure to toxins from the manufacturing processes.

In short, the conclusion is that the AM repair has less environmental and social impacts, followed by CM repair and then manufacturing a new fan blade, but more research is needed to evaluate the real impacts of such methods on the life cycle of products, especially during its use phase/operation time.

Some recommendations for further work could be to:

- Perform a full LCA from cradle to grave, with a reduction of the engine performance by repair to see the real benefits since most emissions come from the usage phase.
- Implement social indicators, and measure them, to evaluate the change in social impacts from new manufacturing to a more circular usage where repair is implemented.

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