SUSTAINABLE PRODUCTION OF AIRCRAFT SYSTEMS:

CARBON FOOTPRINT AND COST POTENTIAL OF ADDITIVE MANUFACTURING IN AIRCRAFT SYSTEMS

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Abstract

The emission of carbon dioxide in Europe per inhabitant amounts to 9.1 tons annually. The aim of the Paris Agreement is to limit the increase of the global warming to 1.5°C compared to the preindustrial temperature.

To achieve this aim, a reduction of CO_2-emissions has to be quartered in the following years. An economy return line flight with an Airbus A320 from northern Germany to southern Spain results in nearly 0.65 tons of carbon dioxide emission per passenger, which corresponds to almost the third of the targeted greenhouse effect for a single person. The sustainable behavior of every single person starts with the production of goods used and consumed. In this context, three aspects are important to achieve sustainability. The first one is the economical one. Its goals are to generate profits in an environmentally and socially responsible manner. The second part deals with the ecology and natural resources – the rate of degradation of resources must not exceed the regeneration rate. Furthermore, the non- renewable resources have to be replaced by renewable resources. The third one concerns the social resources and equal opportunities in career environment. This paper focuses on the economic and environmental aspect of this sustainability approach for the production of aircraft systems.

In additive manufacturing processes, parts are generated by applying heat to the specific materials and generating the component in layers. This does not only provide a way for a force optimal design of parts and a component reduction in a module, but also to reduce the weight of the final product. In this paper, the additive manufacturing processes of Laser Beam Melting (LBM), Laser Metal Deposition (LMD), Electron Beam Melting (EBM), Wire Arc Additive Manufacturing (WAAM) and a milling process as well as the Investment Casting (IC) are compared with respect to the sustainable production in aircraft systems considering several components made of Ti-6Al-4V.

Life Cycle Impact Assessment of the selected components is made from cradle-to-grave with the Carbon Footprint Method (CF) and the Cumulative Energy (CE) Demand. Those Methods offer an inside view in terms of CO_2 emission and the Energy demand of a single component during its whole life cycle.

It is shown that the carbon dioxide emission and the energy demand can be drastically reduced in the production process in aircraft systems especially due to the efficient use of material. Hence, the use of additive manufacturing in aircraft systems contributes to a reduced CO_2 emission per capita and the ecological attitude of green production processes for companies.

1 INTRODUCTION

Sustainability goes hand in hand with global warming and resource degradation. To make life for the further generations feasible, the Paris Agreement was brought into being. The achievement of this agreement and the assurance of the planet wealth require the non-renewable resources to be replaced by analogue matter and the CO_2 pollution to be reduced. To minimize pollution in the aircraft industry (AI) Additive Manufacturing (AM) methods were applied by the manufacturers to optimize the geometry and reduce the weight of the identified parts. Further, the pollution and the Environmental Costs (EC) of the AM processes themselves have to be considered to confirm those methods to be sustainable in the AI.

In the following paper, several additive manufacturing methods LBM, LMD, EBM, WAAM and IC are compared to the conventional CNC milling manufacturing with the Ti-6Al-4V alloy for three different parts in the aircraft industry related to the energy consumption, the CO_2-pollution and the resulting economic costs of the environmental emissions. The objective of this study is to highlight the advantages of the additively manufactured parts with different processes using the same material in different shapes regarding the environmental and the economic aspect of sustainability.

To acquire the data, the different parts are considered from the material extraction until recycling. Detailed processing steps are analysed and the material waste, as well as the consumed energy for each process are taken into account. This leads directly to the carbon dioxide pollution and the cost saving calculation due to the use of AM processes in aircraft industry.

The conventional methods like CNC milling are limited inter alia by the accessibility of the tools to accomplish the desired part geometry. Furthermore, the production of a complex part requires semi-finished bulk material, which have to be produced in the first place. Dependent on the desired geometry, the unnecessary metal has to be cut from the semi. It is shown, that the AM processes contribute less to carbon dioxide pollution than conventional manufacturing methods. The main reason is the high utilization rate of the material, even though the process itself requires more energy and time to produce the same part. Explicitly, the carbon dioxide pollution and the environmental costs are reduced up to a factor of eight using AM technologies.

2 STATE OF THE ART

Several researchers compared the LCA of AM processes to the conventional CNC milling or another CM process. In order to present the current state of sustainability investigation of AM processes, preceding studies are compared and listed in *Table 1*:

Table 1: Literature review of sustainability studies on AM processes

Study	AM[a]	CE consumption	CF calculation	EC determination	Material	AM/CM relation	AI related study
[29]	Casting[h]	✓	✗	✗	Al alloy	✗	✗
[34]	Casting[i]	✓	✗	✗	Al alloy	✗	✗
[20]	Casting[i]	✓	✗	✗	Al alloy	✗	✗
[28]	EBM	✓	✓	✗	Ti alloy[l]	✓	✓
[27]	EBM	✓	✓	✗	Ti alloy[l]	~0.4-1.2	✓
[3]	EBM	✓	✗	✗	Ti alloy[l]	✗	✗
[18]	EBM	✓	✗	✗	Ti alloy[l]	✗	✓
[10]	LBM	✓	✓	✗	Al alloy	✗	✗
[15]	LBM	✓	✗	✗	Polymer[n]	✗	✗
[16]	LBM	✗	✗	✓[b]	Steel alloy[m]	✗	✗
[24]	LBM	✓	✗	✗	Steel alloy[m]	0.1	✗
[2]	LBM	✓	✗	✗	Ti alloy[l]	✗	✗
[23]	LBM	✗	✗	✗	Ti alloy[l]	✗	✓
[26]	LMD	✓	✓	✗	✗[d]	0.38	✓
[17]	LMD	✗	✓	✗	Al alloy[q]	0.23	✗
[22]	LMD[e]	✓	✗	✗	Steel alloy[j]	0.5-300	✗
[33]	LMD[g]	✓	✓	✗	Ni alloy[r]	0.32	✓
[4]	WAAM	✓	✗	✗	✗[d]	✗	✓
[5]	WAAM	✓	✓	✗	Steel alloy[o]	0.72	✗
[14]	WAAM[f]	✓	✗	✗	Steel alloy[k]	✗	✗
[31]	WAAM[f]	✓[c]	✓[c]	✗	Steel alloy[p]	✗	✗

[a]AM or AM related process; [b]Analyzing AM costs;[c]only regarding the process;[d]not mentioned titanium alloy; [e] Direct Metal Deposition; [f] Gas Metal Arc Welding; [g] Laser Direct Deposition;[h] Conventional Casting; [i] Investment Casting;
[j] H13;[k] A36;[l] Ti-6Al-4V; [m] 316L; [n] PA2200; [o] 308L; [p] S355; [q] A48; [r] NiCr20Co18Ti

Due to the amount of varying AM methods and product types, it is tough to produce the similar part for the same application using different AM processes. Most of the researchers concentrated on a very detailed analysis of a single manufacturing process, also using different materials. In contrast to it, this paper compares different processes for the analogue parts with the same material. The goal is to demonstrate the advantage of the AM processes compared to the conventional machining and highlight also the economic aspect of those procedures.

3 METHODOLOGY

The comparison of the different manufacturing processes is based on the ISO 14040 [13], which underlies the procedure of Life Cycle Assessment (LCA). LCAs goal is to improve the environmental impact of manufactured products during their life cycle and to guide the decision-maker of the company regarding to strategic planning. It consists of four phases: Goal and Scope, Inventory Analysis, Impact Assessment and the Interpretation of the results.

The scope of the study is to compare different AM processes to the conventional manufacturing and to determine the aspects of costs and pollution per produced part relatively to CM. The life cycle of any product consists of five elements, the raw material production, transportation, manufacturing, usage and recycle. Here an assumption is made, that the transportation and the amount of transported weight to the production location is similar for each process.

Therefore, the data gathering is determining by the material production, the manufacturing and the recycling milestones in the life cycle of the products. The cumulated data from the considered life cycle stages gives an overview about the environmental impact of the processes, which leads directly to the advantages and disadvantages of the AM processes in terms of environmental aspects. Each processing step is analyzed and the data gathered with for the process suitable parameters. There is a wide amount of methods to determine the impacts of different processes in the scope of LCA. In the political and economic field of view, especially the Carbon Footprint Method, as well as the Cumulative Energy Demand Method represents the most powerful tools, which can be directly combined to determine the monetary costs of the produced energy and carbon dioxide.

4 DATA GATHERING

The five different manufacturing processes for the aerospace industry in the example of three parts are split into several production steps. LCA is focused on the part production itself. The material production and recycling are estimated by given values in the literature, which is given by the Specific Energy Consumption (SEC). The use of those parts is distinguished only in the unit of mass and its contribution to the pollution yielded through the aircrafts.

In the following sections the eco properties of the material are presented and the processes differentiated in terms of required preparation steps and starting material shapes. The three components are shown in *Figure 1*:

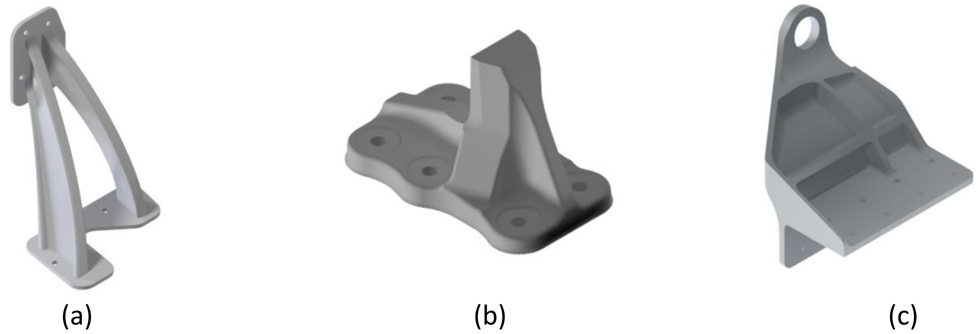

Figure 1: AM and CM manufactured parts – (a): DHA-bracket, (b): door stop, (c): CCRC-bracket

Due to the different preparation steps and manufacturing methods, the required shape of the material and its amount varies. An overview about the different processing steps for the processes is given in *Figure 2*:

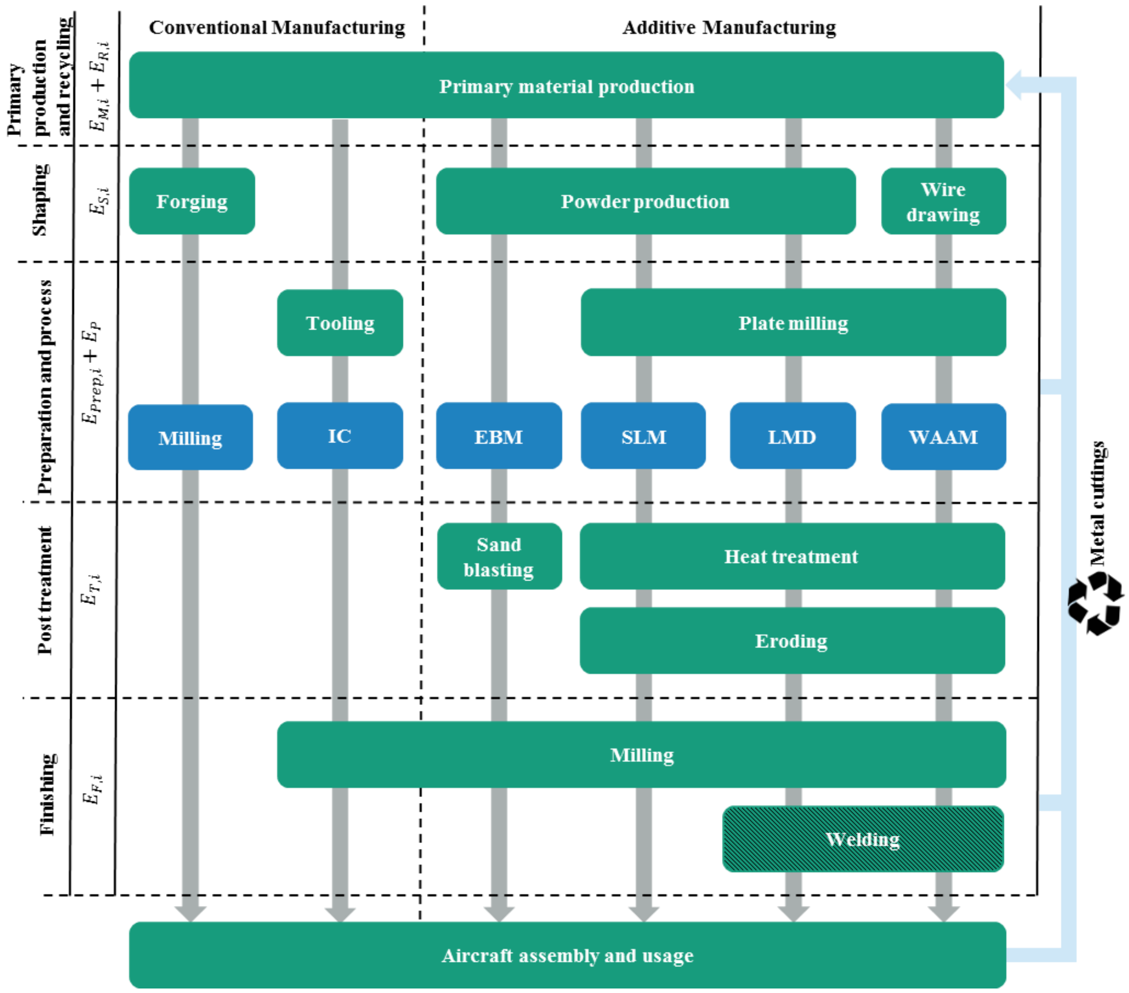

Figure 2: Processing steps of CM and AM ▨ - *optional*

The estimation of the energy consumption per part is estimated by

$$E_{C,i} = E_{M,i} + E_{S,i} + E_{Prep,i} + E_{P,i} + E_{T,i} + E_{F,i} + E_{R,i} \tag{1}$$

where i stays for the considered process. Besides the accumulation of energy, carbon dioxide is considered, as well as the costs for the electricity and the CO_2 pollution. The parameters in each processing steps are chosen in a way, the investigated parts are manufactured. $E_{R,i}$ of those parts is estimated by considering the metal cuttings and unnecessary material to be removed.

4.1 Eco properties of Ti-6Al-4V

The required semis and material shapes differ in each process. Literature provides SEC for material shaping, recycling and several AM and CM processes (see *Table 2*). Those parameters are necessary to calculate the overall energy consumption for the manufacturing of the defined parameters. When considering the examined processes, the combination of the different material shapes is useful for a sustainable and economic production. They include forged ingots and plates (CNC Milling, LMD, WAAM), powder sized particles through atomization (LMD, LBM, EBM), wire shaped continuous material (WAAM) and melt (IC).

Table 2: Eco-properties of Ti-6Al-4V [1, 6, 12, 20, 32]

Eco-properties of Ti-6Al-4V	Average value
EE primary production E_M $[MJ/kg]$[b]	685.0
CF primary production CO_{2_M} $[kg/kg]$ [b]	46.5
EE forging and rolling E_{FR} $[MJ/kg]$[b]	14.5
CF forging and rolling $CO_{2_{FR}}$ $[kg/kg]$[b]	1.15
EE atomization E_A $[MJ/kg]$[d]	20.84
CF atomization CO_{2_A} $[kg/kg]$ [a]	3.12
EE wire drawing $E_W[MJ/kg]$	25.0
CF wire drawing CO_{2_W} $[kg/kg]$	1.5
EE casting E_C $[MJ/kg]$[f]	18.7
CF casting CO_{2_C} $[kg/kg]$[f]	1.76
EE CNC milling E_{CM} $[MJ/kg]$[c]	49.56
CF CNC milling $CO_{2_{CM}}$ $[kg/kg]$[c]	7.38
EE recycling E_R $[MJ/kg]$[b]	87.0
CF recycling CO_{2_R} $[kg/kg]$[a]	12.96
EE eroding E_{ER} $[MJ/mm]$[c]	0.557
CF eroding $CO_{2_{ER}}$ $[kg/mm]$[a]	0.083
EE welding E_{WE} $[MJ/mm]$[e]	0.12
CF welding $CO_{2_{WE}}$ $[kg/mm]$[a]	0.0178

(a) – calculated with $CF = 0.149\ CO_2/MJ$, (b) – adapted from [1], (c) – adapted from [6], (d) – adapted from [32], (e) – from [12] (f) – from [20]

4.2 Process differentiation

Each process requires different processing steps, which can be taken from *Figure 2*. Each process, the parameters as well as the accomplished procedures are described in the following subsections 4.2.1 - 4.2.6.

4.2.1 Laser Beam Melting

In the LBM process, the powder is locally melded by a laser beam layer by layer with the laser-scanner principle, which results in a near net shaped part [7]. The manufactured parts are completely built from powder, but require further manufacturing steps as eroding and finishing of the functional surfaces. The estimation of the energy consumption is performed with a $240\,W$ Laser, with a scan speed of $1200\,mm/s$ on SLM 500 HL. The components are produced on a building platform, which have to be separated by the eroding process. Those parts are built on support structure, which is $2\,mm$ thick. To ensure the functionality of the interfacing surfaces, additional material of $20\,\mu m$ is added. This additional material is eliminated by the following CNC machining process. To release stress after the manufacturing process, the parts are put into a vacuum furnace with a power consumption of $5\,kW$ for several hours with a defined preheating, holding and cooling strategy. This processing step is similar for LBM, WAAM and LMD.

4.2.2 Electron Beam Melting

EBM is performed by Arcam A2X, with an overall energy consumption of $6.5\ kW$. The parts are generated by selectively melting atomized Ti-6Al-4V powder via electron beam layer by layer. Those parts are built in the same manner as in the LBM process to the near net shape. As well as in the LBM process, $20\ \mu m$ of additional material thickness on the functional surfaces are considered. In contrast, no eroding is required to separate the part from the platform. The building platform consists of a different material, which leads to a different residual stress. Hence, no heat treatment is required. The additional sand blasting after the process separates the powder material from the manufactured part and has to be added into the energy consumption calculation, which are $800\ W$.

4.2.3 Laser Metal Deposition

LMD manufactured parts are manufactured by applying and simultaneously laser melting atomized powder to a building platform [8]. The kinematic is performed by a six axis industrial robot, which is placed in a robotic cell. As well as the process, the cell requires energy, which is estimated to be $13\ kW$. The process is performed with a $1500\ W$ laser [6]. Due to the process uncertainty of $1{,}4\ mm$ [6], the final volume is estimated by the Computer Aided Design (CAD) model. The building platform is considered to be $40\ mm$ thick and the contour shape as close as possible to the final surface in a rectangular form. To ensure the plate tolerances, CNC milling is performed to remove $2\ mm$ of the building platform. Therefore, the primary production of the building platform has to be considered as well as the following interfacing surfaces. After the eroding process, CNC milling is performed to shape the interfacing surfaces and to remove material in case of part (c). Here, LMD is used to generate the massive contour of the structure as close as possible to the final shape.

4.2.4 Wire Arc Additive Manufacturing

In contrast to LMD, a wire is fed through the nozzle and melded by an electric arc. This process is based on GMAW [14] and additionally added kinematics by a six axis industrial robot. WAAM is performed with a current of $96\ A$, the voltage of $12.7\ V$, the wire feed speed of $2500\ mm/min$ with a diameter of $1{,}2\ mm$ and the travel speed of the kinematics of $1200\ mm/min.$. For the WAAM process, the tolerances and the preparation steps are considered to be the same as for LMD.

4.2.5 Investment Casting

IC is a method of casting metals, which includes the steps of tooling, wax melting and injection, dewaxing, ceramic shell firing, casting and finishing [20]. Furthermore, IC is considered to be one of the most energy consumable processes along casting processes [20]. The parts are manufactured near net shape, where the material is added on the interfacing surfaces by $2\ mm$ of thickness, which are removed in the part finishing. For the energy consumption, especially the tooling is considered in the manufacturing process of the parts.

4.2.6 CNC Milling

The flow chart of the conventional subtracting process is unpretentious compared to the AM processes. Here, a massive cuboid block of Ti-6Al-4V has to be machined into the desired shape. Due to the value of CNC milling for the titanium alloy of $49.56\ MJ/kg$, the energy consumption is calculated by multiplying the value with the subtracted material.

5 USE PHASE OF THE PART

From [23] can be obtained, that the CO_2 pollution of an aircraft per kilogram of weight is $1417.51\ t$ during the whole life time of an aircraft, considering a 30 years lifespan. This results in about $\sim 28{,}000€/kg$ per part of emission costs according to EEA [9]. Due to the layering techniques in the AM methods, the geometry of the parts can be optimized and the weight reduced. From this follows, that the produced components with AM techniques contribute the same or even least to the CO_2 pollution during their lifetime in an aircraft and therefor to the reduction of economic costs.

6 RESOURCE EFFICENCY

This study focuses on the manufacturing processes of several aircraft components and the necessary material, as well as the recycling of those parts. The results of the study are shown as relative values compared to CNC milling in *Figure 3*:

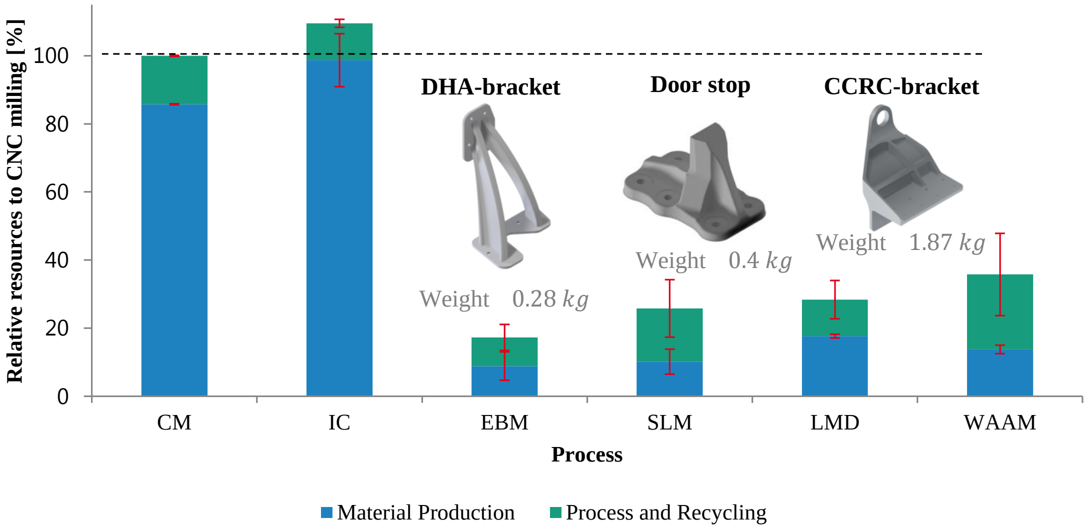

Figure 3: Relative resource consumption compared to CM processes

Here, CNC Milling is used as benchmark for the different processes. It has been shown, that the overall resource consumption regarding the observed parts is significantly smaller for AM processes due to the steps listed in *Figure 2*. In 6.1 and 6.2 a more detailed description of the Carbon Footprint method and the Cost Potential are presented, especially with the additional view on manufacturing costs.

6.1 Carbon Footprint

Carbon Footprint is determined by the eco properties stated in 4.1 and the calculation due to the different processing steps in CM, LMD, LBM, IC and WAAM. Regarding the results seen in *Figure 4*, the AM methods of producing the brackets or the door stop show a significant CO_2 saving potential and they ecological advantage.

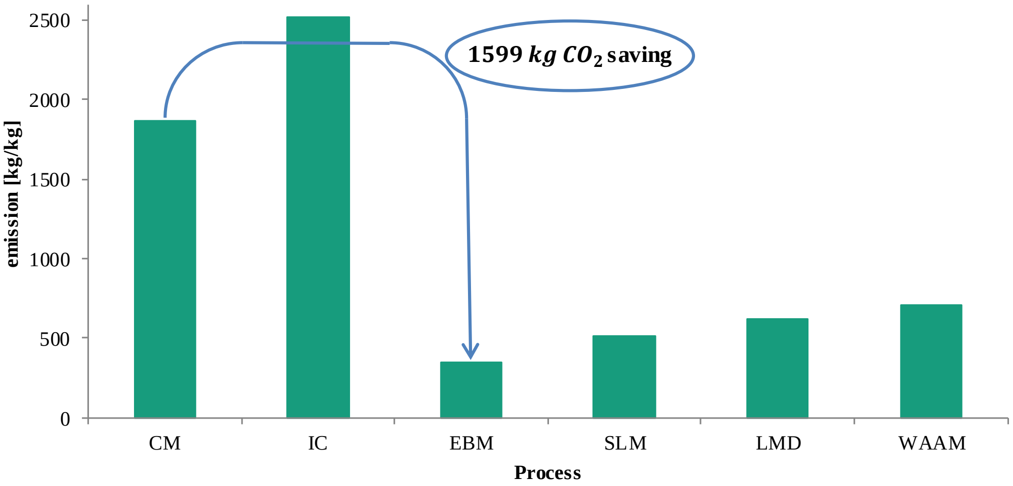

Figure 4: Carbon Footprint of the processes

6.2 Cost Potential

The costs are determined by cumulating the costs of the manufacturing process itself, as well as the observation of potential ecological costs regarding [9].

6.2.1 *Manufacturing costs*

Manufacturing costs are calculated exemplary for the LMD process by the formula adapted from [31] for the calculation of the LBM process:

$$C_{LMD} = C_{D,LMD} + C_{I,LMD} + C_{M,LMD} + C_{P,LMD} + C_{O,LMD} \tag{2}$$

C_{LMD} are here the total costs of a part manufactured by the LMD process. This contains the direct material costs $C_{D,LMD}$, the indirect material costs $C_{I,LMD}$, machine costs $C_{M,LMD}$, the personal costs $C_{P,LMD}$ and the overhead expenses $C_{O,LMD}$. Those costs are directly added to the ecological costs described in 6.2.2.

6.2.2 *Ecological costs*

CO_2 produced during the energy generation is calculated with the Electricity Index from German Federal Environment Office (GFEO), which results in 0.149 CO_2/MJ [6]. The certificates of the European Emission Allowance (EEA) determine the current value of a ton of carbon dioxide pollution in the major production industry. Thus, the costs of this carbon dioxide will be approximated additionally with the price of the current CO_2 certificate of 20.73 € [9].

6.2.3 Cumulated costs potential

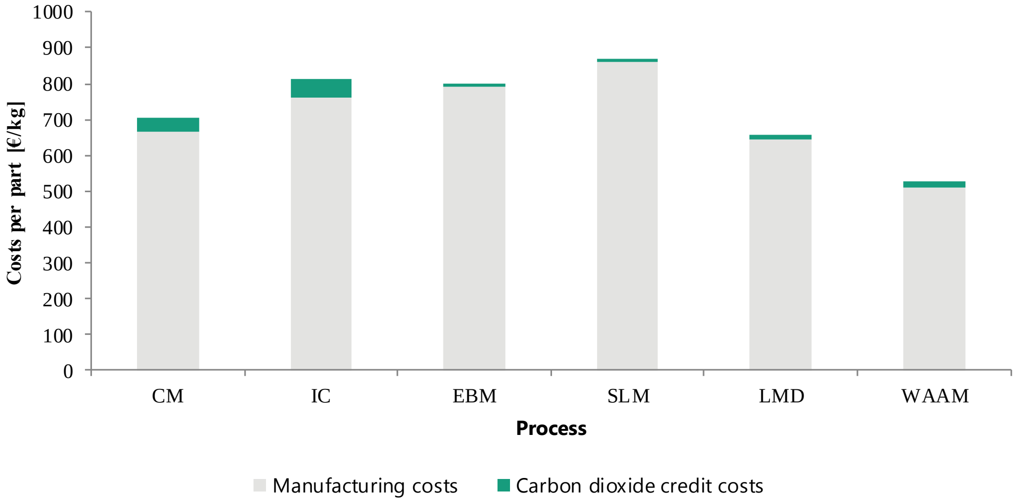

Figure 5: Cost Potential of AM parts

7 CONCLUSION

The calculation of the energy consumption during the process show, that the AM processes require a higher energy demand than the CM processes. The approximated results for the calculation of SEC, CO_2-emission and Environmental Costs are shown in *Table 3*:

Table 3: Results of SEC for different parts

	CM	IC	EBM	LBM	LMD	WAAM
$EE\ [MJ/kg]$	12796 ± 4146	16909 ± 6701	2300 ± 591	3449 ± 1195	4137 ± 1463	4799 ± 937
$CF\ [kg/kg]$	1868 ± 584	2519 ± 998	342 ± 88	513 ± 178	616 ± 218	704 ± 153
$EC\ [€/kg]$	357 ± 246	605 ± 251	75 ± 31	123 ± 50	$147{,}36 \pm 63$	143 ± 63

Nevertheless, the material utilization of the AM processes leads to a significantly smaller resource consumption compared to the CM processes. Also the amount of material, which has to be recycled, is minimized due to the geometry optimization and the material utilization. Furthermore, the parameters used in this study are not optimized in the processes. Compared to the usage of those parts, the contribution of the processes is $< 0.1\%$, but considering the limited resources and the utilization of the material, AM processes highlight their advantages compared with CM.

8 SUMMARY

This study compared AM processes (LBM, EBM, WAAM, LMD) to CM processes (CNC Milling and IC). The focus in the paper is on considering all the processing steps in the manufacturing chain of three different components for an aircraft system, as well as the energy consumption of the necessary material. It is shown, that the SEC of the AM processes is more than double as high as in the CM processes. Considering the whole manufacturing chain, the AM processes are up to 87 % less energy consuming, CO_2 polluting and cheaper in respect to EC. *Figure 6* illustrates the Carbon Footprint and the ecological costs due to its pollution:

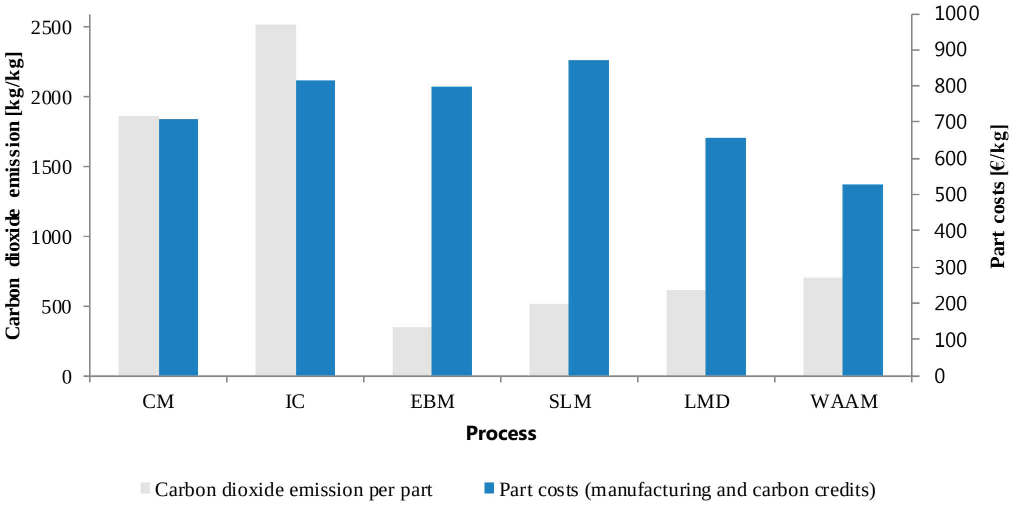

Figure 6: Carbon footprint and ecologic cost potential of investigated parts

9 OUTLOOK

In this study it was shown, that due to the utilization of the material especially powder based AM processes are more environmentally sustainable, than other processes. To optimize the entire manufacturing chain regarding resource consumption, the process parameters have to be adapted to the single manufactured parts, but also receiving powder from the supplier. Receiving powder produced by the Metalysis process halves the energy for primary material production [21].

Regarding the potential costs due to the CO_2 pollution from aircrafts, project CORSIA [30] has to be considered. Here, certificates for the carbon dioxide pollution have to be purchased by the airlines. The optimization of further aircraft parts and minimization of resource consumption in the production stage would not only lead to more environmental sustainability.

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