



**COMPARATIVE LIFE CYCLE ASSESSMENT OF CONVENTIONAL AND
ADDITIVE MANUFACTURING: CASE PAPER MACHINE PART MODULE**

Lappeenranta–Lahti University of Technology LUT

Master's thesis in Sustainability Science and Solutions

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ABSTRACT

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Comparative Life Cycle Assessment of Conventional and Additive Manufacturing: Case Paper Machine Part Module

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In this master's thesis, a comparative life cycle assessment of conventionally manufactured and additively manufactured paper machine part module is conducted. The aim was to provide answers for the following questions: What is the environmental impact of conventionally manufactured and additively manufactured paper machine part module; Which factors affect the environmental impact of conventionally manufactured and additively manufactured paper machine part module, and what causes the differences; In which type of cases can additive manufacturing decrease the environmental impact of part manufacturing compared to conventional manufacturing. The part module was chosen for the study, since primary data is available for both manufacturing routes. The system boundary of the study is cradle-to-gate.

When comparing the additively manufactured part module to conventionally manufactured part module, the results are the following in the chosen impact categories; 58 % lower global warming potential over 100 years, 76 % lower abiotic depletion potential of non-fossil resources, and 59 % lower abiotic depletion potential of fossil resources. The most affecting factors in conventional manufacturing route are raw materials and manufacturing electricity, and in additive manufacturing route raw materials, atomization and manufacturing electricity. The results show that through part optimization, additive manufacturing can be a viable manufacturing route for decreasing the environmental impact of part manufacturing.

TIIVISTELMÄ

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Vertaileva elinkaariarviointi perinteiselle ja lisäävälle valmistukselle: Case paperikoneen osamoduuli

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Tässä diplomityössä tehdään vertaileva elinkaariarviointi perinteisesti valmistetusta ja lisäävästi valmistetusta paperikoneen osamoduulista. Tarkoituksena oli vastata seuraaviin kysymyksiin: Mikä on perinteisesti valmistetun ja lisäävästi valmistetun paperikoneen osamoduulin ympäristövaikutus; Mitkä tekijät vaikuttavat perinteisesti valmistetun ja lisäävästi valmistetun osamoduulin ympäristövaikutukseen, ja mikä aiheuttaa eroavaisuudet; Millaisissa tapauksissa lisäävä valmistus voi vähentää osanvalmistuksen ympäristövaikutuksia, kun verrataan perinteiseen valmistukseen. Paperikoneen osamoduuli valittiin tutkittavaksi osaksi, koska primääritietoa oli saatavilla molemmille valmistusreiteille. Systemirajaus tutkimuksessa on kehdosta tehtaan portille.

Kun verrataan lisäävästi valmistettua osamoduulia perinteisesti valmistettuun osamoduuliin, tulokset ovat seuraavat valituissa vaikutusluokissa; 58 % matalampi ilmaston lämmityspotentiaali 100 vuoden aikana, 76 % matalampi ei-fossiilisten luonnonvarojen ehtymispotentiaali, ja 59 % matalampi fossiilisten luonnonvarojen ehtymispotentiaali. Perinteisessä valmistuksessa raakamateriaalit ja valmistuksen sähkö olivat eniten vaikuttavat tekijät, ja lisäävässä valmistuksessa merkittävimpiä tekijöitä olivat raakamateriaalit, atomisointi sekä valmistuksen sähkö. Tulokset näyttävät, että osan optimoinnin kautta lisäävä valmistus on varteenotettava vaihtoehto vähentämään osanvalmistuksen ympäristövaikutuksia.

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ABBREVIATIONS AND UNITS

Abbreviations

ADPE	Abiotic Depletion of non-fossil Resources
ADPF	Abiotic Depletion of Fossil Resources
AM	Additive Manufacturing
AOD	Argon Oxygen Decarburization
AWJC	Abrasive Water Jet Cutting
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAD	Computer Aided Design
CCGA	Close-Coupled Gas Atomization
CNC	Computer Numerically Controlled
DfAM	Design for Additive Manufacturing
DfMA	Design for Manufacturing and Assembly
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EIGA	Electrode Induction Gas Atomization
EoL	End of Life
EPD	Environmental Product Declaration
FFGA	Free-Fall Gas Atomization
GTAW	Gas Tungsten Arc Welding
GWP ₁₀₀	Global Warming Potential over 100 years
IEA	International Energy Agency

ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LPBF	Laser Powder Bed Fusion
NPI	Nickel Pig Iron
PBF	Powder Bed Fusion
Ro-ro	Roll-on-roll-off
SSINA	Specialty Steel Industry of North America
USD	United States Dollar

Units

ADPE	[kg Sb eq.]
ADPF	[MJ]
Energy	[kWh, MWh]
GWP ₁₀₀	[kg CO ₂ eq.]
Mass	[kg, t, Gt]
Power	[W, kW]
Time	[min, h, a]
Volume	[l, m ³]

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1. Introduction

Industry 4.0 (4th industrial revolution, 4IR) is a term first introduced in 2011. It is characterized by factors like faster delivery times, automated processes and customised products, and it mostly impacts the manufacturing sector. (Zheng et al. 2021, pp. 1922, 1927.) Industry 4.0 consists of nine key points, which are additive manufacturing, big data and analytics, autonomous robots, simulation, horizontal and vertical system integration, Internet of Things, cybersecurity, the cloud, and augmented reality (Sorooshian & Panigrahi 2020, pp. 905-907). In the 22nd century, a concept of Industry 5.0 has emerged, which complements and extends the Industry 4.0 concept. Industry 5.0 focuses on human-centric approach, sustainability, and resilience. Some of its key technologies are bio-inspired technologies and smart materials, digital twins and simulation, artificial intelligence, and technologies for energy efficiency, renewables, storage and autonomy. (Breque et al. 2021, pp. 6-7.) Additive manufacturing is seen as one of the cornerstones of both Industry 4.0 (Godina et al. 2020, p. 2) and especially the sustainability aspect of Industry 5.0 (Breque et al. 2021, p. 14).

Additive manufacturing (AM), often referred to as 3D printing, is a technology that adds material in layers to create an object from a three-dimensional computer aided design (CAD). With AM, the production of geometrically complex parts has become significantly easier. The origins of additive manufacturing date back to 1980s, when first patents of AM technologies were submitted. After the patents concerning key AM processes expired in the 2010s, it resulted in rapid development of technologies, machines, and competition worldwide. (Gibson et al. 2021, pp. 2, 43-45.) In 2022, the global market size of AM was 15 billion United States dollars (USD), and it is forecasted to grow to over 95 billion USD by 2032. Therefore, it is a significant industry and is expected to continue expanding. (Precedence Research 2023.)

AM can be used to manufacture a wide range of materials, including polymers, metals, composites and ceramics (Bhatia & Sehgal 2023, pp. 1061-1062). Among the available materials, metal AM is perceived to have the most significant impact, as it has a large industrial potential in sectors like medical, aerospace, and construction. In addition, metal AM can be used to optimize designs. (Armstrong et al. 2022, p. 1002.) While there are a

variety of technologies for metal AM, including wire laser beam energy deposition, electron powder bed fusion and binder jetting, the most industrially widespread and mature technology in the market is laser powder bed fusion (LPBF). Some reasons for its popularity are good mechanical properties and high resolution of the resulting parts, large material variety, and high design customization opportunities. (AMPOWER 2022.)

1.1. Background context

This master's thesis topic is given by Etteplan Finland Oy. Etteplan Finland Oy is a technology service company, that offers services in areas like engineering, software and technical communication (Etteplan 2024). The need for the thesis emerges from the desire to understand the environmental impact of AM and the factors that affect it. The thesis focuses on a paper machine part module. The part studied is a flow channel, which is made of stainless steel for corrosion resistance. The part module can be manufactured both conventionally and by AM. Conventionally, the paper machine part module is manufactured by combining multiple manufacturing technologies, including abrasive water jet cutting, computer numerically controlled (CNC) machining, and welding. The AM part module is manufactured with LPBF technology. The LPBF manufactured part has two conventionally manufactured stainless steel parts attached to it to complete its functionality. (Santala 2024.) Illustrations of both conventional and additively manufactured paper machine part module are shown in figure 1.

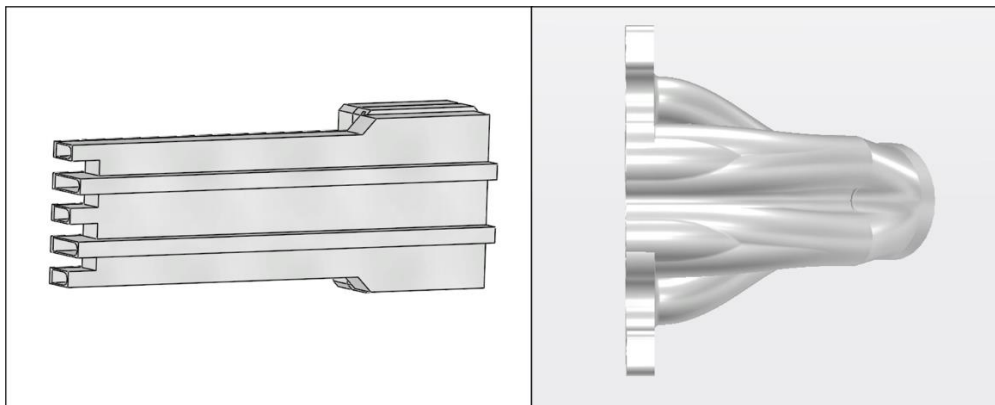


Figure 1. Design of the paper machine part module. Conventional design is on the left, and additively manufactured design on the right. (Santala 2024.)

Globally, the paper and pulp industry accounted for approximately 2 % of the industry sector emissions, resulting in 0.15 gigatonnes (Gt) of CO₂ emissions in 2022 (Simon et al. 2023). The demand of the paper and pulp industry is expected to grow, which is why its emission reduction strategies are crucial. The industry is also energy intensive due to the need to evaporate the water in drying of pulp and paper. New innovations and ways to decrease both emission intensity and energy intensity are needed. (Papadimoulis & Lynch 2023.) One way to lower the intensity are part redesigns, that increase the performance of the system or reduce the needed material for the machinery. According to Javaid et al. (2021, pp. 315-316), AM can be considered as a more environmentally sustainable manufacturing method compared to conventional manufacturing methods in some cases due to resource efficiency, waste and scrap reduction, and material recycling. Furthermore, the International Energy Agency (IEA 2023) has recognized that metal AM can have an effect in lightweighting of components, and reducing metal forming losses. Even so, there are multiple aspects that affect the environmental impact of AM, such as part geometry, material choice, layer thickness, and process time (Khosravani & Reinicke 2020, pp. 5-8). In addition, Ribeiro et al. (2020 p. 8) states that most environmental studies of AM are based on estimations and simplifications of different life cycle stages of AM. Ribeiro et al. also declares that there is a lack of assessment methodologies to evaluate the energy and material consumption, and supply-chains of AM, causing data gaps in the life cycle studies.

Life cycle assessment (LCA) is one of the best methodologies for evaluating the environmental impact of products and services, and it is widely used in scientific studies. Awareness of sustainability challenges, such as climate change, acidification, and eutrophication has been increasing in the last decades. The increased awareness has driven businesses to investigate their environmental impact and to form and implement strategies for improvement. Life cycle assessment offers a tool for systematically analysing the environmental impact of a certain product or service. The LCA results can be utilized for improving process or product design, backing up environmental claims, comparing different products or manufacturing techniques, and setting environmental goals. By conducting a LCA study, businesses can achieve cost savings, support long-term decision-making and carry out risk-management. Legislative changes, competitiveness in environmental advertising, and stakeholders' expectations considering sustainability can be realized with the help of LCA. (Soukka et al. 2020, pp. 3-5, 12-13.)

1.2. Research questions of the study

The aim of the thesis is to investigate that while in specific cases AM can improve the performance of the parts, whether it can also decrease their environmental impact. The uncertainties in the sustainability of AM create a need for further studies for the environmental impact of AM. New studies generate an opportunity for further data specifications, and can increase the overall knowledge on the topic. The focus of the study is in comparing a part, paper machine part module, manufactured both conventionally and using AM, specifically LPBF. The aim is to spot the differences and environmental hotspots in the manufacturing techniques. The research questions of the thesis are the following:

1. What is the environmental impact of conventionally manufactured and additively manufactured paper machine part module?
2. Which factors affect the environmental impact of conventionally manufactured and additively manufactured paper machine part module, and what causes the differences?
3. In which type of cases can additive manufacturing decrease the environmental impact of part manufacturing compared to conventional manufacturing?

With the help of these research questions, the aim is to conduct a thorough analysis of the environmental impact of AM, using the paper machine part module as a case example throughout the thesis. The goal is to identify the factors influencing the environmental impact of both conventional and additive manufacturing. In addition, the theory part of the thesis will provide an overview of both manufacturing routes and the environmental aspects of the manufacturing steps. The three impact categories studied in the LCA of this thesis are global warming potential, abiotic depletion potential of non-fossil resources, and abiotic depletion potential of fossil resources.

1.3. Structure of the thesis

In addition to the introduction, this thesis consists of a theory part, followed by a case life cycle assessment study of the paper machine part module, and ending in conclusions and

summary. The theory part is divided into three main chapters. The theory chapters address conventional metal manufacturing, metal additive manufacturing, and the life cycle assessment method.

The conventional metal manufacturing chapter is divided into subchapters according to the life cycle stages. The raw material acquisition focuses on the process of steel manufacturing. The different manufacturing methods used in the manufacturing of paper machine part module are explained and discussed. The transportation, use and end-of-life of the part are discussed briefly. The metal additive manufacturing chapter is divided similarly into the life cycle stages. The subchapter of raw material acquisition focuses specifically on the impact of the LPBF technology on the material, and discusses the powder manufacturing process. Lastly, the theory chapters end with a life cycle assessment chapter, which explains the life cycle assessment methodology and introduces the specifics of a comparative life cycle assessment study. Additionally, the chapter gives a brief overview of some of the previous life cycle assessment studies of LPBF.

The theory is followed by the comparative life cycle assessment of the two manufacturing routes for the paper machine part module. The LCA is divided into two main chapters, from which the former chapter consists of the goal and scope definition of the assessment, inventory analysis, and impact assessment. The latter chapter focuses on the results interpretation of the previous chapter, and includes sensitivity analysis, completeness and consistency analysis, and data quality assessment.

Lastly, the conclusions chapter explains the findings of the thesis, and provides answers to the research questions. Limitations of the study and possible future research areas are also considered. The summary chapter summarizes the whole study, including both the theory and the case chapters.

2. Conventional manufacturing of paper machine part module

In this chapter, the process steps of the conventionally manufactured paper machine part module are explained. The steps considered are product design, raw material acquisition, manufacturing process, transportation, use, and end-of-life. The subchapters include an explanation of the life cycle steps and the relating technology, and discuss the environmental impact of each step.

2.1. Product design

For product design, there are several different methodologies established, most common of which are design for X methods. The X from the method indicates an optimization goal, such as manufacturing, assembly, or cost. (Formentini et al. 2022, pp. 4307-4308.) One of the most well established product design concepts for part manufacturing is design for manufacturing and assembly (DfMA). The manufacturing optimization is driven by factors such as raw material choices, part geometry, required tolerances, roughness and specific shape constraints of the manufactured part. Then, the design for assembly focuses on reducing the number of components for the assembly, and optimizing the easiness of the assembly process. The general steps of DfMA include first analysing the number of parts in an assembly, then simplifying the overall design, and lastly aiming to use standard components and materials for the part. By applying DfMA in the product design process, benefits like optimized manufacturing from start to finish, and cost reductions can be achieved. (Naiju 2021, pp. 7473-7474.)

The design of conventional paper machine part module is complex. The complexity is a consequence of a challenging use purpose, as well as limitations in shapes by conventional manufacturing methods. In addition, the need for fine surface roughness in the part module increases its manufacturing time significantly. (Santala 2024.)

2.2. Raw material acquisition

The raw material used to fabricate the conventionally manufactured part is stainless steel, specifically 316 L (EN 1.4404) stainless steel. 316 L mainly consists of iron, chromium, nickel and molybdenum. It is a low-carbon version of 316 stainless steel, making it excellent for welding applications, and more corrosion resistant for intergranular corrosion compared to 316. (Sandmeyer Steel 2023.) The composition of 316 L is presented in table 1.

Table 1. Composition of 316 L stainless steel (Adapted from Sandmeyer Steel 2023).

Element	316 L [wt. %]
Chromium	16.0-18.0
Nickel	10.0-14.0
Molybdenum	2.00-3.00
Manganese	2.00
Silicon	0.75
Nitrogen	0.1
Phosphorous	0.045
Sulfur	0.030
Carbon	0.030
Iron	Balance

Stainless steel is a highly recycled material, but due to long service life of stainless steel applications, and increasing demand of stainless steel, scrap does not fulfil all the production. The recycled content of stainless steel varies between regions due to maturity differences in the stainless steel market. In Europe, the average recycled content of stainless steel is 85 %, while in China it is only 31 %. (Team Stainless 2022.) Two main production routes of stainless steel are therefore scrap-based electric arc furnace (EAF) production, and nickel pig iron (NPI) -based production. The latter is widely used in regions where stainless steel scrap is scarcely available. Other raw material sources of stainless steel production include ferrochrome, ferronickel, and primary iron, as well as other alloying element reserves. (Worldstainless 2023.) The main production routes for stainless steel are presented in figure 2.

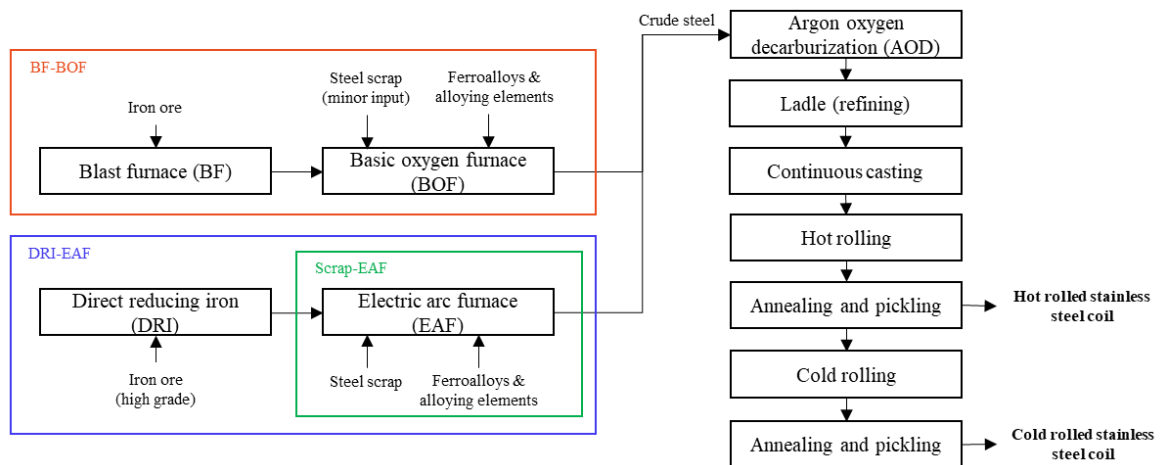


Figure 2. Main production routes of stainless steel.

In the subchapters, scrap-EAF steel production route is explained first in chapter 2.2.1., and then NPI production is described in chapter 2.2.2., since they are the two main routes for stainless steel production. In the figure 2, NPI is included in the Ferroalloys & alloying elements -input. Next, in chapter 2.2.3. primary iron -based production, including both BF-BOF and DRI-EAF routes, is explained. Chapter 2.2.4 focuses on other alloying elements of stainless steel than nickel pig iron, and lastly in chapter 2.2.5, the rest of the stainless steelmaking steps are explained, from argon oxygen decarburization to products.

2.2.1. Steel from scrap – Electric arc furnace

An electric arc furnace (EAF) is the most efficient steel scrap recycling process. It can use up to 100 % of scrap as a raw material. The scrap used in the EAF can be divided into three categories: obsolete, industrial and internal scrap. Obsolete scrap refers to end-of-life consumer product (cars, machinery, etc.) scrap, industrial scrap to processing scrap from steel strips or bars, and internal scrap to production rejections such as quality rejection and steel from slag. Obsolete scrap requires pretreatment, such as shredding and sorting to ferrous, nonferrous and residue materials. The scrap quality depends on alloying elements and material separation degree. Low-quality scrap use results in higher energy consumption, and increased slag amount. Direct reduced iron can be added to the mix to increase the

quality of the produced steel, but it results to higher energy consumption due to the reduction process. (Cavaliere 2019, pp. 316-317.)

The separated steel scrap is fed into the EAF. The EAF melts the added material by high-power electric arcs between a cathode and anodes. The process is highly energy intensive due to electricity being the source of heat, so the source of electricity creates a big variation in the emissions of EAF. The overall electricity consumption of EAF can be reduced via different technological innovations, such as scrap preheating, burner optimization, and post combustion. (Cavaliere 2019, pp. 303-304, 306.)

2.2.2. Steel from nickel pig iron

Nickel pig iron (NPI) refers to a low-grade (4-15% nickel) ferronickel, that can be used as a raw material feedstock for stainless steel. NPI is produced from a low-grade laterite ore. Laterite is an open pit mined ore, that consists of magnesia, silica, and a low amount of nickel (< 3%). The low-grade laterite ore is dried, and then fed into blast furnace with coke and slag formers, producing NPI. NPI is mainly produced in China to meet the increasing demand in the stainless steel market. It is often favoured over refined nickel due to its lower cost. NPI production has a high energy intensity due to high operating temperatures and slag formation. In addition, the low nickel content of NPI increases energy and emission intensity of the production per contained nickel. (Wei et al. 2020, pp. 2-3, 14.) The high emission intensity of NPI is mainly caused by mining operations of laterite ore, and coke consumption and flaring in the blast furnace. (Reuter et al. 2015, p. 688).

2.2.3. Steel from primary iron

Iron ore needed for steel production is mined by either surface mining or deep mining. Surface mining is a more common method due to iron reserves being close to the ground surface and because of the simplicity of the method. However, to maximize its productivity, surface mining still requires highly modern equipment with high capacity volumes but with low costs. Deep mining of iron ore utilizes automated and remote control equipment for safe extraction. Both of the mining methodologies have environmental issues. The mining

process requires a lot of energy, results in tailings, and causes air pollution from the equipment used. In addition, mining causes water pollution in the form of heavy metal contamination, fuel spills, and increased total solids load in the water bodies. (Zhang 2023, pp. 140-141.)

There are two main routes for converting iron to steel: blast furnace-basic oxygen furnace (BF-BOF) route and direct reduced iron-electric arc furnace (DRI-EAF) route. In 2022, BF-BOF route accounted for 72 % of the global crude steel production, and DRI-EAF for 7 % of global production. The rest, 21 %, was scrap-EAF based production. (Worldsteel 2023.) The BF-BOF route utilizes coal in the BF for reducing oxygen from the iron ore, producing molten pig iron. After the BF, the pig iron is fed into BOF, in which unwanted elements are burned from the liquid pig iron by blowing oxygen into the iron. Next, the steel is cast into slabs or ingots via continuous casting. (Cavaliere 2019, pp. 167-168, 275-276.) In direct reduction of iron, the oxygen is removed from high-quality (>65 % iron) solid iron ore by using natural gas, gasified coal (syngas) or pure hydrogen. Then, the DRI is converted into steel in EAF. EAF melts the DRI and possible additives with high-power electric arcs, forming steel ready for casting. (Cavaliere 2019, pp. 303, 419-424, 435.)

The main environmental issues of BF-BOF route are dust, emissions to air (such as CO₂, NO_x, SO₂), heavy metal contamination and high energy intensity. Especially the blast furnace causes a large amount of CO₂ emissions due to high coke consumption. (Li et al. 2018, pp. 52-53.) The environmental impact of DRI depends on the reduction gas used. While hydrogen-based DRI is energy intensive due to hydrogen production, with clean electricity source it can be more environmentally friendly compared to natural gas or coal based DRI. (Cavaliere 2019, p. 468.) According to Worldsteel (2023), the average CO₂ emissions intensity of different steelmaking routes, including direct, energy-based and main upstream emissions, were the following in 2022: BF-BOF with 2.33 tCO₂/t crude steel cast, DRI-EAF with 1.37 tCO₂/t crude steel cast, and steel scrap-EAF with 0.68 tCO₂/t crude steel cast.

2.2.4. Alloying elements of stainless steel

The main alloying elements of 316 L stainless steel by mass-% are chromium and nickel. Generally, chromium is the most important alloying element of stainless steels. Chromium creates a passive surface film for the stainless steel, which prevents oxidation and corrosion of the steel. Nickel then enhances the stability of the film, and improves the mechanical properties of stainless steel. Other alloying elements such as molybdenum, manganese, and silicon are added to the steel achieve specific stainless steel grades with desired properties. (Sun et al. 2021, pp. 1, 7-10.)

The main market of ferrochrome is the stainless steel market. Ferrochrome consists of 50-70 % chromium, and it is produced from chromite ore. Chromite ore is fed into an electric arc furnace, where the chromium and iron of the chromite ore react with carbon, and are reduced. The main producer of chromite ore is South Africa, as it has most of the world's chromium reserves. The mining of chromite ore and the ferrochrome production industry cause land, water, and air pollution. The environmental impacts include chromium particulate matter to air, and toxic hexavalent chromium pollution to soil and water via high chromium waste. (Coetzee et al. 2018, pp. 52-54.)

Ferronickel consists of 20-40 % of nickel, and it is mainly produced from high-grade laterite ore with rotary kiln-electric furnace combination. In the rotary kiln, nickel ore is partially or fully reduced, and then either reduced fully or only melted in the electric furnace. Ferronickel is widely used as a raw material for stainless steel. (Zevgolis & Daskalakis 2021, pp. 4-5.) The extraction of nickel from lateritic ore is energy intensive, and the mining process of laterite has a high energy demand (Wei et al. 2020, p. 2-3). In addition, the laterite slag can contain hexavalent chromium, which is toxic to soil and water (Economou-Eliopoulos & Megremi 2021, p. 9). Even though ferronickel is a higher-grade nickel product than NPI, its demand is decreasing. This is due to its higher cost compared to NPI. (Wei et al. 2020, p. 14.)

2.2.5. From crude steel to stainless steel

The alloying elements of the steel are added to the melt in the EAF or BOF, depending on the production route. The melted steel from EAF or BOF is called crude steel. To refine the crude steel, the melt is moved to an argon oxygen decarburization (AOD) converter. In the AOD converter, the carbon and sulfur content of the steel is reduced by blowing argon or nitrogen mixed with oxygen to the converter. The specific chemical composition of the desired stainless steel grade is then fine-tuned in a ladle furnace. (Cai & Li 2022, pp. 73-74.)

The liquid stainless steel is formed into solid slabs by continuous casting. The steel slabs are hot rolled into sheets and plates. The hot rolled products can then be cold rolled into thinner products. To finish the stainless steel material (either hot rolled or cold rolled), it is then heat treated to soften the structure, and pickled, which is an acid wash that cleans the steel. (SSINA n.d.) Overall, the steel production is energy intensive due to the high temperatures, and results in waste flows, like slags, dust, and heavy metals. (Li et al. 2018, p. 54.)

2.3. Conventional manufacturing processes

The conventional manufacturing processes can be divided into traditional and non-traditional machining. The traditional machining processes are based on tools that are harder than the material being machined, and it includes techniques such as milling, turning, drilling, and grinding. Non-traditional machining is based on thermal, mechanical, electrochemical or chemical energy, which is used for machining the material. The non-traditional technologies include plasma beam machining, abrasive water jet machining and chemical milling. (Kumar et al. 2018, pp. 43-46.) The fabricated parts can then be assembled to a product by using bolts or screws, or by welding the pieces together (Formentini et al. 2022, p. 4313).

The conventional manufacturing of paper machine part module has multiple manufacturing steps because of the complexity of the part. The main manufacturing technologies used are abrasive water jet cutting and computer numerically controlled milling. The paper machine part module assembly is then joined together with gas tungsten arc welding and bolts. (Santala 2024.)

As mentioned before, the additively manufactured paper machine part module has two parts attached to it, which are manufactured conventionally. The conventional parts are manufactured by CNC milling and turning. The assembly process utilizes GTAW. (Santala 2024.)

2.3.1. Abrasive water jet cutting

Abrasive water jet cutting (AWJC) is a technology in which thin, high pressure water jet and abrasive slurry added to the water flow is used to cut through a material. The method is based on erosion, as the water-slurry mix erodes the cutting line. The system consists of a water pump, abrasive material adding system, mixing tube for the water and slurry, computer display system for controlling the process, and a storage tank that dissipates the remaining energy of the jets after the cutting. Materials like garnet, glass, and steel can be used as the abrasive material, from which garnet is the optimum material in most cases. The main advantages of AWJC are that it can cut through very hard materials, the resulting part has no thermal distortion due to water acting as a coolant, and process flexibility in the cutting track. (Alsoufi 2017, pp. 1-4.)

The environmental impact of AWJC is mostly caused by the abrasive material used. The abrasive material can be recycled in the process, but not infinitely as the particles lose their sharp edge. Moreover, the recycling process is often not an economically viable choice, so the abrasive particles regularly end up in landfills. The AWJC process itself also consumes a significant amount of electricity and water, affecting its environmental impact. (Guglielmi et al. 2021, pp. 4, 14.)

2.3.2. Computer numerically controlled machining

In computer numerically controlled (CNC) machining, computer control system is used for controlling the machining operations. The CNC machine cuts the workpiece according to the model of the part fed into its program. The main advantages of CNC machining are automation of the process, and accuracy of the resulting part. Both turning and milling processes can utilize CNC. Turning is a process in which the workpiece is rotating, and the

cutting tool removes material from the workpiece. In a milling process the workpiece is stationary, and a rotating cutting tool removes material from the workpiece. The workpiece can be attached to a moving base in the milling process, which enables versatile angles and reaching points for the cutting tool. (3D HUBS n.d., pp. 5-11.)

The main environmental impact of the machining processes are energy consumption and waste generation. The CNC machining requires a significant amount of energy, which is consumed during the idling and cutting operations of the machine. The total energy consumption of CNC machining can be lowered with optimized cutting parameters, efficient cutting tools, and reduction of the idling time of the machine. The waste that results from the machining process is primarily auxiliary fluids, such as coolants and cutting fluids, and a significant amount of metal waste in the form of chips. The metal chips can usually be recycled, but the cutting fluids can be hard to dispose. Components produced with CNC are usually complex, and therefore result in a lot of metal scrap as a waste. Thus, waste recycling is essential for lowering the environmental impact of CNC machining. (Soori et al. 2024, pp. 73-76, 84-85.)

2.3.3. Gas tungsten arc welding

Gas tungsten arc welding (GTAW), often referred to as tungsten inert gas (TIG) welding, is used for the assembly of the different metal parts of the paper machine part module (Santala 2024). In GTAW, the process is controlled with an electrode made of tungsten. The welding process creates an arc between the electrode and the workpiece. The electrode is inert, so it is not consumed in the process. A filler material is usually used to weld the pieces together, and the welding is conducted in an inert gas atmosphere. The welding depth of GTAW is generally shallow, limiting its applications. Furthermore, the welding process speed is low and has a lot of operating parameters, making it a complex welding technology. The GTAW also results in cytotoxic and biotoxic fumes, which is why a good ventilation system is essential. (Mehta 2018, pp. 130, 141.)

Generally, the GTAW welding process has a high environmental impact compared to other welding processes, such as gas metal arc welding and flux-cored arc welding. The reasons for the poor environmental performance of GTAW are due to its low welding speed and high

power input. The low welding speed results in high overall electricity consumption and high consumption of the inert welding gas. Still, GTAW is a widely used welding method due to its wide material versatility and high quality of the weld (Favi et al. 2019, pp. 2143, 2170.)

2.4. Transportation

Transportation occurs between multiple steps in the life cycle of parts. The raw materials need to be transported to the production site, and if the production chain has multiple sites, the components need transportation between them. Then, the finished part needs to be transported to the customer. When the part is no longer in use, it is transported to the end-of-life treatment facility. Similarly, the different waste flows during the manufacturing of the part are transported to the end-of-life treatment sites. The conventionally manufactured paper machine part module is manufactured in multiple sites, requiring mainly road transport between the locations. The high amount of manufacturing waste needs to be transported to treatment sites, increasing the transportation total.

Freight transport has multiple affecting factors to its environmental impact, some of which are transport mode, load factor, fuel type, and emission class of the vehicle. The transport modes can be divided into road, rail, water, and air. The load factor refers to the share of maximum payload in use in the transport. The fuel type includes the fuel used and the biofuel amount of the fuel, and the emission class defines the maximum emissions of a certain vehicle. In the EURO emission classes for road transport, the higher the emission class, the stricter the emission limits. Newer vehicles have a higher emission class, resulting in a lower emission intensity. (Farkavcova et al. 2018, pp. 70-74.)

2.5. Use phase

Different types of flow channels are used in a wide range applications, including heat exchangers, power components, and fuel cells. Ideally, a flow channel should avoid harsh angles, as they can increase flow separation and stagnation in the channel. In addition, the flow channel part design needs to consider its impact and fit for the machinery on which it is intended to be used in. In conventional part manufacturing, both optimal flow design and

fit on the machinery are often hard to achieve. The internal flow channels can be highly complicated or small, making their manufacturing by machining challenging. Therefore, often the mass and fit optimization of the part are a priority, forgoing the optimal flow channel design, which results in efficiency losses. (Zhang et al. 2020, pp. 1-5.) The part studied is used as a flow channel in the papermaking process. The service life of the part module is the lifetime of the paper machine. Therefore, the estimated service life is 30 years, but can be even longer in some cases. (Santala 2024.)

Paper is made from pulp, which is produced from wood, recycled paper, or agricultural residues. The lignin and cellulose fibers are separated by adding water and heat. The pulping is then executed either mechanically or chemically. In mechanical pulping, the wood chips are grinded resulting in high pulp yield but low quality. The process uses electricity mainly for heating, and some of this heat can be recovered for use in other processes or in district heating. In chemical pulping, the chips are cooked in a digester with chemicals to separate the cellulose fibers. The process produces more energy than it uses, mainly due to a high-energy by-product, black liquor containing wood waste, chemicals and impurities. Black liquor is burned in a recovery boiler, producing steam. The chemical pulping process has a lower yield, but results in higher quality fibers compared to mechanical pulping. Overall, the energy consumption of pulp and paper industry is high due to the need for thermal energy in drying the pulp and paper. Some of the mills are self-sufficient in energy due to the high-energy by-products, even selling electricity to the grid. The energy produced is mainly biomass-based, which is considered carbon neutral. With efficiency improvements, the energy produced could be increased further. Still, the paper and pulp industry uses a lot of chemicals in chemical pulping process, and the water use and wastewater yield are high. (Moya & Pavel 2018, pp. 8-9, 26.)

2.6. End-of-life

The end-of-life (EoL) treatment of the stainless steel paper machine part module is recycling. The EoL recycling rate of stainless steel was 70 % in 2019, and as high as 95 % if the carbon steel cycle is included (Worldsteel 2023). Recycling of steel starts with the collection of scrap. Scrap is collected from obsolete consumer products and industrial equipment. Large scrap is then fed into a shredder, which breaks the scrap into smaller pieces, making the

separation of different materials easier. Stainless steel can be either magnetic or non-magnetic. The magnetic (ferritic) fraction usually ends up as carbon steel scrap, while the recovery rate of non-magnetic (austenitic) fraction as stainless steel is high. The shredded material is separated using magnetic separation, sieving, and air separation. If the material is sought to be separated further, methods like density separation, weak magnetic separation and hand sorting can be implemented. The separated scrap can then be melted in EAF with other raw materials, producing new stainless steel. (Worrell & Reuter 2014, pp. 67-73.)

The main hindrance of steel recycling is tramp elements. Tramp elements refer to elements in steel that are hard to separate from it. They can be a result of impure ores, reductants used or alloying material added. For example, molybdenum, copper, chromium, and cadmium are considered to be tramp elements. The tramp elements can accumulate in the recycled steel over time, and decrease the quality of the produced steel. (Worrell & Reuter 2014, pp. 74-76.)

3. Additive manufacturing of paper machine part module

In this chapter, the additive manufacturing (AM) process steps are explained. The AM technology that the chapter focuses on is laser powder bed fusion (LPBF). The steps described are part design, raw material acquisition, manufacturing, transportation, use, and end-of-life. The environmental impact of each step is considered, focusing on the manufacturing of the paper machine part module. The AM part also has two conventionally manufactured parts attached to it. The conventional parts are manufactured with CNC machining, the process of which was explained in chapter 2.3.2.

3.1. Design for additive manufacturing

Design for additive manufacturing (DfAM) is a process which focuses on the variants and process chain that are representative of AM production. With AM, properties like reduced mass, surface modification, functional internal geometry, and functional assemblies can be achieved. The reduced mass of AM parts can be achieved through topology optimization, generative design, and lattice structure filling. Topology optimization refers to a numerical approach, which optimizes the material use for a desired functionality. With topology optimization, the needed material for a part can be reduced while still maintaining the required properties. Generative design refers to a rule- or algorithm-based system that explores the design space and generates possible solutions for designers. With lattices, high stiffness structures with low mass can be achieved. (Vaneker et al. 2020, pp. 581, 585-590.)

In addition to mass reduction, AM allows integrating functional internal geometry into parts. AM creates a possibility for designing internal features to the part to optimize its performance. For example, AM can be used for achieving acoustic damping through internal pathways, optimizing fluid channels, or integrating conformal cooling channels that follow the external geometry of the part. With conformal cooling, more consistent and effective heat transferring can be achieved in different thermal use cases, like injection molding tools and hot sheet metal forming. Furthermore, AM allows an assembly of parts to be merged into one single AM part. This can potentially reduce the mass of the part, improve its

efficiency and durability, and eliminate or significantly reduce the assembly time of the part. Similarly, AM can be utilized to produce assemblies that have moving parts in them. For example, joints, gears, and hinges can be produced as an assembly, only requiring clearance and powder removal after the initial printing. (Thompson et al. 2016, pp. 741-746.) For the LPBF manufactured paper machine part module, mass, geometry, and assembly are all optimized in the redesign, utilizing the advantages of AM well (Santala 2024).

3.2. Raw material acquisition

A broad range of materials can be manufactured with laser powder bed fusion. In general, all materials that are weldable are a possible option for metal powder bed fusion manufacturing. The materials that can be manufactured with LPBF include common metals like steel, aluminium and titanium, but also precious metals such as gold and silver. (Gibson et al. 2021, pp. 128-130.) According to Abd-Elaziem et al. (2022, p. 682), the most common materials in LPBF manufacturing are titanium, steel, aluminium, nickel, cobalt-chromium alloys, and superalloys. Research by Zhang et al. (2018, pp. 1-2) supports this claim as titanium alloys, steels, aluminium alloys and nickel alloys were the most studied metal AM materials between 2007 and 2017.

Material used to manufacture the paper machine part module with LPBF is 316 L stainless steel. Before a material can be manufactured using LPBF, it needs to be in powder form. The first subchapter explains the powder production process, and the second subchapter focuses on the properties of 316 L manufactured with LPBF.

3.2.1. Powder production

The powder quality and properties affect the quality of the AM part. Ideally, the powder used for AM has a high purity and flowability, is spherical and uniform in size, and does not have porosities. (Soong et al. 2023, p. 1.) While there are multiple different processes for producing powders for metal AM, the most common method is atomization (Popov et al. 2021, p. 6). Atomization process can generally be divided into three main steps; melting the feedstock metal, atomizing the melted material, and solidification of the powder via rapid

cooling. Since atomization results in a wide size range of powders, post-processing like air classification or sieving, as well as measurement and examining of properties is needed. Atomizing is done to a shear of liquid metal, and the process equipment is usually vertical. Depending on the atomization method of the melted material, the available processes can be divided into gas, plasma and water atomization. (Kassym & Perveen 2020, pp. 1728-1729, 1731.)

Gas atomization is the most common technology for producing AM metal powders. The form of the feedstock material in gas atomization is flexible, but generally metal ingots are used. (Kassym & Perveen 2020, pp. 1728-1729.) In gas atomization, metal is melted in a furnace in vacuum or inert gas conditions. The stream of molten metal is then atomized using a high-velocity gas flow. The atomizing gas must be inert, so oxidation and gaseous reactions are reduced in the atomization process. Atomizing gases commonly used are nitrogen, helium or argon, which all result in high purity and sphericity of the powder. Air is not recommended as an atomizing gas due to its oxygen and moisture content. Gas atomization can be divided further into free-fall gas atomization (FFGA), close-coupled gas atomization (CCGA) and electrode induction gas atomization (EIGA). In FFGA, there is a gap between the molten metal spraying nozzle and atomization gas, which makes the metal free fall a short distance before the atomization. FFGA has flexible feedstock options, but produces a wide size range with satellite particles. In CCGA, the atomization gas jet is positioned right after the nozzle, eliminating the free falling distance. It is an efficient method, resulting in a high fine powder yield. In EIGA, an electrode tip is used to melt the metal, and it produces oxide-free powders. (Soong et al. 2023, pp. 1, 4-5, 10.)

In plasma atomization, a wire feedstock is fed into plasma torches. The plasma torches melt the material, and simultaneously atomize the molten material. With plasma atomization, powder with high flowability and spherical particles is achieved. One disadvantage of plasma atomization is that the feedstock needs to be in a wire form, which limits the available materials and increases the production cost. In addition, porosity caused by trapped gas in the particles is a problem. Water atomization uses high-pressure water sprays to atomize the molten material. Though being an effective and cost-saving method, water atomization produces powders with high oxygen content and large particle size. In addition, the particles have irregular surface morphology, and low flowability. These factors make it a less-used

technology for producing powders for AM. (Soong et al. 2023, pp. 3-4.) Different powder atomization processes are summarized in table 2.

Table 2. Atomization processes (adapted from Kassym & Perveen 2020 and Soong et al. 2023).

Process	Common feedstock	Advantages	Disadvantages
Gas atomization	Fe, Ni, Al, Ti (EIGA)	Multiple technologies for different cases Fine powder yield with CCGA Oxide free with EIGA Wide feedstock options Efficient	Porosity of particles Satellite particles Oxygen contamination Wide particle size distribution
Plasma atomization	Ti	Highly spherical particles Fine powder yield	Wire feedstock High cost
Water atomization	Non-reactive	Efficient Low cost	High oxygen content Large particle sizes Wide particle size distribution Satellite particles Low flowability Irregular morphology

The environmental impact of atomization differs between processes. As gas atomization is the most common process for producing powders for metal AM, the focus of the environmental impact consideration in the thesis is on gas atomization with argon gas. Gas atomization process has a high energy consumption due to the melting process of the metal. Melting is commonly achieved via induction. (Kassym & Perveen 2020, p. 1729.) Argon gas is produced via cryogenic air separation. In cryogenic air separation, low-grade argon is withdrawn from low-pressure column, and then refined into high purity argon in the argon column. The cryogenic air separation of argon is a highly energy intensive process. (Ceylan et al. 2018, pp. 523-524.) As the particle size distribution ranges from 0 to 500 micrometres (μm) in gas atomization, not all the resulting powder can be utilized in LPBF due to too large diameter of the particles. This lowers the yield of usable powder for LPBF. In addition, a fraction of the material is lost during the atomization process, lowering the powder yield further. (Böckin & Tillman 2019, 980.)

3.2.2. 316 L stainless steel

One of the most widely used LPBF steel materials is 316 L stainless steel. Its popularity is explained by its ease of processing, high corrosion resistance and toughness, and relatively low cost. (Narasimharaju et al. 2022, p. 375.) Due to these properties of 316 L, it is commonly used in industries like aerospace, automotive, petrochemical and prosthetics (D'Andrea 2023, p. 3). The part studied in this thesis, paper machine part module, uses 316 L powder as a raw material in the LPBF manufacturing.

The LPBF process alters the mechanical properties of 316 L compared to conventional manufacturing methods. The hardness of 316 L components is commonly higher with LPBF manufacturing. The fatigue behaviour and tensile strength depend on the building orientation and possible internal defects of the part. On the other hand, corrosion resistance often suffers from LPBF, as the alloying elements can vaporize. (D'Andrea 2023, pp. 14-15.) These vaporized alloying elements, such as chromium, can be toxic (Coetzee et al. 2018, p. 55).

Two main problems with LPBF manufacturing of 316 L can be recognized: residual stresses and cracking. Both of these are essentially caused by temperature changes in the process. The residual stresses can be countered with a higher preheat temperature and shorter scan vectors. Cracking can be mitigated with optimizing hatch spacing and laser exposure time, as well as with post-process treatment strategies. Post-process treatment can be also used to alter the final properties of the product. (Narasimharaju et al. 2022, pp. 380-384, 408.) The parameters influencing the overall quality of LPBF manufactured parts are presented in chapter 3.3.1., while the general properties of 316 L, and the production and environmental impact of stainless steel manufacturing were explained in chapter 2.2.

3.3. Additive manufacturing process

According to the additive manufacturing standard ISO 17296-2 (2016) prepared by International Organization of Standardization (ISO), AM can be divided into seven process categories; vat polymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition and sheet lamination. The division is done based on fundamental parts of functionality of the machines. Four of these technologies can typically

use metals as a feedstock material; binder jetting, powder bed fusion, directed energy deposition and sheet lamination. (SFS-EN ISO 17296-2 2016.)

In the sheet lamination process, sheets of materials are cut, stacked, and bonded. Bonding can be achieved by thermal bonding or clamping. Sheet lamination does not have noticeable commercial success due to anisotropic mechanical properties, high material waste, and safety concerns. (Gibson et al. 2021, pp. 253, 259-261, 279-280.) Binder jetting is based on a roller that spreads a layer of powder, which is then jetted with liquid binding agent to create a patterned layer. Then the platform is lowered and the process is repeated to create a part. (Ziaee & Crane 2019, p. 781). Metal binder jetting has uncertainties in the mechanical performance of parts (Mostafaei et al. 2021, p. 119), and overall binder jetting is still waiting for a wider industrial breakthrough (AMPOWER 2021a). In directed energy deposition, wire or powder material is fed into a thermal energy (laser, electron beam etc.) source, and then the molten material then builds the part layer-by-layer. While directed energy deposition processes are used in industrial applications, it produces parts with high surface roughness, and lacks in precision. (Ahn 2021, pp. 704-705.)

In powder bed fusion (PBF), a part is built inside a build chamber with an inert gas flow. Thin layers of powder material are spread and distributed evenly as a bed with a powder spreader. Then, a high-power beam melts the powder particles to the building platform in a pattern according to the design model. After the layer has been scanned, the building platform is lowered so the next layer of powder can be spread, and the sequence is repeated melting the powder to the previous layer instead of the building platform. When the part is finished, excess powder is removed and the part is separated from the building platform. Based on the energy source, PBF processes can be divided into laser powder bed fusion and electron beam powder bed fusion. Electron beam powder bed fusion is not as commonly used as laser powder bed fusion. (Armstrong et al. 2022, p. 1012.)

3.3.1. Laser powder bed fusion

In laser powder bed fusion (LPBF), a high-power laser beam is used to selectively melt layers of powder to create a part (Narasimharaju et al. 2022, 378). LPBF can produce parts with higher dimensional accuracy and generally better surface accuracy compared to other

metal AM technologies, making it a widely used technology. Available LPBF machine sizes range from research and development machines to heavy industrial machines. (Khorasani et al. 2020, pp. 191-192.) According to AMPOWER (2021b), LPBF is the leading technology in metal AM, as the technology is widely adopted in different industries and broadly available. LPBF process schematic is presented in figure 3, while the PBF process was described step-by-step at the end of the previous chapter.

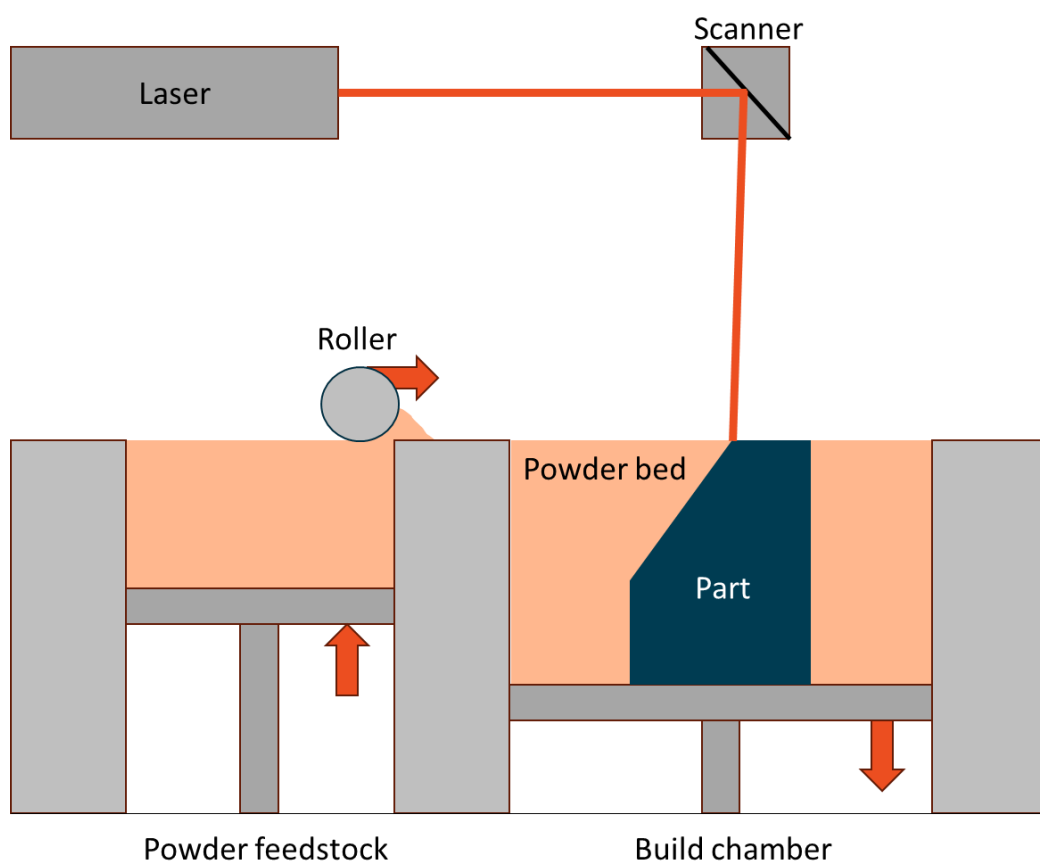


Figure 3. Schematic of LPBF process (adapted from Ninpetch et al. 2020). The powder can be spread with a roller as depicted in the picture, or with a blade.

One of the main advantages of LPBF is its versatility, as it can produce complex structures due to freedom of design. This makes the production of customized parts attractive, and it can be utilized in aerospace, automotive, and medical industries. (Narasimharaju et al. 2022, p 407.) Complex geometries with relatively small features and internal cavities can be manufactured using LPBF, while strength, density, and stiffness of the part can be achieved.

In addition, a wide range of materials are available for LPBF, ranging from stainless steel to titanium, aluminium, and nickel alloys. (Jiménez et al. 2021, p. 67)

LPBF process has a low build rate compared to other metal AM methods due to low layer thickness and hatch spacing. While increasing the layer thickness increases the build rate, it reduces the accuracy of the printed part. In addition, the combination of layer thickness, hatch spacing, scan speed, and laser power affects the mechanical properties of the part. (Chowdhury et al. 2022, pp. 2127-2128.) The high thermal energy and instability of the melt pool can cause shrinkage, residual stresses and porosity in the parts (Jiménez et al. 2021, p. 68). Due to the complexity of the abovementioned factors, monitoring the different process parameters is essential to achieve the required mechanical properties and part accuracy, as well as high density of the part (Chowdhury et al. 2022, pp. 2111.) The process parameters and their effect on the produced part are summarized in table 3.

Table 3. LPBF process parameters and their effect (adapted from Chowdhury et al. 2022).

Element	Parameter	Effect
Laser	Power	Fusion depth, melt pool diameter, residual stress accumulation, distortion, part accuracy, mechanical properties
	Pulse duration	
	Scan speed, spacing and pattern	
	Beam profile	
Powder	Particle size, shape and size	Powder spreading, microstructure, mechanical properties
	Distribution width	
	Layer thickness	
	Powder bed density	
Temperature	Powder bed temperature	Mechanical properties, microstructure, phase transformation in materials
	Powder feeder temperature	

Typically the LPBF manufacturing process is energy intensive since the process has a high electricity consumption. The build rate and layer thickness affect the energy consumption of the LPBF process. If high dimensional accuracy and mechanical properties are required for the part, layer thickness is thin, increasing the manufacturing time. The increased manufacturing time increases the total energy consumption. The powder used in LPBF can be reused in the process, but some of it is insufficient for reuse, ending in recycling. (Gao et al. 2021, pp. 461-462, 467.) The inert gas used in LPBF is most commonly argon or nitrogen, while also a combination of for example argon and helium can be used. While manufacturing

highly reactive materials, argon is the most viable option. (Santechhia et al. 2020, p. 7.) The argon production process is energy intensive, as was explained in chapter 3.2.1.

After the LPBF manufacturing process, the manufactured part requires post-processing treatment. The first process is the removal of excess powder from the build chamber. Next, stress-relief heat treatment or surface finishing is often performed to achieve good part quality. (Narasimharaju et al. 2022, p. 408.) Then, the part needs to be removed from the build plate, if the plate is not part of the final design. The part is usually removed by sawing. If support structures are used in the manufacturing, they have to be removed after the process. (Ochs et al. 2021. p. 615). Lastly, cold post-processing, such as shot peening can be applied, improving the microhardness, surface roughness, and compressive yield strength of the treated part. (Narasimharaju et al. 2022, p. 408.) Overall, the post-processing treatment can require a lot of energy, depending on the part manufactured and its required properties, and therefore can have a significant environmental impact (Ochs et al. 2021. p. 618). The AM paper machine part module requires removal of excess powder, shot peening, cleaning and grinding after the LPBF process.

3.4. Transportation

The transportation steps of the additively manufactured paper machine part module are similar to the conventionally manufactured part. Raw materials are transported to powder manufacturing, the powder is transported to manufacturing and lastly the part is transported to the user. The no-longer used part, as well as the waste of production is transported to end-of-life treatment. For the additively manufactured paper machine part module, the powder is manufactured in central Europe, so it requires transportation to the LPBF manufacturing site in Finland. Post-processing is done in a different site in Finland, so the part requires road transport between the steps.

Additive manufacturing can offer benefits to the supply chain of parts. It can enable local manufacturing of parts, and reduce upstream supply chains with only one manufacturing site. In addition, the need for large inventories is reduced, since AM can enable shorter lead times and high customization of parts. AM also enables having inventories digitally, rather than a large physical inventory. The additive manufacturing of parts can also reduce

disruptions in supply chains due to the need for only localized transportation. (Attaran 2017, pp. 197-198.)

3.5. Use phase

The additively manufactured part module is used in the same setting as the conventionally manufactured part, as a flow channel in a paper machine. It offers some benefits compared to the conventionally manufactured part, including geometrically optimized design for its purpose, and reduced mass of the component. These in turn can improve the performance of the whole paper machine, leading into reduced energy losses and increased quality. Therefore, the advantages of AM are utilized well in the part redesign. The estimated service life of the LPBF part module is the same as the conventionally manufactured part module, which is the whole life cycle of a paper machine. The estimated service life is therefore 30 years, but can be even longer in some cases. (Santala 2024.) Since LPBF manufacturing can cause residual stresses and cracking in the paper machine part module, its service life could be shorter. However, this is unlikely due optimized LPBF manufacturing parameters, and post-treatment strategies, which aim to mitigate these hindrances.

3.6. End-of-life

The LPBF manufactured paper machine part module is recycled as stainless steel, similarly to the conventionally manufactured part. Since the mass of the part is reduced, less material ends up in recycling. The overall waste material amount is also reduced in the LPBF production compared to the conventional manufacturing, so the quantity of metal ending up in recycling is lower. The excess powder of the LPBF process can mostly be recycled in the process, therefore only a small proportion of it ends up in recycling (Gao et al. 2021, p. 467).

4. Life cycle assessment methodology

Life cycle assessment (LCA) is a methodology to quantify and assess the potential environmental impacts of a product or service throughout its life cycle considering raw material acquisition, production, use, end-of-life, recycling and disposal. A complete LCA study considers all of the life cycle steps of the system being studied, known as a cradle-to-grave study. Cradle-to-gate study excludes the phases after production of the part, ending the assessment to the factory gate. Furthermore, a specific part of the life cycle, like waste management, can be studied using the LCA method. LCA can be utilized to identify environmental performance improvement areas, inform decision-makers and assist them in areas such as strategic planning and process design, identify relevant environmental performance indicators, and marketing in instances like environmental claims or environmental product declarations. LCA is standardized by ISO, and it is divided into two standards; ISO 14040 and ISO 14044. ISO 14040 defines the principles and framework of LCA, while ISO 14044 sets requirements and guidelines for conducting a LCA study. (SFS-EN ISO 14040 2006.)

LCA is an iterative methodology that consists of four phases, which are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. In the first phase, goal and scope definition, the goal of the study is defined, including intended application, reasons for the study, intended audience and if the results can be used in comparative assertions disclosed to the public. Determining the scope involves setting a system boundary for the study, and defining data requirements, functional unit, allocation procedures, cut-off criteria, LCIA methodology and types of impacts considered, assumptions, and limitations of the study. System boundary defines the unit processes included in the study, frequently in the form of a flow diagram showing the processes and flows of the system. Functional unit defines and quantifies the object of the study. All the inputs and outputs of the system are referred to the functional unit, indicating the amount of product or process needed to fulfill the functional unit. In addition, functional unit ensures LCA results to be comparable. LCIA methodology and types of impacts includes choosing impact categories, category indicators and characterization models that are considered. The goal and scope phase forms a base for the LCI phase. (SFS-EN ISO 14044 2006.)

The second phase, LCI, focuses on data collection and processing. Data from the identified input and output flows of the processes is collected. The data is then calculated in relation to the functional unit, resulting in all the inputs and outputs being in reference to the functional unit. When a process is shared with other product systems, allocation may be needed. Allocation refers to dividing the inputs and outputs and therefore the environmental impact of the unit process for the products and co-products. Allocation should be avoided when possible by dividing processes into sub-processes focused only on one product, or by expanding the product system to include the co-products. If allocation cannot be avoided, it shall be conducted using physical qualities of the products, such as mass. If physical qualities are not applicable, other relations like economic value can be used. Allocation should not consider waste flows. (SFS-EN ISO 14044 2006.)

In the LCIA phase, impact categories, category indicators and characterization models are further defined. The choices need to be justified and consistent, and reflect the environmental issues of the system. Next, classification of the LCI results is conducted, assigning the results to selected impact categories. Then, category indicator results are calculated, referred to as characterization. It involves converting the LCI results to common units and aggregating the converted results of each impact category. LCIA phase has optional elements, such as normalization, grouping and weighting, which are not carried out in this study. (SFS-EN ISO 14044 2006.)

LCIA is followed by the last step, life cycle interpretation. The objective of life cycle interpretation is to draw conclusions based on the LCI and LCIA results of the study. The conclusions shall be consistent with the goal and scope of the study. The limitations of the study are also identified, and recommendations are made based on the conclusions. In the interpretation phase, completeness, sensitivity, and consistency checks are conducted. Completeness check is conducted to ensure that all relevant data for the interpretation has been considered in the study. Sensitivity check assesses the reliability of the results. Consistency check focuses on assumptions, methods and the data being consistent with the goal and scope. (SFS-EN ISO 14044 2006.)

4.1. Specifics of comparative LCA

In this thesis, the LCA is conducted to compare the performance of two different manufacturing methods, conventional and additive manufacturing. There are a few additional requirements stated in ISO 14044 for LCA studies that aim to compare two or more systems. The equivalence of the systems needs to be evaluated before analysing the results. The inclusion or exclusion of material and energy flows need to be justified for both systems. Same functional unit and methodological considerations for the systems are required to enable a fair comparison. The methodological considerations include system boundary, data quality, allocation procedures and performance. The data precision, completeness and representativeness should be examined. If there are dissimilarities between the systems being compared, they need to be identified clearly. A detailed sensitivity check and uncertainty analysis is required to further evaluate the results. The differences of the systems also need to be evaluated. (SFS-EN ISO 14044 2006.)

4.2. Previous LCA studies of LPBF

The environmental studies of metal AM have been increasing in the recent years due to its rising popularity as a manufacturing technology. Wurst et al. (2022) conducted a systematic literature review on the existing LCA studies of metal AM, specifically focusing on LPBF. As a result, they identified three main challenges regarding LCA in metal AM; 1: Lack of available data, 2: Methodological weaknesses, and 3: Limitations in knowledge of the processes. Even though different databases provide a wide range of datasets for conventional manufacturing, they lack in data considering additive manufacturing processes. This creates a need for case studies that generate knowledge to support future studies. There is no clear guidelines for LCA in additive manufacturing, and the process chain is often not well known, which is why the studies are lacking in consistency. In addition, multiple studies lack comprehensive sensitivity and uncertainty analyses, as well as consistent description of the system boundary. The lack of process knowledge is mostly caused by scarcity of long-term experience on the processes. (Wurst et al. 2022, pp. 246-247.)

Böckin & Tillman (2019) conducted an LCA study on LPBF technology in the automotive industry. The study compared the manufacturing of a truck engine with LPBF to conventional manufacturing methods, including casting and machining. The mass of the engine could be reduced with the LPBF manufacturing, even though all the parts of the engine cannot be manufactured with LPBF. Database information was used for the conventional manufacturing methods, while both atomization of material and LPBF process were modelled with estimations of the processes. The post-processing of parts was not considered, even though it can have a significant impact on the environmental impact of LPBF. The study found that while the production phase of LPBF manufacturing has a higher environmental impact compared to conventional manufacturing, the reduced mass of the engine lowered the fuel consumption in the use phase. It also highlights the importance of a clean electricity source in the LPBF manufacturing. Overall, while considering the whole life cycle, LPBF manufacturing was concluded to be a potential emissions reducing technology. (Böckin & Tillman 2019, pp. 979-986.)

Peng et al. (2020) conducted a cradle-to-gate study for a hydraulic valve body, where the design was optimized with LPBF manufacturing. The study compared conventional and LPBF manufacturing. The study considered both atomization and the LPBF process. The conventional manufacturing values were based on databases, while the atomization and LPBF process parameters were collected from producers or measured. The study shows that even without considering the use phase, LPBF can show a lower environmental impact compared to conventional manufacturing, if the part manufactured is complex. The highest environmental impact in the LPBF process was calculated for the atomization of powder due to its high argon consumption. (Peng et al. 2020, pp. 4-9.)

Landi et al. (2022) also conducted a cradle-to-gate study of LPBF compared to conventional manufacturing, specifically CNC. The case study focused on a spur gear, which was not optimized in any way with the LPBF manufacturing. The study did not include the gas consumption of the atomization of raw material, but included electricity and raw material consumption of the atomization. The study used mainly primary data for the process variables for both manufacturing routes. The study did not conclude which technology is better overall due to variation of the results in different impact categories. For instance, LPBF was deemed better in terms of climate change, resource use and human toxicity, while CNC performed better in land use and in ozone depletion. The study emphasized the need

for future studies concerning optimized designs and specific cases, as the results show uncertainties. (Landi et al. 2022, pp. 702-705.)

Overall, the previously mentioned studies show that the environmental impact of LPBF manufacturing can be lower compared to conventional manufacturing, but there are uncertainties. The most crucial factors to consider are the electricity source of the LPBF, atomization phase, and the use phase of the product, if there are significant benefits with design optimization. The studies introduced show that there is a need for more research comparing two different designs based on primary data. The benefits of LPBF can vary case-by-case, which is why further specifications are essential.

5. Comparative life cycle assessment of paper machine part module

In this chapter, a comparative life cycle assessment is conducted for the two manufacturing routes of paper machine part module. This chapter is divided into subchapters according to the first three steps of a LCA study, which are goal and scope definition, life cycle inventory analysis, and life cycle impact assessment. The last step of the LCA study, life cycle interpretation, is conducted in the next chapter.

5.1. Goal and scope definition

In this LCA study, the aim is to compare two different manufacturing routes for a paper machine part module. The manufacturing routes considered are conventional manufacturing and additive manufacturing, and the different steps of both routes were explained in the theory chapters 2 and 3. The part under study, a paper machine part module, was chosen for this study since it is a real-life case, and has primary data available for both manufacturing routes. In the previous comparative studies conducted in AM, especially the conventional manufacturing route was frequently based on secondary data. The additively manufactured paper machine part module also represents the advantages that can be achieved via AM, specifically mass reduction. Therefore, the aim is to also study if the benefits in part optimization create a chance for improving the environmental impact of a part.

The audience for this LCA is external as the study will be published in LUTPub, and is therefore publicly available. The study was commissioned by Etteplan Finland Oy, and is a part of a master's thesis. As previously mentioned, Etteplan Finland Oy is a technology service company, and therefore has no incentive to make either manufacturing method look superior. The study is conducted in accordance with ISO 14040 and ISO 14044 standards, which were examined in chapter 4. The modelling of the system is done with LCA for Experts (LCAfE) program version 10.8. LCAfE is a life cycle assessment tool created by Sphera, and it is widely used for LCA studies (Sphera 2023). Critical review will not be performed for this LCA study. As the critical review is not performed even though the study is of comparative nature, it causes a deviation from the ISO 14044 standard. The results of

this study shall not be used for comparisons to other similar products, as the consistency, validity, data requirements, and interpretation of the study are not ensured by a critical review.

The product system studied is the life cycle of a paper machine part module. The functional unit of the study is one paper machine part module produced. The functional unit ensures that the two manufacturing routes are comparable, as the mass of the part module varies between the production routes. Both manufacturing routes produce a part with the same service life and function. The service life of the part module is estimated to be 30 years, and it acts as a flow channel in a paper machine. The functional unit is specified in table 4 below.

Table 4. Functional unit specification of the paper machine part module for both manufacturing routes.

Functional unit specification	Final part mass	Service life
Conventional manufacturing route	11.1 kg	30 years
Additive manufacturing route	4.7 kg	30 years

The system boundary of the study is cradle-to-gate with end-of-life. The use phase is not considered in this study, as the differences caused by the design change in the system cannot be clearly stated, and there is no data available for the use phase. This can affect the comparability of the results. The end-of-life of the part module is assumed to be recycling. The system boundary is illustrated in figure 4, where the additive and conventional routes are depicted separately. For the conventional manufacturing route, the life cycle steps considered are raw material acquisition, machining, post-processing, transportation between the steps, and end-of-life. For the additive manufacturing route, the considered steps are raw material acquisition, gas atomization, laser powder bed fusion, machining of the conventional parts, post-processing, transportation between the steps, and end-of-life.

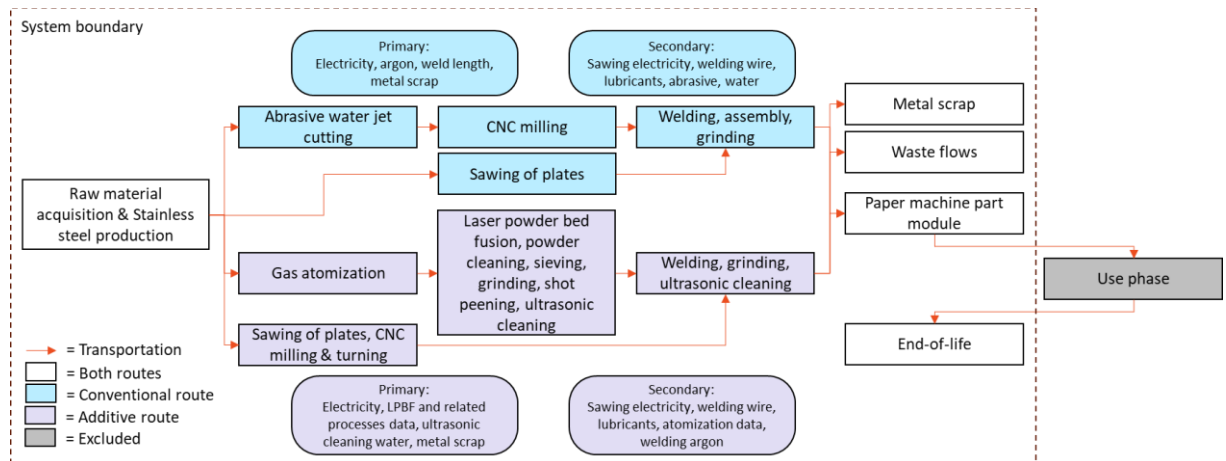


Figure 4. System boundary of the study.

Primary data was used in the study whenever possible. When primary data is not available, data from databases or scientific studies is used. The geographical area of the research is Europe, specifically Finland for the manufacturing. Atomization process is performed in Germany. When available, country-specific data for the processes is used. The primary data collected is from the years 2023 and 2024 for both manufacturing routes. Relevant technologies are covered in the data. The data received from primary sources is given per part, and the manufacturing processes have only one valuable output. Therefore, allocation is mainly avoided in this study.

As a cut-off criteria, only the flows that are expected to have a marginal effect on the impact results are excluded. The mass or energy flows are only excluded, if no appropriate data is available for both routes. Machinery production of both conventional and additive manufacturing processes are excluded, since data is not available for all the manufacturing steps.

The impact assessment methodology used in this study is EN 15804 + A1, since it is widely accepted and continually used in environmental product declarations (EPD). The choice allows both the use of EPDs and databases as a data source. EN 15804 + A1 has been renewed with EN 15804 + A2, but the older version is used to enable the use of Outokumpu EPDs for stainless steels. The Outokumpu EPDs are based on the EN 15804 + A1. The chosen impact categories for the study are global warming potential over 100 years (GWP_{100}), abiotic depletion potential for non-fossil resources (ADPE), and abiotic depletion potential for fossil resources (ADPF). The impact categories were chosen to give an

overview of the greenhouse gas emissions and resource use of both manufacturing routes. Normalization and weighting are not performed in this LCA study. Only GWP₁₀₀ is considered in the sensitivity analysis of this study.

The end-of-life of both metal scrap and the part module are calculated according to the EN 15804 + A2 standard. Avoided burdens are considered in this study to show the benefits of recycling the material. In addition, considering the credits makes comparison more fair, as the conventional manufacturing route results in a noticeable amount of recyclable scrap. To avoid double counting of the material recovery operations, the recycling operations, such as melting the steel scrap, is considered only once, in this case in the raw material side. (SFS-EN 15804 + A2 2019.) Thus, only the recycling and avoided burdens of raw materials from virgin sources is considered in this case. The recycling credit calculated for the part module is the amount of new scrap generated in the production (melted virgin material) replacing the global average steel. The global average steel uses a mix of scrap and virgin materials as a raw material. The global average steel was chosen for the credits, because the scrap is considered to end up in the global steel production cycle.

Sensitivity analysis for the results is conducted as a part of the interpretation and discussion of the results. The purpose of the sensitivity analysis is to consider the sensitivity of certain choices and assumptions made in the LCA. In this case, the generalization of the results was also studied through the sensitivity analysis. In addition, in one of the sensitivity analyses, the use phase is considered with estimated values, but the values are not linked directly to this case. The use phase difference is based on possible energy savings that the implementation of an optimized flow channel can yield.

5.2. Life cycle inventory analysis

The life cycle inventory analysis is conducted separately for the conventionally and additively manufactured paper machine part module, as the manufacturing routes differ significantly from each other. All the data considered in the study is explained, and totals of the different flows are presented. In addition, assumptions of the different life cycle steps are explained. Datasets used from databases are listed in Appendix 1.

5.2.1. Conventional manufacturing route

The conventionally manufactured paper machine part module weighs 11.1 kg when it is ready for use. The part module is the functional unit, and all the values given are per functional unit. The stainless steel material used for the conventional manufacturing of paper machine part module is assumed to be from Outokumpu EAF steel production, which is located in Tornio. According to Outokumpu data, for the hot rolled stainless steel, the average recycled steel scrap input is 71.35 % (Outokumpu 2019a), and for cold rolled stainless steel 65.2 % (Outokumpu 2019b). Amount of raw material needed to produce one paper machine part module is 34.5 kg. From this, 33.5 kg is modelled as stainless steel, hot rolled, and 0.9 kg as stainless steel, cold rolled. Steel for welding wire is assumed to be cold rolled steel. The rest, 0.1 kg, is screws for the assembly. The division of the raw material type was done based on the thickness of the plates, thicker being hot rolled and thinner cold rolled stainless steel. All of the processes in conventional manufacturing route are performed in Finnish manufacturing sites.

Manufacturing data for the conventional route was received from Valmet. The main manufacturing steps of the conventional part include AWJC, CNC milling and GTAW. The electricity consumption of each process is based on machining times and average power consumption of each process step. In addition, a number of flat plates are sawed before the assembly with a metal band saw. As a post-processing treatment, the paper machine part module is grinded with an electric grinder. The production of the machinery used in all the manufacturing steps is excluded from this study.

For AWJC, the electricity consumption was received from the producer. Electricity source is not known, so the market grid mix of Finland is used. The metal waste of AWJC is excluded, as it is estimated to be marginal, especially compared to the waste of CNC machining. The consumption of abrasive material and water is based on a LCA study by Guglielmi et al. (2021), as no primary data is available, and the power of the machinery used is similar in the study. For abrasive material, the consumption used is 0.73 kg per minute (min), and for water, 5 litres (l)/min. Sphera dataset chosen for the abrasive is Silica sand (Excavation and processing) with the geography of Germany. In reality, the abrasive used is most likely garnet, but no dataset for garnet was available. Therefore silica sand was chosen, since it can be used for abrasive water jet cutting, and has a higher environmental impact

compared to general sand -dataset. For water, dataset used is Tap water from groundwater with the geography of Europe. The mix of the abrasive material and water is expected to end up in the local wastewater treatment facility. For wastewater treatment, the dataset chosen is Municipal wastewater treatment (sludge incineration) with the geography of Europe.

CNC milling and sawing of the plates is done in a different location than AWJC. For CNC milling, both the electricity consumption and amount of steel waste was received from the producer. The amount of lubricating oil, compressed air, and water needed in the milling is taken from Ecoinvent dataset of Chromium steel milling, average with the geography of Europe, as no primary data is available. For lubricating oil, dataset used is Lubricants at refinery, with the geography of Europe and for compressed air Compressed air 7 bar (medium power consumption). Electricity grid mix for Finland is used for both the CNC process electricity and compressed air production. Water consumption is included in the Ecoinvent dataset as non-tracked flow, so it is not modelled separately. The lubricating oil waste treatment is modelled with Ecoinvent dataset of Treatment of waste mineral oil, hazardous waste incineration, with energy recovery, with the geography of Europe without Switzerland. For the sawed metal plates, the electricity consumption of the band saw was not received from the producer, but estimated with a general metal band saw power and cutting time. The estimated power is 550 watts (W), with 0.05 hour (h) cutting time. The metal waste of sawing is not considered, as it is a marginal flow and no data is available. Electricity source for both processes is not known, so the grid mix of Finland is used.

Assembly and post-processing of the part is done in the last manufacturing location. For GTAW, in addition to the electricity consumption, an estimation of argon gas consumed and the total weld length was received from Valmet. With the weld length, the consumption of the filling material of welding is estimated using a Sphera dataset of Steel sheet (1mm) MAG welding. Welding slag formed in the process is excluded, as it is a minor flow and no valid data to model the treatment is available. For the welding wire, wire drawing process is excluded, as it is expected to have an insignificant impact due to low consumption of the wire. The welding wire input is modelled with Outokumpu cold rolled coil. Argon production is modelled with Sphera dataset of Argon (gaseous) with the geography of Germany, as no other geographies are available. The screw production for the part module assembly is also included, but transportation of the screws was excluded. Sphera dataset used for the screws is Fixing material screws stainless steel with the geography of Europe.

For grinding, electricity consumption was received from the producer, and the waste material treatment is not considered. The electricity source for these processes is nuclear energy. Therefore, Sphera dataset of Electricity from nuclear energy with the geography of Finland is used.

The total amount of stainless steel scrap produced in the conventional route is 23.4 kg, and the total electricity consumption is 235 kilowatt hours (kWh) with a cradle-to-gate boundary. CNC milling causes all of the scrap waste in the conventional manufacturing route. The scrap treatment is modelled correspondingly to EoL treatment, which is described later. Most of the electricity is consumed in AWJC and CNC milling. Other flows include argon, lubricant for machining, water and abrasive material. The life cycle inventory of the conventionally manufactured paper machine part module is summarized in table 5. For confidentiality reasons, no further numbers of the data are disclosed, although the data was received from Valmet by process.

Table 5. Life cycle inventory of the conventional manufacturing steps. The paper machine part module is not shown in the table, only the variable flows are shown.

Process	Input	Data source	Output	Data source
AWJC	Abrasive material	Guglielmi et al. 2021	Recyclable scrap	Excluded
	Electricity	Primary	Water & abrasive mix	Calculated
	Water	Guglielmi et al. 2021		
Sawing	Electricity	Estimated	Recyclable scrap	Excluded
CNC milling	Compressed air	Ecoinvent dataset	Recyclable scrap	Primary
	Electricity	Primary	Waste oil	Ecoinvent dataset
	Lubricating oil	Ecoinvent dataset		
	Water	Ecoinvent dataset		
GTAW	Argon	Primary	Argon to air	Primary
	Electricity	Primary	Recyclable scrap	Excluded
	Welding wire	Sphera dataset		
Grinding	Electricity	Primary	Recyclable scrap	Excluded

Use phase is not included in the base LCA, other than the transportation to a general user. 100 % of both the scrap and the part module in end-of-life is expected to be recycled. The scrap treatment and EoL treatment choices were explained in the Goal and scope -chapter. Dataset chosen for the scrap melting is Steel Engineering steel (2019) from Worldsteel with the geography of European Union, since the input of the process is fully scrap based. The

chosen process for the recycling credits is Steel hot rolled coil with global geography, as the steel is thought to replace global average production.

All the relevant transportations are included in the conventional manufacturing route. Only the auxiliary material transports are excluded. First, the stainless steel material is transported to the first manufacturing site. As there are multiple manufacturing sites in the conventional manufacturing route, transportation between the sites is considered. The manufactured part module is transported to post-treatment site after manufacturing, and from there to a general customer location. From the customer, the part is transported to EoL treatment. In addition, the transportation of waste materials is considered with general values. Estimated distance to the waste treatment is 100 km for the waste produced in the manufacturing steps. Wastewater is expected to be transported through sewage pipes, and therefore the transportation was not separately modelled for the wastewater. The EURO classification of the transportation was assumed to be 5, as the trucks used in Europe are relatively new. For the main transportation, truck-trailer with 22 t payload was used. For waste transportation, a truck with 11 t payload was used, as waste generally transported with smaller trucks. Transportation distances and their source (primary or assumption) for the manufacturing are presented in table 6.

Table 6. Transportation distances of conventional manufacturing route.

Location	Processing steps	Distance to next location	Primary or assumption
1	Raw material production (steelmaking)	475 km (location 2) 625 km (location 3, raw material for sawing)	Primary (with estimated steel producer)
2	Abrasive water jet cutting	150 km	Primary
3	CNC milling, sawing of plates	150 km	Primary
4	Assembly, welding, grinding	250 km	Assumption
5	Use	100 km	Assumption
6	End of life	-	-

5.2.2. Additive manufacturing route

The additively manufactured paper machine part module weighs 4.7 kg. The raw material source of the additive manufacturing route is expected to be the same as for conventional

manufacturing, from Outokumpu EAF steel production. The raw material was chosen to be identical since no primary data is available, and to make the manufacturing phase of the paper machine part module more comparable. The difference in the raw material manufacturing is that the stainless steel requires atomization before LPBF manufacturing. The gas atomization process is done in Germany, with the raw material of hot rolled stainless steel. Other manufacturing steps are performed in Finland. As discussed in chapter 2.3. the additively manufactured paper machine part module has two conventionally manufactured parts in the design. The manufacturing of these parts is also considered in this LCA. The raw material for the conventional parts is cold rolled stainless steel. Similarly to conventional manufacturing route, the production of machinery is excluded to ensure comparability.

For the two conventionally manufactured parts, they are first sawed. No data of the sawing is available, so the same assumptions were used as in conventional manufacturing route. The assumed cutting time is 0.1 h as the cutting length is doubled. The assumed band saw power is 550 W. The parts are manufactured with CNC machining. Electricity consumption and stainless steel scrap amount was received from Valmet. Electricity source is not known, so grid mix of Finland was used. The rest of the data, including lubricating oil, water, and compressed air, was taken from the Ecoinvent dataset of Chromium steel milling, average with the geography of Europe.

For the gas atomization process, primary data was not received from the producers. Therefore, the values are taken from a scientific study by Peng et al. (2020). Following estimations are used: argon consumption of 3.5 m³/kg, electricity consumption of 2 kWh/kg, cooling water consumption of 280 l/kg. All the values are given per kilogram of fine powder, and the yield of fine powder is set to 85 % of the input. Water and treatment of wastewater are modelled with the same datasets as in conventional manufacturing route. Peng et al. (2020) treated the material not suitable for LPBF as solid waste, so a similar assumption was done in this study. The treatment of the waste is modelled with Sphera dataset Ferro metals on landfill, with the geography of Europe. The atomization phase is further focused on in the sensitivity analysis of this study.

The LPBF process, powder cleaning, sieving, initial grinding with compressed air grinder, shot peening and ultrasonic cleaning of the part is done in the same location. For these processes, primary data was received for a lower mass paper machine part module than the one considered in this study. All of the processes are performed for two part modules at the

same time, and therefore the received data was divided by two. The received data was then scaled to match the production of the paper machine part module under study. Scaling of the data was done in cooperation with the manufacturer, utilizing their expertise. The different ratios for scaling were chosen based on the interdependence of the factors as estimated by the manufacturing operator.

For the LPBF process, primary data was received for consumptions of argon, compressed air, and electricity, as well as amount of waste material and laser condensate generated. Argon consumption was received directly for the part under study, based on the printing time. Compressed air and printing electricity are scaled with printing time ratio. Electricity consumed in the preparation and disassembly and cleaning of the LPBF machine was not scaled, as it is assumed to stay constant between prints. The amount of laser condensate formed in the printing process is scaled with the lasered volume ratio. Waste material from disassembly and cleaning of the machinery was not scaled, as it is assumed to stay constant. The electricity used is from renewable sources, so 50-50 mix of Electricity from wind power and Electricity from hydro power with the geography of Europe was used. Wind power and hydro power were chosen for the renewable electricity due to their abundance. For argon and compressed air, the same datasets were used as in conventional manufacturing route. Laser condensate is considered to be easily flammable waste, so it cannot be recycled. The condensate is assumed to end up in incineration, which is modelled with Ferro metals in waste incineration with the geography of Europe. Other metal waste of the LPBF process is assumed to end up in landfill, as it is not separately collected for recycling. The dataset used for landfilling is the same as in atomization.

For the post-processing conducted in the LPBF manufacturing site, datasets used for electricity, compressed air, and non-recyclable waste are the same as for the LPBF process. For powder cleaning, data of compressed air, electricity and waste was received. The data was not scaled, as the process is the same for both part module sizes. The metal waste is not separately collected in the powder cleaning process. For the sieving of the material not lasered in the LPBF process, electricity consumption and the amount of powder that is recycled was received. Electricity consumption was not scaled between the part module sizes, as the sieving time is fairly constant. The amount of sieving scrap for recycling was scaled with the printing time ratio. For grinding, compressed air consumption and material losses were received. The data was scaled with mass ratio. The scrap material is not

separately collected, and therefore modelled to end up in a landfill. For shot peening, compressed air and electricity consumption was received. Data was scaled with the mass ratio, and scrap is expected to end up in a landfill. The shot peening material is not considered in this study, as the consumption of the material is marginal and can be reused multiple times. For ultrasonic cleaning, electricity and water consumption was received. The cleaner liquid is excluded from this study, as the consumption is low. Ultrasonic cleaning data was not scaled, as the process does not change between the part module sizes. Datasets used for water consumption and wastewater treatment are the same as in conventional manufacturing route.

Lastly, the part is assembled, grinded, and again cleaned using ultrasonic cleaning in the next location. Electricity source of these steps is not known, so grid mix of Finland is used. GTAW is used to assemble the LPBF manufactured part to the conventional parts. For the GTAW welding, the electricity consumption and the length of the weld was received from the producer. The argon consumption was not received, so the consumption was scaled based on the length of the weld, using the value received for the conventional manufacturing route. The grinding is done with a compressed air grinder. The amount of compressed air used was calculated based on the grinding time and air consumption of the grinder. The waste generated in grinding is excluded. For the final ultrasonic cleaning, only the electricity consumption is considered, as no data about the water consumption is available.

Total material consumption of the additive manufacturing route is 8.2 kg, from which 4.6 kg is used as a raw material for atomization. The rest, 3.6 kg, is used as a raw material for the conventional parts of the part module assembly, and includes the welding wire consumption. Total electricity consumption of the additive manufacturing route is 137 kWh. The LPBF process and final grinding of the part module require most of the electricity. The high electricity consumption of the grinding is explained by high compressed air consumption. Total amount of metal scrap is 3.5 kg, from which 1.8 kg is assumed to end up in recycling. Other flows of the additive manufacturing route include argon, water, compressed air, and water. The life cycle inventory of the additive manufacturing route is summarised in table 7. As in the conventional manufacturing route, for confidentiality reasons, no further numbers of the data are disclosed. The flows that were scaled using ratios of printing time, lasered volume, or mass are marked with * in the table.

Table 7. Life cycle inventory of the additive manufacturing steps. Scaled flows are marked with *. Recyclable scrap refers to scrap that ends up in recycling, and scrap losses to incinerated or landfilled metal scrap. The paper machine part module is not shown in the table, only the variable flows are shown.

Process	Input	Data source	Output	Data source
Atomization	Argon	Peng et al. 2020	Argon to air	Peng et al. 2020
	Electricity	Peng et al. 2020	Powder	Peng et al. 2020
	Water	Peng et al. 2020	Water	Calculated
LPBF	Argon	Primary	Laser condensate*	Primary
	Compressed air*	Primary	Scrap losses	Primary
	Electricity*	Primary		
Powder cleaning	Compressed air	Primary	Scrap losses	Primary
	Electricity	Primary		
Sieving	Electricity	Primary	Recyclable scrap	Primary*
Grinding	Compressed air*	Primary	Scrap losses	Primary*
Shot peening	Compressed air*	Primary	Scrap losses	Primary*
	Electricity*	Primary		
	Peening material	Excluded		
Ultrasonic cleaning	Cleaner liquid	Excluded	Water	Primary
	Electricity	Primary		
	Water	Primary		
CNC milling	Compressed air	Ecoinvent dataset	Recyclable scrap	Primary
	Electricity	Primary	Waste oil	Ecoinvent dataset
	Lubricating oil	Ecoinvent dataset		
	Water	Ecoinvent dataset		
GTAW	Argon	Primary (from conventional route)	Argon to air	Primary (from conventional route)
	Electricity	Primary	Recyclable scrap	Excluded
	Welding wire	Sphera dataset		
Grinding	Compressed air	Primary	Recyclable scrap	Excluded
Ultrasonic cleaning (final)	Cleaner liquid	Excluded	Water	Excluded
	Electricity	Primary		
	Water	Excluded		

For the recyclable scrap treatment and EoL treatment of the additively manufactured paper machine part module, same choices and datasets are used as in conventional manufacturing route. For the scrap losses, the treatment chosen is landfilling, and for laser condensate, incineration.

For the use phase, only the transportation to a general user is considered. Correspondingly to the conventional route, all the relevant transportations are considered in the additive manufacturing route. The stainless steel for the two conventional part manufacturing is

transported from Outokumpu to the first manufacturing site. One of the conventionally manufactured parts is then transported to the LPBF manufacturing site, while the other is transported straight to the assembly site. The stainless steel for atomization is transported from Outokumpu to Germany with a roll-on-roll-off (ro-ro) ship from Outokumpu to Hamburg port. From the port, the steel is transported to the manufacturing site with a truck. After atomization, the powder is manufactured from the manufacturing site back to the Hamburg port with a truck, and from there to Helsinki port with a ro-ro ship. Then, the powder is transported with a truck to the additive manufacturing site. After the LPBF process and related processes, the part is transported to the assembly and post-processing site, and from there to a general customer location. Lastly, the part is transported to an estimated EoL treatment facility. All the waste generated during production is also transported to treatment sites, with the estimated distance of 100 km. Similarly to conventional manufacturing route, wastewater is expected to be transported through sewage pipes, and therefore the transportation was not separately modelled for the wastewater. The assumptions are the same as in the conventional route, EURO 5 trucks with 22 t payload in main transportations, and 11 t payload for waste transportations. The transportation distances are summarized in table 8.

Table 8. Transportation distances of additive manufacturing route.

Location	Processing steps	Distance to next location	Primary or assumption
1	Raw material production (steelmaking)	420 km (location 2) 2760 km (location 3, 800 km truck, 1960 km ro-ro ship)	Primary (with estimated steel producer)
2	CNC milling and turning	150 km (location 4) 250 km (location 5)	Primary
3	Gas atomization	2400 km (1070 km truck, 1330 km ro-ro ship)	Primary
4	Laser powder bed fusion, related processes	130 km	Primary
5	Assembly, post-processing	250 km	Assumption
6	Use	100 km	Assumption
7	End of life	-	-

5.3. Life cycle impact assessment

The three impact categories chosen for the assessment are GWP_{100} , ADPE and ADPF. The subchapters are divided accordingly, and the results of both manufacturing routes are presented in the same figure for each impact category.

5.3.1. Global warming potential over 100 years

Global warming potential over 100 years (GWP_{100}) quantifies the greenhouse gas (GHG) emissions associated with the manufacturing of paper machine part module. The unit of GWP_{100} is kilograms of carbon dioxide equivalent ($kg\ CO_2\ eq.$). GHG emissions cause climate change, which is currently one of the most crucial phenomenon worldwide. Results of GWP_{100} are presented in figure 5 below for both manufacturing routes.

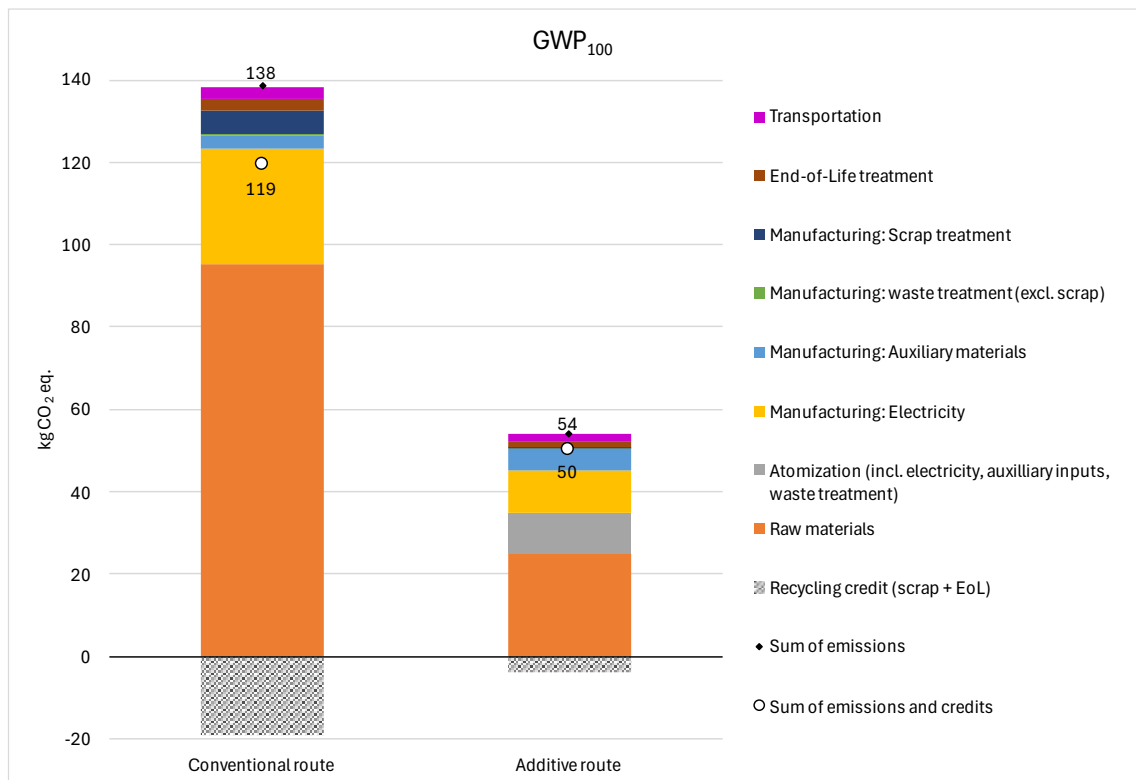


Figure 5. GWP_{100} results for the conventional and additive manufacturing routes.

In figure 5, GWP₁₀₀ of the conventional manufacturing route is presented on the left. In the conventional manufacturing route, raw materials have the largest impact, accounting for 69 % of the emissions. A large amount of metal scrap is generated in the conventional manufacturing route, increasing the impact of raw materials. In addition, manufacturing electricity has a noticeable impact on the GWP₁₀₀, accounting for 20 % of the emissions. Specifically, the electricity consumption of AWJC and CNC milling is high, and due to the electricity source of the steps being grid mix of Finland, they cause majority of the GWP₁₀₀ impact of the manufacturing electricity. The total credits of scrap and EoL recycling is -19 kg CO₂ eq., resulting in 119 kg CO₂ eq. of sum of emissions and credits.

GWP₁₀₀ results of the additive manufacturing route are presented on the right in figure 5. Similarly to the conventional manufacturing route, raw materials have the largest impact on GWP₁₀₀ in the additive manufacturing route, accounting for 46 % of the emissions. Atomization of the raw materials for LPBF accounts for 18 % of the emissions in GWP₁₀₀. The Atomization -category covers all the related processes to atomization, including argon, electricity and water consumption, as well as the related waste treatment. Atomization has a high impact primarily due to the argon and electricity consumption. The total manufacturing electricity accounts for 19 % of the emissions. Majority of the impact of electricity consumption is caused by the compressed air grinding of the part module. The electricity source of the compressed air production for grinding is not known, so it is expected to be the grid mix of Finland. While the electricity consumption of LPBF is also high, the impact to GWP₁₀₀ is low due to the electricity being from renewable sources. The impact of auxiliary materials is 10 % of the total GWP₁₀₀, mostly caused by the argon consumption in the LPBF process. The total recycling credits of scrap and EoL recycling is -4 kg CO₂ eq. in the additive manufacturing route, making the sum 50 kg CO₂ eq. with the credits considered. The impact of the two conventionally manufactured parts in the additive manufacturing route, including raw materials and CNC machining, accounts for 26 % of the sum of emissions and credits.

As can be seen from the figure 5, the additive manufacturing route has a lower GWP₁₀₀ than the conventional manufacturing route, regardless whether the recycling credits are included or excluded. If the credits are excluded, the additive manufacturing route has 61 % lower impact, and if they are included, 58 % lower impact on GWP₁₀₀ compared to the conventional manufacturing route. Conventional route has a higher recycling credit due to

more scrap produced. The atomization process is only present in the additive manufacturing route, increasing its emissions. The difference between the emissions of the routes is mainly caused by the raw material consumption, and electricity consumption and source.

5.3.2. Abiotic depletion potential for non-fossil resources

Abiotic depletion potential for non-fossil resources (ADPE) covers the use of metals and minerals. The unit of ADPE is kilograms of antimony equivalent (kg Sb eq.). ADPE takes into consideration the annual production and the ultimate reserve of a resource. (Oers et al. 2019, p. 294.) The impact category was chosen to present the differences in resource use of the two different manufacturing routes. Results of ADPE are shown in figure 6 below for both manufacturing routes.

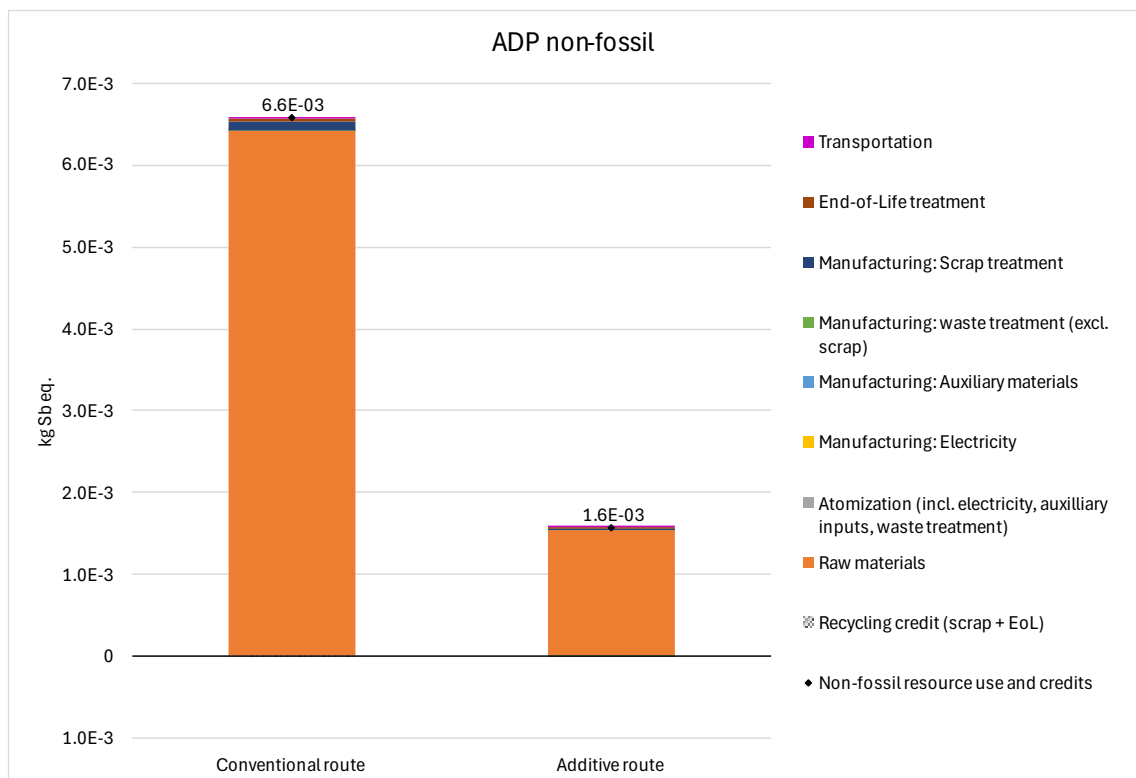


Figure 6. ADPE results for the conventional and additive manufacturing routes.

In figure 6, the non-fossil resource use without credits is not shown separately, as the value is approximately equal to the non-fossil resource use and credits. The recycling credit is insignificant because of dataset differences between the dataset used for stainless steel production and the dataset of steel that is being substituted in the credits. The likely reason for the difference is that the steel that is substituted in the credits is general hot rolled steel, while the raw material used is stainless steel. Generally, stainless steel has a lot of rare metals with a high characterization factor mixed with iron, making its ADPE per kg of steel significantly higher compared to general steel. For example, for iron the characterization factor is $5.24\text{E-}8$ kg Sb eq./kg while for chromium the characterization factor is $4.43\text{E-}4$ kg Sb eq./kg.

For the conventional manufacturing route, the results are on the left in figure 6. The raw materials account for 98 % of the ADPE. The raw material of the paper machine part module is stainless steel, explaining the high impact of raw materials in the ADPE result. Scrap treatment accounts for approximately 1.6 % of the ADPE. Sum of ADPE and credits in the conventional manufacturing route is $6.6\text{E-}03$ kg Sb eq.

Results of the additive manufacturing route are presented on the right in figure 6. The affecting factors for the additive manufacturing route are similar, with raw materials accounting for 97 % of the ADPE, and EoL treatment for 1.4 % of the ADPE. The high impact of raw materials is explained with the raw material being stainless steel, similarly to the conventional manufacturing route. Non-fossil resource use and credits in the additive manufacturing route is $1.6\text{E-}03$ kg Sb eq. Compared to the conventional manufacturing route, the ADPE of the additive manufacturing route is 76 % lower, mainly due to the reduced use of raw materials.

The impact of the two conventionally manufactured parts in the additive manufacturing route, including raw materials and CNC machining, accounts for 54 % of the ADPE of additive manufacturing route. The impact is high due to almost half of the raw materials being used for the manufacturing of the two conventional parts.

5.3.3. Abiotic depletion potential for fossil resources

The abiotic depletion potential for fossil resources (ADPF) considers all fossil resources used in the production with a net calorific value. The unit of ADPF is megajoules (MJ). The ADPF of the two manufacturing routes is presented in figure 7.

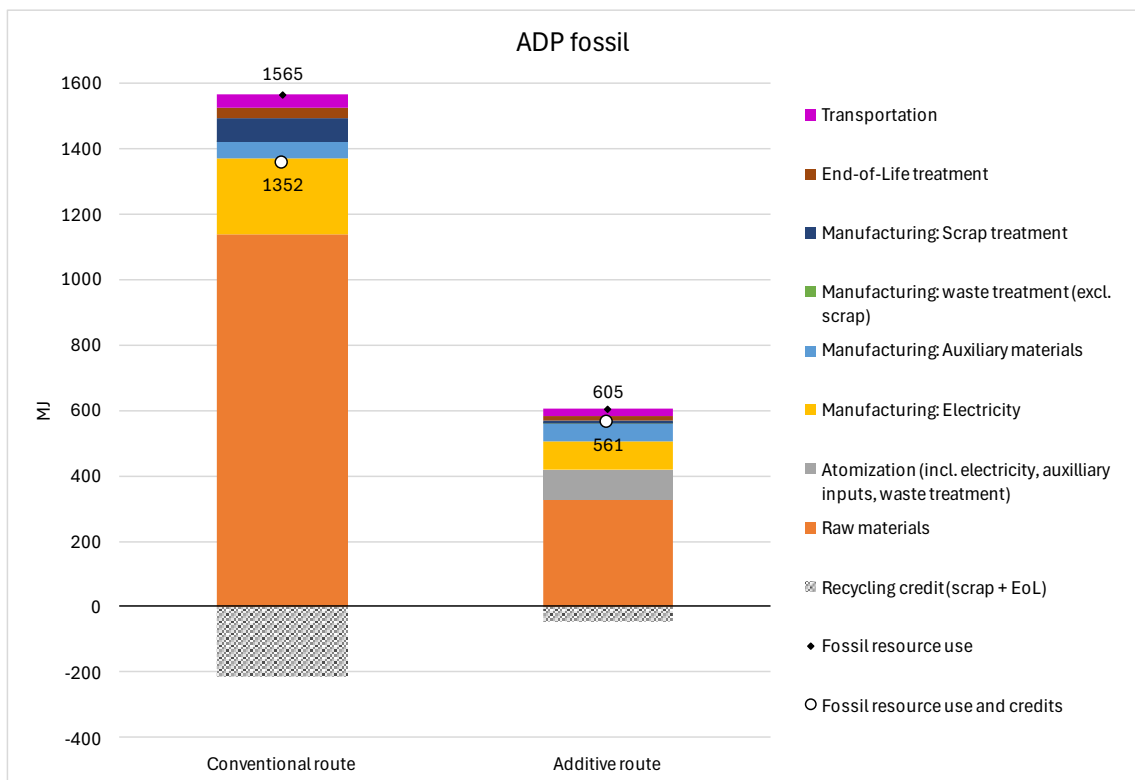


Figure 7. ADPF results for the conventional and additive manufacturing routes.

For the conventional route, results are presented on the left in figure 7. Raw materials account for 73 % of the ADPF. The high impact of raw materials is explained by the energy intensive process of stainless steel making, as well as the use of fossil resources in the manufacturing process. Manufacturing electricity accounts for 15 % of the impact, caused by the fossil fuel use in the electricity production. The total fossil resource use of the conventional manufacturing route is 1565 MJ. The credit of metal scrap and EoL recycling is -212 MJ, resulting in 1352 MJ of fossil resource use and credits.

In the additive manufacturing route, on the right in figure 7, raw materials account for 55 % of the ADPF, and atomization for 15 %. High effect of the raw materials is caused by the same reasons as in conventional manufacturing route, while the impact of atomization is caused by argon and electricity consumption. Manufacturing electricity consumption accounts for 14 % of the ADPE, caused by the use of fossil fuels in the electricity production. Auxiliary materials of manufacturing have the contribution of 9 %, mostly caused by the argon used in the LPBF process. The fossil resource use of the additive manufacturing route is 605 MJ and with the recycling credit of -44 MJ, fossil resource use and credits is 561 MJ. The two conventionally manufactured parts account for 26 % of the total ADPE of the additive manufacturing route, including raw materials and CNC machining.

Similarly to the previous impact categories, additive manufacturing route has a lower impact on the ADPF. The lower impact is explained by decreased resource use, and the renewable electricity source of the LPBF manufacturing step. The impact of auxiliary materials is higher in additive manufacturing due to increased argon consumption in the production. The fossil resource use of additive manufacturing route is 61 % lower compared to the conventional manufacturing route, and fossil resource use and credits is 59 % lower.

6. Result interpretation and discussion

In this chapter, the results of the LCI and LCIA are interpreted. First, sensitivity analysis is performed for a set of factors. In addition, break-even points for certain factors are studied. After the sensitivity analysis, the completeness and consistency of the LCA is evaluated.

6.1. Sensitivity analysis

The focus of the thesis is in comparing the manufacturing routes, and the factors studied in the sensitivity analysis are chosen accordingly. For this reason, raw materials were not chosen for the sensitivity analysis, even though they have the largest contribution in the GWP₁₀₀ results in both manufacturing routes. However, it is important to note that in reality, differences in raw material feedstocks can cause a significant difference in the GWP₁₀₀ results. If one of the manufacturing routes uses a scrap based feedstock while the other uses virgin based feedstock, the GWP₁₀₀ results change significantly.

For the conventional manufacturing route, sensitivity analysis is conducted for the electricity source of manufacturing. The base scenario is compared to a scenario where all the electricity used in manufacturing is from renewable sources, specifically 50 % wind and 50 % hydropower. Analysis of changing all the manufacturing electricity to grid mix was not conducted, as the major electricity consuming processes, AWJC and CNC, are assumed to use market grid mix electricity already in the base scenario. Other clear factors to adjust were not found in the conventional manufacturing route. The amount of metal scrap generated in the production is considered in the break-even chapter. The factors of base scenario and sensitivity analysis for the conventional manufacturing route are shown in table 9.

Table 9. Sensitivity scenarios of the conventional manufacturing route. Compared to base scenario, modified values are shown in light blue, unmodified values with light grey.

Conventional manufacturing	AWJC electricity	CNC electricity	Sawing electricity	Welding electricity	Grinding electricity
Base Scenario	Grid mix	Grid mix	Grid mix	Nuclear power	Nuclear power
Renewable electricity	Renewable	Renewable	Renewable	Renewable	Renewable

For the additive manufacturing route, four sensitivity analyses are performed. Impact of manufacturing and atomization electricity is studied by two analyses, first changing all of the electricity used to renewable electricity and then to market grid mix electricity. For atomization, the grid mix of Germany is used, and for others, the grid mix of Finland is used. The uncertainty of atomization is considered by changing the yield of atomization to 60 %. The yield percentage was chosen based on Teubler et al. (2019), as they used 60 % as a conservative evaluation for atomization. Literature presents multiple different values for atomization yield, and therefore the factor has been considered in the sensitivity analysis. Lastly, the impact of the final grinding process is studied. In the sensitivity analysis, the compressed air grinding is changed to electric grinding. The compressed air grinding had a large effect on the results, and therefore it has been investigated further. In reality, the grinding could be done with an electric grinder instead. Electric grinding is modelled based on the grinding process of conventional manufacturing, and scaled based on the grinding time. The factors of the base scenario and all the sensitivity analyses are shown in table 10.

Table 10. Sensitivity scenarios of the additive manufacturing route. Compared to base scenario, modified values are shown in light blue, unmodified values with light grey.

Additive manufacturing	Atomization electricity	LPBF & post-processing electricity	Sawing electricity	CNC electricity (conventional parts)	Finishing electricity	Atomization yield (%)	Grinding (compressed air/electric)
Base Scenario	Grid mix	Renewable	Grid mix	Grid mix	Grid mix	85	Compressed air
Renewable electricity	Renewable	Renewable	Renewable	Renewable	Renewable	85	Compressed air
Grid mix electricity	Grid mix	Grid mix	Grid mix	Grid mix	Grid mix	85	Compressed air
Atomization: 60 % yield	Grid mix	Renewable	Grid mix	Grid mix	Grid mix	60	Compressed air
Manufacturing: Electric grinder	Grid mix	Renewable	Grid mix	Grid mix	Grid mix	85	Electric

The results of the sensitivity analysis are presented in figure 8 below. In figure 8, base scenario results for both the conventional and additive manufacturing route are shown in a different color. The number shown in figure 8 for each scenario is the sum of emissions and credits.

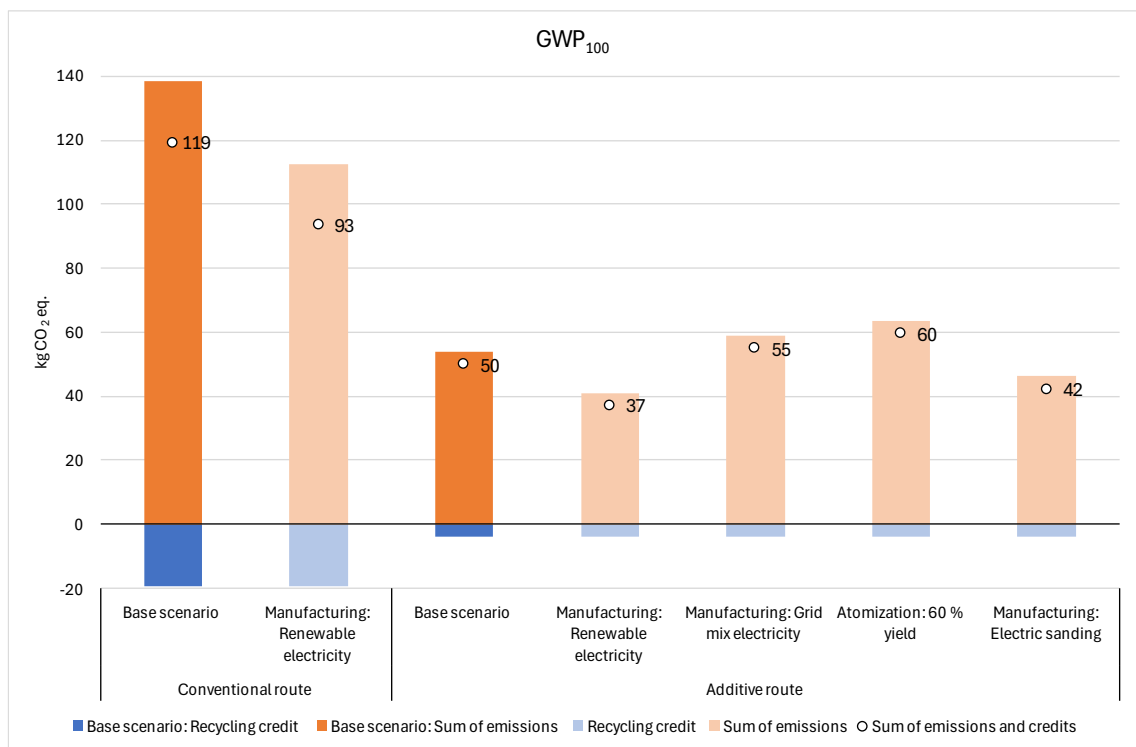


Figure 8. Results of the sensitivity analysis.

By changing all the electricity used in the conventional manufacturing route to renewable electricity, the GWP_{100} is 22 % lower compared to the base scenario of conventional manufacturing. The reduction is significant, but the GWP_{100} of the base scenario of additive manufacturing is still 47 % lower compared to the conventional manufacturing with renewable electricity.

If all the electricity used in additive manufacturing is changed to renewable electricity, the GWP_{100} is 26 % lower compared to the base scenario of additive manufacturing. The reduction seems significant, but most of the reduction is caused by the change of compressed air grinder electricity source. Therefore, if the compressed air grinding can be replaced by electric grinding, the reduction would not be as significant. If all the manufacturing electricity is changed to grid mix electricity, the GWP_{100} value increases by 10 % compared to base scenario of additive manufacturing. The increase is mainly due to the LPBF electricity source changing from renewable sources to grid electricity.

If atomization yield is changed from 85 % to 60 %, electricity, argon, water and raw materials consumption of atomization increases. The increase of GWP_{100} is 19 % compared to the base scenario of additive manufacturing. If the grinding process is changed from compressed air grinder to an electric grinder, the electricity consumption of manufacturing decreases. The decrease in electricity consumption causes a GWP_{100} decrease of 15 % compared to the base scenario of additive manufacturing.

6.1.1. Break-even points

In addition to the sensitivity analysis above, break-even points for the two manufacturing routes of the paper machine part module are studied for two parameters: metal scrap reduction of the conventional manufacturing route, and mass increase of the part module in the additive manufacturing route. The finding of the break-even points are shown in figure 9 below. The GWP_{100} values of emissions and credits are read from the left axis in kg CO_2 eq., while the mass of metal scrap or final part are read from the right axis in kg.

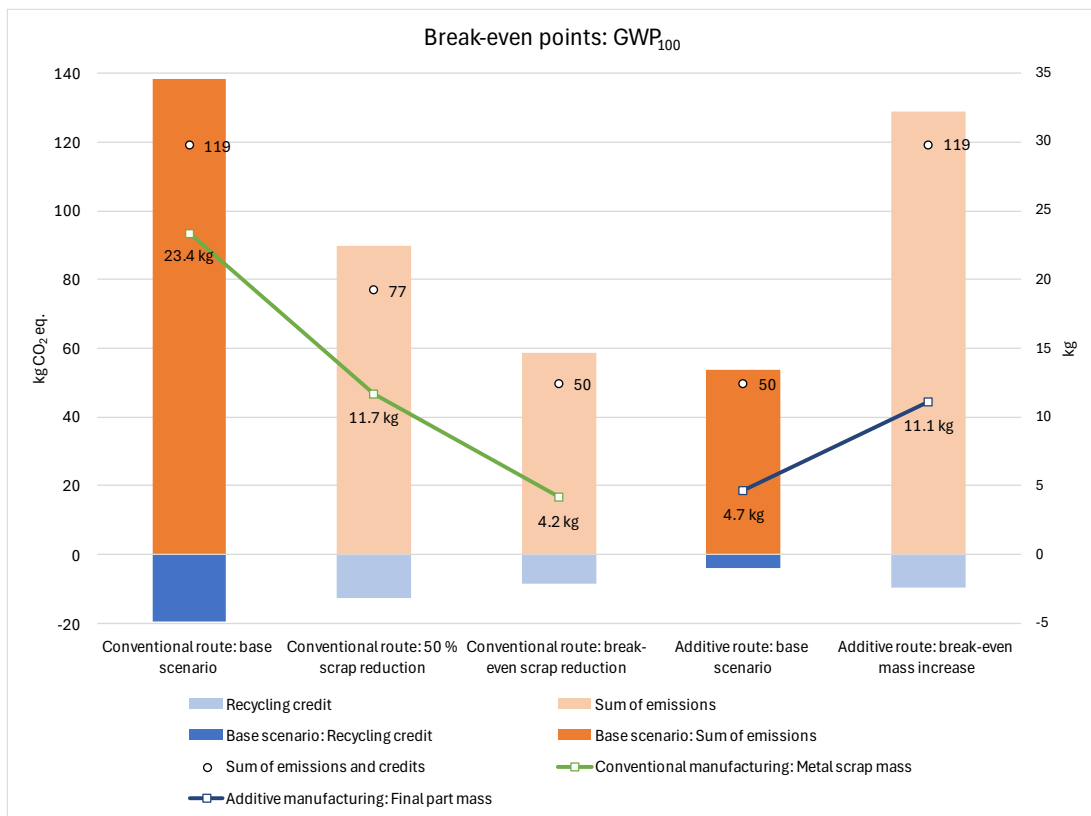


Figure 9. Results of the break-even points.

The reduction of metal scrap reduces the amount of CNC machining and AWJC processes, as well as the amount of raw materials needed in the production. If the metal scrap generation is reduced by 50 % or 11.7 kg, the GWP₁₀₀ sum of emissions and credits is 77 kg CO₂ eq. The reduction is 35 % compared to the base scenario of conventional manufacturing. To break even with the base additive manufacturing scenario, the emissions of the conventional manufacturing scenario would need to reduce by 58 %. To achieve this, the scrap reduction required is 19.2 kg. This corresponds to a reduction of 82 % compared to the base scenario of conventional manufacturing. In reality, the break-even point of metal scrap reduction would require significant changes in the production technologies or alternatively in the part design.

The mass increase of additively manufactured paper machine part module increases the GWP₁₀₀ of all the life cycle steps. The raw material consumption is increased, more raw material needs to be atomized, the manufacturing steps require more electricity and auxiliary materials, transported masses increase, and more scrap needs to be treated. With the mass increase of 6.6 kg, the sum of emissions and credits of the additively manufactured part

module is the same as for the conventionally manufactured part. The increase in mass is 143 % compared to the base additive manufactured part module mass. Coincidentally, the mass of the additively manufactured part module is then the same as for the conventionally manufactured part module, 11.1 kg. The part mass for the break-even point is dependent on different factors, such as electricity source, manufacturing processes, and amount of metal scrap generated. In reality, if the volume of the additively manufactured part module increased significantly, only one part could be manufactured at a time, increasing the manufacturing consumptions per part. This was not considered in this sensitivity analysis. In addition, the ratio of LPBF manufactured and conventionally manufactured fractions of the additively manufactured part module were kept constant, affecting the break-even point. Thus the break-even point would not be the same part mass in different cases.

6.1.2. Use phase

For the use phase, possible energy savings are evaluated using general values. The values are completely hypothetical, and are not linked to the paper machine part module, but show the possible benefits of part optimization. The use phase calculations are based on a thesis by Kuhn (2002). The measured pump efficiency was 68 % on average in a year (a) when the pump was in use. The total energy consumption of the pump was 845 MWh in a year, and therefore the total power outage of the pump was 575 MWh/a. (Kuhn 2002, pp. 36-37). The increase in efficiency was calculated for three different values: increase of 0.25 percentage points (%pt.), resulting in energy consumption of 842 MWh/a, increase of 0.5 %pt., resulting in energy consumption of 839 MWh/a, and increase of 1 %pt., resulting in energy consumption of 833 MWh/a. The energy savings were calculated as the difference of initial energy consumption and the increased efficiency energy consumption.

Since the energy savings are calculated in a yearly basis, the sum of emissions and credits of the manufacturing routes were also calculated per year. The service life of the paper machine part module is estimated to be 30 years, so the sum of emissions and credits was divided by 30 to get the GWP_{100} value per year for both manufacturing routes. The summary of the calculations is shown in table 11.

Table 11. Summary of the use phase calculations. Energy input corresponds to the input needed to produce 575 MWh of pumping power.

Use phase	Efficiency [%]	Energy input [MWh]	Energy savings [MWh/year]	Manufacturing: Sum of emissions [kg CO ₂ eq. / year]
Conventionally manufactured flow channel	68	845	-	4
Additively manufactured flow channel	68.25	842	-3	2
	68.5	839	-6	2
	69	833	-12	2

The impact of the energy savings to GWP₁₀₀ were modelled with electricity grid mix of Finland. The savings are shown as a negative in the figure 10. As can be seen from the figure below, the use phase can have a substantial impact on the results. Even a minor increase in energy efficiency can result in significant energy savings. The energy savings of 0.25 % efficiency increase result in -376 kg CO₂ eq./a, while the impact of additive manufacturing is only 2 kg CO₂ eq./a. With 0.5 % efficiency increase, the effect of energy savings on GWP₁₀₀ is -749 kg CO₂ eq./a and with 1 % efficiency increase, -1486 kg CO₂ eq./a.

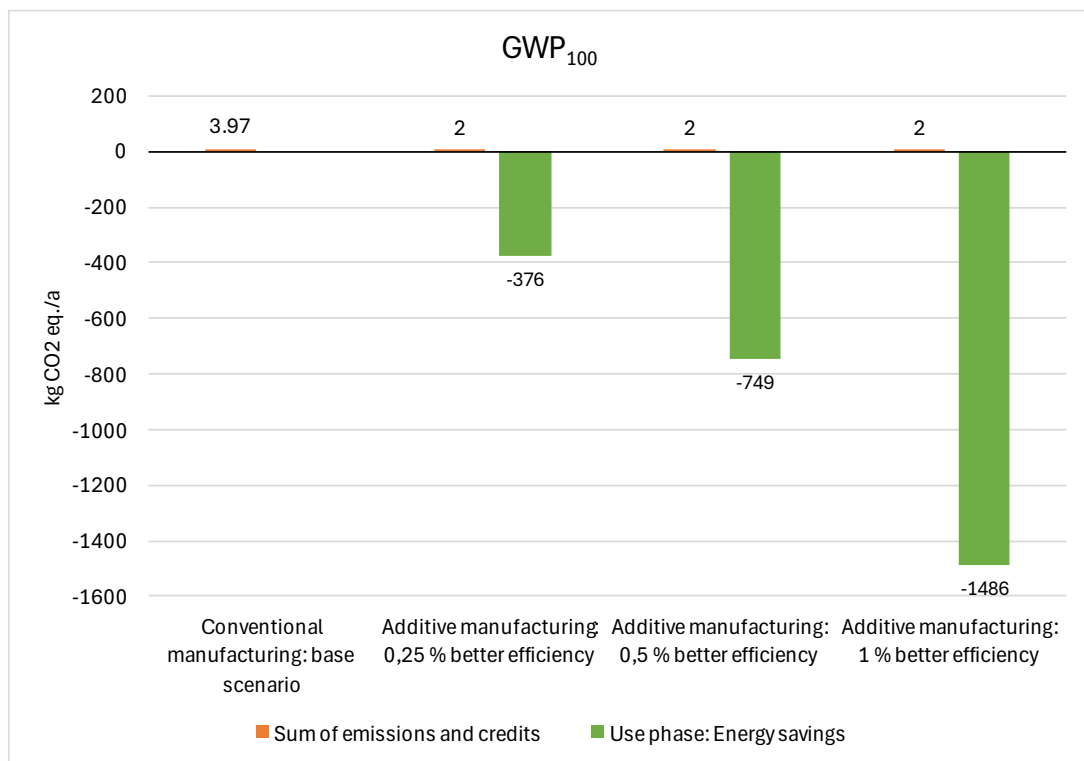


Figure 10. Hypothetical use phase energy savings achieved by part optimization.

6.2. Completeness and consistency analysis

Some of the data used in this study is confidential, and therefore is not disclosed in detail. Still, all the included flows are presented in the life cycle inventory, verifying the completeness of the study. Only flows that were deemed insignificant in the total result, such as cleaning fluids and auxiliary material transportations, were excluded due to lack of data. The systems are described in detail, and data sources are explained for each process step. Both manufacturing routes include the main manufacturing steps, as well as transportations and raw material consumption, making them comparable. The use phase is studied as a hypothetical scenario, even though it is outside the original system boundary.

Assumptions in the study were consistently made throughout both manufacturing routes. When applicable, same datasets were used in the study, for example for waste treatment. The source of raw material was assumed to be from Outokumpu in both manufacturing routes to ensure comparability of the manufacturing routes. There is no certainty of the true amount of scrap steel in the raw material, which would affect both the raw materials and credits results. For transportation distances not known, same distances were used for both manufacturing routes. The same system boundary and functional unit were set for both manufacturing routes to ensure comparability. All relevant flows were included in the study. Excluded flows for both manufacturing routes are presented in chapter 5.2. To ensure comparability of the manufacturing routes, the same raw material was used, and machinery production was excluded from both manufacturing routes because of lack of data.

6.3. Data quality assessment

The best available data was used in this LCA study. Primary data was gathered for both manufacturing routes, and used whenever possible. Primary data was supplemented with databases and literature sources. Both manufacturing routes are mainly based on primary data gathered, making them comparable. Data gathered from the producers is from years 2023-2024, making it representative of the current technology. Geographically, country-specific data was used whenever possible. When country-specific data was not available, European data was used.

The quality of atomization data is questionable. The data was gathered from literature sources, which did not specify, if the consumptions given were per kilogram of feedstock or per kilogram of fine powder. In this study, the consumptions were used per kilogram of fine powder, concluded from the calculations done with the data in the source literature. Other values taken from literature were the water and abrasive consumption of the abrasive water jet cutting.

7. Conclusions

The additively manufactured and conventionally manufactured paper machine part module were compared in three impact categories, which were global warming potential over 100 years (GWP_{100}), abiotic depletion potential of non-fossil resources (ADPE), and abiotic depletion potential of fossil resources (ADPF). The additively manufactured paper machine part module has a 58 % lower GWP_{100} , 76 % lower ADPE and 59 % ADPF compared to the conventionally manufactured part module. Therefore, additive manufacturing route of the part module has a noticeably lower environmental impact in all the impact categories studied. The main reason for the reduction in the results is decreased raw material consumption due to decreased mass of the part module, as well as decreased metal scrap generation of the production.

It should be noted that the additive manufacturing route also has two conventionally manufactured parts in the design, which have been considered in this study. The two conventionally manufactured parts account for 26 % of GWP_{100} , 54 % of ADPE, and 26 % of ADPF in the additive manufacturing route. If the part could be manufactured entirely with LPBF technology, the results would be even more representative of the additive manufacturing technology. The needed raw material would have decreased, but more powder would be needed for the production, increasing the impact of atomization and LPBF process.

For the GWP_{100} , most contributing factor is raw materials for both manufacturing routes. For conventional manufacturing, electricity consumption in manufacturing is the next most contributing factor in the GWP_{100} category. For additive manufacturing, the next most contributing factors are powder atomization and manufacturing electricity consumption. In the ADPE category, raw materials account for over 95 % of the emissions for both manufacturing routes. In the ADPF category, most contributing factors are the same as for GWP_{100} for both manufacturing routes.

As the raw materials were the most contributing factor in all the impact categories studied, a different raw material choice would have had a noticeable effect on the results. If a completely virgin-based feedstock was chosen, the impact of raw materials would have increased even further, while the amount of credits would have also increased. If a fully

scrap based feedstock was chosen, the impact of raw materials would have decreased in both manufacturing routes. Additionally, if a fossil-free stainless steel feedstock was an option for the manufacturing routes, GWP₁₀₀ results would be lower for both manufacturing routes, since raw materials would not have an impact. The GWP₁₀₀ results would be closer to each other for the additive and conventional manufacturing routes, as the raw materials cause the biggest difference.

For metal scrap and EoL treatment, the recommended methodology of EN 15804 + A2 was chosen to show a realistic situation. If the credited amount of steel would be the total amount of scrap produced, the more scrap produced, the lower the sum of emissions and credits would be. Thus, it would be beneficial for the producer to increase the amount of metal scrap in the production. Conversely, if the credits were not considered at all, the benefit of recycling would not be accounted for.

The biggest uncertainty of this study is the atomization phase of additive manufacturing. No data was received from powder producers, which is the case in many other studies as well. The unwillingness of providing data could be because the numbers would show their cost structure. Another possible reason would be that the process is significantly more energy or resource intensive than is currently assumed, making the additive manufacturing route a less competitive option in terms of environmental impact. In this study, the atomization values used are based on secondary data. Secondary data was gathered from literature sources, but was scarcely available. The uncertainty of atomization was studied in sensitivity analysis, by decreasing the yield of fine powder in atomization. The decreased yield had a noticeable impact on the results, increasing the GWP₁₀₀ by 19 %. For future research, the atomization of powder should be in focus. For powder manufacturers, recommendation would be to provide data about the environmental values. Due to the increasing requirements and interest in environmental values, such as carbon footprint, the manufacturers could gain a competitive advantage over others and in certain markets by providing data.

In the sensitivity analysis, the electricity source of manufacturing was also researched further. In conventional manufacturing, GWP₁₀₀ decreased by over a fifth from the base scenario, when all the electricity was changed to be from renewable sources. In additive manufacturing, the GWP₁₀₀ decreased by over a quarter compared to the additive manufacturing base scenario, when electricity was changed to be from renewable sources. In the additive manufacturing route, all the electricity was also sourced from market grid

mix in the sensitivity analysis, increasing its GWP_{100} by 10 %. Therefore, the electricity source has a significant effect on the GWP_{100} of the manufacturing. Only the market grid mix and renewable electricity scenarios were studied in the sensitivity analysis. The impact of manufacturing electricity in the GWP_{100} results would increase even further, if the electricity was entirely from fossil sources.

For the paper machine part module case in particular, the recommendation would be to gather data from the use phase. Therefore, a complete LCA could be conducted for the paper machine part module. The previous studies conducted in AM highlighted the impact of use phase, making further specifications essential. The use phase was focused on in one of the sensitivity analyses with completely hypothetical values. The results of the sensitivity analysis shows, that even if the efficiency increase achieved by part optimization is marginal, the resulting energy savings can have a substantial impact on GWP_{100} . If the design can be optimized, the cradle-to-gate of part manufacturing can be insignificant, making the choice of manufacturing route irrelevant in the big picture.

If the part cannot be optimized in any way, additive manufacturing may be a worse choice compared to conventional manufacturing. AM requires a lot of argon and electricity in the atomization step, increasing its environmental impact. Therefore, if mass reduction is not feasible, the cradle-to-gate GWP_{100} impact of additive manufacturing may be higher compared to conventional manufacturing. Still, the sensitivity analysis of the use phase shows that if the AM route can provide energy savings, the cradle-to-gate impact may be marginal in the full life cycle.

The results presented in this thesis are only applicable for stainless steel parts, and should be taken with caution when considering other materials. For materials with higher values in the impact categories considered, the additive manufacturing route could be a potential choice due to waste reduction possibilities. However, the change in material can affect the conventional manufacturing techniques used, as well as the atomization process and printing duration. Especially the electricity needed to melt the material in the atomization phase is dependent on the specific melting point of a material. Therefore, the evaluation should be done case-by-case to be certain of the reduced impact.

The results of this study do not consider other additive manufacturing technologies than laser powder bed fusion. As the different metal additive manufacturing technologies vary greatly

in terms of feedstock used, electricity consumption, auxiliary materials used, et cetera, the results cannot be generalized to cover different technologies. For future research, the LPBF process could be compared to other metal additive manufacturing technologies.

8. Summary

Additive manufacturing is a fast-growing industry in part manufacturing, and therefore the market is expected to expand in the future. Additive manufacturing is seen as one of the cornerstones of sustainable manufacturing. Especially metal additive manufacturing is expected to have a large impact on sectors such as aerospace, medical, and construction, the most industrialized technology being laser powder bed fusion.

In this thesis, the focus was on comparing the environmental impact of conventional manufacturing to additive manufacturing, specifically laser powder bed fusion. The comparison was conducted through a case life cycle assessment of a paper machine part module. The research questions of the study were the following: What is the environmental impact of conventionally manufactured and additively manufactured paper machine part module; Which factors affect the environmental impact of conventionally manufactured and additively manufactured paper machine part module, and what causes the differences; In which type of cases can additive manufacturing decrease the environmental impact of part manufacturing compared to conventional manufacturing. These questions were studied through three impact categories: global warming potential over 100 years (GWP_{100}), abiotic depletion potential of non-fossil resources (ADPE), and abiotic depletion potential of fossil resources (ADPF). The GWP_{100} results were investigated further with a sensitivity analysis.

Compared to conventional manufacturing, additively manufactured paper machine part module has lower results in each studied impact category; 58 % lower GWP_{100} , 76 % lower ADPE, and 59 % lower ADPF. Most affecting factors for conventionally manufactured part module are raw materials and manufacturing electricity. For additively manufactured part module, raw materials, atomization, and manufacturing electricity have the highest impact. For the conventionally manufactured part module, same GWP_{100} value was achieved in the sensitivity analysis by reducing metal scrap of the production by 82 %. The reduction was deemed to be unrealistic due to the complexity of the part. If the weight of the part module in additive manufacturing increased by 143 %, the GWP_{100} would be the same for both manufacturing routes. Therefore, the additive manufacturing route performs better in this case due to part optimization. The use phase was only studied through a sensitivity analysis. With hypothetical use phase energy savings, the effect on GWP_{100} would be significant.

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Appendix 1. Datasets used from databases.

Datasets from databases	Geography
Argon (gaseous) Sphera	DE
Compressed air 7 bar (medium power consumption) Sphera	GLO
Diesel mix at filling station Sphera	RER
Electricity from nuclear Sphera	Finland
Electricity from wind power Sphera	RER
Electricity grid mix (2022) Sphera	DE
Electricity grid mix Sphera	Finland
Electricity from hydro power Sphera	RER
Ferro metals in waste incineration plant (0% H2O content) Sphera	RER
Ferro metals on landfill Sphera	RER
Fixing material screws stainless steel (EN15804 A1-A3) Sphera	RER
Light fuel oil at refinery Sphera	RER
Lubricants at refinery Sphera	RER
Municipal wastewater treatment (sludge incineration) Sphera	RER
Ro-ro-ship, 1,200 to 10,000 dwt payload capacity, Sphera	GLO
Silica sand (Excavation and processing) Sphera	DE
Steel Engineering steel (2019) worldsteel	EU
Steel hot rolled coil worldsteel	GLO
Tap water from groundwater Sphera	RER
Treatment of waste mineral oil, hazardous waste incineration, with energy recovery ecoinvent 3.10	Europe without Switzerland
Truck, Euro 5, 14 - 20t gross weight / 11.4t payload capacity Sphera	GLO
Truck, Euro 5, 28 - 34t gross weight / 22t payload capacity Sphera	GLO