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ORIGINAL RESEARCH ARTICLE

Gate-to-Gate Life Cycle Assessment of Printed AlSi10Mg Laser Powder Bed Fusion Jobs in Additive Manufacturing Factories

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Among the different advantages, powder bed fusion (PBF) processes allow obtaining the parts having complex geometries, avoiding additional steps to assemble the parts. As a result, time and costs are strongly reduced. Nevertheless, energy and resource consumption in PBF processes is not negligible. Given the lack of real primary data on additive manufacturing (AM) processes in open-source software life cycle assessment (LCA) databases, an in-depth analysis of real industrial situations on the of manufactured products is essential for global knowledge of the real green aspect of the technology used. What is more, studies existing in the literature are sometimes contradictory on the consumption of resources to perform the PBF processes. This is due to the high variability among the different systems used, on the one hand, and also to the proper and efficient use of the machine in AM environments. Also, since a lot of studies are based on the estimation of resource consumption, they can overestimate or underestimate, effectively, the real usage. Especially, on argon consumption, literature seems to be very contradictory. This work aims to fill this gap of knowledge existing. In particular, a "gate-to-gate" LCA of AlSi10Mg components produced by the laser powder bed fusion (LPBF) process is presented in this work. Four scenarios of different production mixes have been performed, monitored and evaluated from a sustainable perspective. Based on the results obtained by the LCA carried out using experimentally measured data of typically printed LPBF jobs, guidelines for sustainable decision-making in AM factories are provided.

Keywords additive manufacturing, life cycle assessment, laser powder bed fusion

1. Introduction

The growing awareness of the environmental impact due to industrial activities has led to the adoption of more sustainable approaches in the design and manufacturing of industrial components (Ref 1).

The production sector contributes significantly to the increase in emissions into the environment and is driven to search for solutions that embrace the theme of sustainability as well as improving the standard of living of human society also from an economic point of view. In fact, in the European context, the manufacturing sector accounts for 15% of the gross product absorbing almost 30% of final energy and producing approximately 20% of greenhouse gas emissions (Ref 2). Therefore, there is a need to activate the manufacturing of goods using economically intelligent proposals that reduce negative impacts on the planet while preserving natural resources and energy. According to Rashid et al. (Ref 3), sustainable production can be achieved by reducing waste, with better energy efficiency and decreasing the demand for raw materials, use of natural resources and having a greater focus on the economic aspects of goods and services that reduce environmental impact. All of this certainly involves the choice of unconventional technologies which will show less technological maturity and repeatability of results (Ref 4), but they improve material efficiency and the production of complex parts with reduction of material, reduction of delivery times and inventories by decentralizing production (Ref 5).

Additive manufacturing (AM) allows the use of innovative materials from renewable and biocompatible sources. Furthermore, these technologies give the possibility of customizing the design of the products and therefore complete satisfaction of customer specifications, low energy consumption, when compared with conventional processes, and reduced waste of raw materials.

Additive processes such as powder bed fusion (PBF), which consists of selectively dissolving and melting metal powders using lasers, are efficient production technologies in terms of materials for complex parts producing less material waste and finding applications in various industrial sectors (Ref 6). However, these technologies are more energy-intensive than

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subtractive conventional ones (Ref 7, 8) and require more expensive machine tools as well as post-processing operations to obtain the desired surface finish. Among the various technologies in development, laser powder bed fusion (LPBF) guarantees better material efficiency but has lower energy and economic efficiency than conventional technologies. Each stage of the life cycle of an additive product such as raw materials, energy and consumables results in waste generation and environmental emissions.

Therefore, these environmental emissions need to be quantified to determine the environmental compatibility of AM processes. To ensure a sustainable production process selection, it is necessary to evaluate the environmental and economic impact of industrial production (Ref 9-11). With the rising cost of energy, the need to analyze energy consumption in the manufacturing industry is challenging. Forecasting energy consumption is an increasingly important topic for companies that aspire to control, monitor and improve their production system.

In this context, the life cycle assessment (LCA) emerges as a fundamental tool for assessing the environmental impact of a product throughout its entire life cycle, from the raw materials extraction phase to the end of its life. With this analysis, all incoming resources and outgoing waste are recognized and quantified in the different phases of the production process in order to calculate the environmental impact in different impact categories (Ref 12-14).

Given the growing application of AM technologies, the lack of real primary data and the absence of useful data relating to additive processes in open-source software LCA databases, an in-depth analysis of real industrial situations on the life cycle assessment of manufactured products is essential for global knowledge of the real "green" aspect of the technology used and the specific product created. What is more, studies existing in the literature are sometimes contradictory on the consumption of resources to perform the powder bed fusion (PBF) processes. This is due to the high variability among the different systems used, on the one hand, and also to the proper and efficient use of the machine in AM environments. Also, since a lot of studies are based on the estimation of resource consumption, they can overestimate or underestimate, effectively, the real usage. Especially, on argon consumption, literature seems to be very contradictory.

This work aims to fill this gap of knowledge. In particular, a "gate-to-gate" LCA of AlSi10Mg components produced by the laser powder bed fusion (LPBF) process is presented in this work. Four scenarios of different production mixes have been performed, monitored and evaluated from a sustainable perspective to provide guidelines deriving from experimentally measured data from typically printed LPBF jobs in AM factories.

2. Materials and Methods

This study investigates the environmental impact of the LPBF process in an AM environment. A gate-to-gate LCA of different production mixes (few medium parts, few big parts, many medium parts, many small parts) has been investigated to carry out a comparison in terms of life cycle impact assessment (LCIA). The typical stages of the LPBF process, which are printing, unpacking, depowdering and sandblasting, have been experimentally monitored and included in the LCA. Section 2.1 describes how the LPBF process has been performed, Sect. 2.2 explains the purpose and the boundaries considered in the LCA and Sect. 2.3 illustrates the data used for the life cycle inventory (LCI).

2.1 LPBF Process

AlSi10Mg aluminum powders (20-63 μm) have been used to manufacture parts for aerospace applications using the SLM®500 machine produced by SLM Solutions. It has a total build envelope of 500 × 280 × 365 mm (L × W × H) which utilizes two IPG fiber lasers, potentially operating independently or in parallel, by selecting a laser power ranging from 400 to 700 W. The machine makes use of two additional subsystems: the powder supply vacuum (PSV) and the part removal station (PRS). The PSV protects the operator from exposure to dust and keeps the material under an inert gas atmosphere throughout the handling process. The PSV is equipped with a 90-liter tank for pre-loading and storing metal powder. The automatic system sifts the material before transport to the machine, collects overflow powder to be returned to the sieve during the process and connects to the PRS extraction station for dust removal after a process is completed. The PRS reduces machine downtime by allowing the removal of a finished part while the next process is already underway. Build cylinders with finished parts are transported out of the SLM®500 for cooling and dust removal in an inert gas atmosphere. Integrated gloves allow material removal without exposing operators to metal dust. A vacuum tube, located directly in the PRS chamber, returns unused powder to the PSV for sieving and use in the next process. Moreover, SLM Solutions' advanced quality control system enables detailed documentation of testing processes. Variables such as chamber temperature, oxygen level, gas flow and others are constantly monitored and recorded. This high level of control ensures the production of high-quality components with uniform mechanical characteristics. After completion of the printing, the build chamber in the printer is moved to the unpacking station to uncover the part from the excess powder. In this stage, called unpacking, the powder is removed using a vacuum that transfers the contaminated powder to the sieving to be filtered in a closed loop system. This sieve is designed to easily be emptied of the uncovered contaminants from the excess powder. In both the printing machine and the unpacking station, an inert environment is established to protect the powder from oxidization using argon gas. After the unpacking, the depowdering is usually performed to remove the excess powder from the cavities of the part. That is because if no exit holes exist that let the powder out of these cavities, this excess powder can be stuck inside the shape when more layers encapsulate them, consequently adding unnecessary weight. After depowdering, sandblasting was performed to improve the surface finishing of the LPBFed parts. This method uses abrasive particles that strike the surface at high speed to smoothen out the texture. An air compressor and sandblasting machine are needed to pressurize the sand. Figure 1 depicts an IDEF0 diagram illustrating inputs, outputs, controls and mechanisms needed to perform the LPBF process, LPBF post-process and sandblasting. All the processes are performed under the control of the OEM recommendations and standards to obtain a high-quality of results by following safety regulations. Equipment and resources are needed to perform

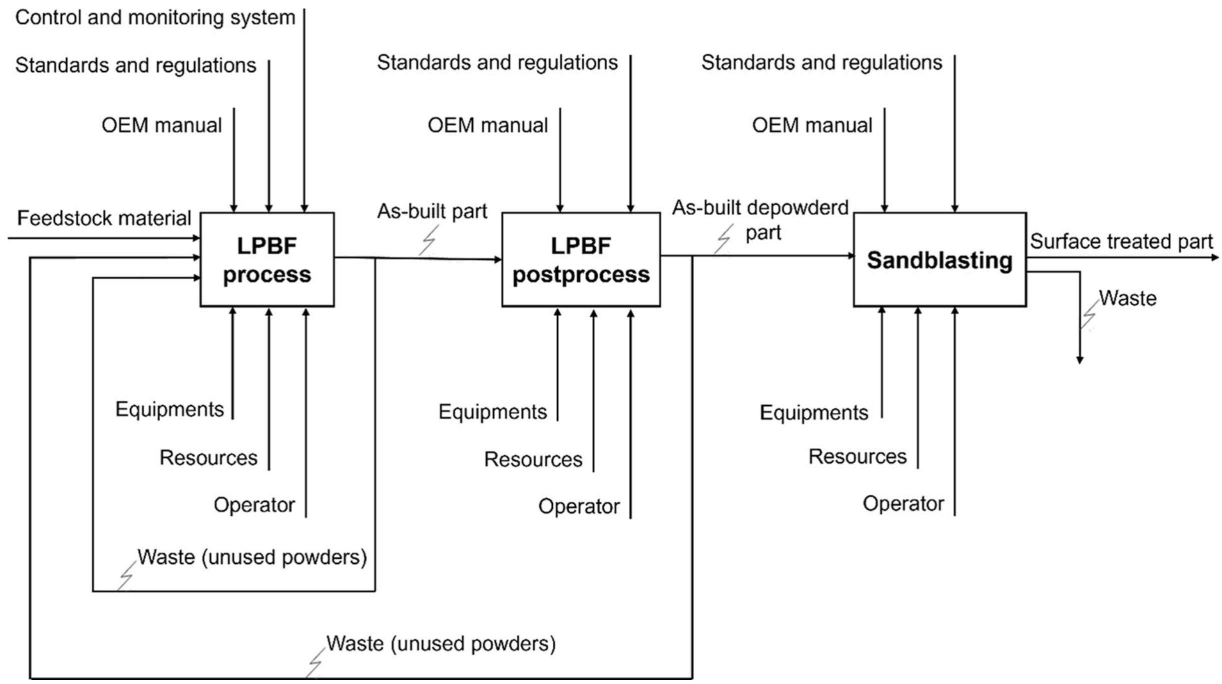

Fig. 1 IDEF0 diagram of the inputs, outputs, controls and mechanisms needed to perform the LPBF process, LPBF post-process and sandblasting

Table 1 Chemical composition (wt.%) of the AlSi10Mg powders used for all the jobs

Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	Sn	Other total
Balance	9.00-11.00	0.55	0.05	0.45	0.20-0.45	0.10	0.15	0.05	0.05	0.05	0.15

each process, as deeply described in the following sections. Also, always is indicated the presence of the operator because he activates, controls and in some cases (LPBF and sandblasting) perform manually the process.

A life cycle assessment (LCA) of the LPBF process has been carried out. It includes the LPBF process (including the resources contribution of the machine use, machine maintenance and the chiller), depowdering and sandblasting. Energy consumption of the SLM machine, the chiller, the depowdering station and sandblasting machine has been measured by using the Chauvin Arnoux CA 8331 device. It is equipped with current sensors and tension cables, used to measure current, tension and then power and energy consumption. Energy consumption of the maintenance LPBF machine has been estimated based on the technical documentation of the production system where the machine operates. The following sections describe the first stages of the LCA, which are the goal and scope definition and the life cycle inventory (LCI).

2.2 LCA: Goal and Scope Definition

In this study, a gate-to-gate LCA of four jobs containing AlSi10Mg parts manufactured by the LPBF process has been performed. The chemical composition of the powders used is included in Table 1. The LPBF process parameters are recommended by the original equipment manufacturer (OEM). The jobs differ in the number, mass and volumes of the printed pieces and supports. This choice derives from the purpose of life cycle assessing typical industrial operations in AM factories, where highly customized parts are realized. Table 2 contains the details of each job under investigation, representing the four jobs, representing the four scenarios under investigation.

GaBi (Sphera) software has been used to carry out the LCA. Fabrication, maintenance and dismission of buildings and equipment have been neglected. Also, transportation has not been considered since all the jobs have been realized in the same plant. CML 2001 is the methodology used to perform the LCA, according to ISO 14040 and ISO 14044.

The international standards ISO 14040 and ISO 14044 do not specify a single method for the performance of life cycle impact assessment (LCIA). As a result, many different LCIA methods have been developed over the years and the choice among them for carrying out the analyses is not always obvious. In particular, although various LCIA methods have been developed and are available for the assessment of environmental impacts in the LCA, results from existing literature show that ReCiPe, followed by ILCD 2011, CML 2012 and IMPACT 2002 + , is the most commonly used multi-impact LCIA methods at the midpoint level worldwide (Ref 15). Differences in methodological approaches to characterization modeling and substance coverage by individual impact categories influence the results of LCA. In this regard, some researchers (Ref 16) recently investigated the comparison results of four LCIA methods: ReCiPe 2016, ILCD 2011,

Table 2 Details of the four jobs/scenarios investigated

	Job 1	Job 2	Job 3	Job 4
Part Volume, cm^3	818.48	899.63	1206.91	1455.9
Support Volume, cm^3	57.17	29.64	59.95	120.95
Part mass, kg	2.17	2.39	3.20	3.87
Support mass, kg	0.26	0.27	0.66	0.32
Part + support mass, kg	2.43	2.66	3.86	4.16
Duration purging, min	15	15	15	15
Duration printing, h	24	32	43	67
Duration unpacking, min	90	90	90	90
Duration depowdering, min	5	5	5	5
Duration sandblasting, min	20	20	20	20
Number of Parts	15	6	27	63
Production mix	few medium parts	few big parts	many medium parts	many small parts

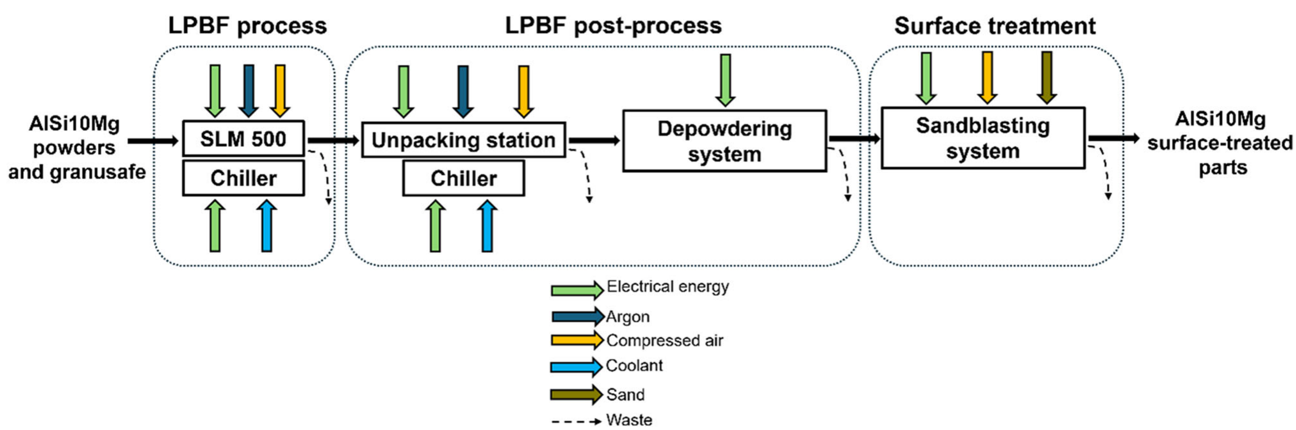

Fig. 2 Schematization of the gate-to-gate LCA modeled for all the scenarios

CML-IA baseline and IMPACT 2002 + at the midpoint level to compare the environmental profiles of the electricity consumption mix in the EU-27, Norway, Switzerland and the UK, taking into account the electricity consumption mix in individual countries. Their results were consistent and comparable for climate change and ozone depletion, except for the ReCiPe 2016 method, and acidification and eutrophication, except for the IMPACT 2002 + method. They concluded that the choice of the LCIA method in terms of climate change does not have a significant impact on the final LCIA results. On these premises, among all the impact categories of the CML method, only the global warming potential (GWP) was investigated, as representative of climate change. Also, the cumulative energy demand (CED) was calculated as a result of the energy consumption measurements.

The LCA analysis includes the LPBF process, the unpacking, depowdering and sandblasting. Functional units are the mass outputs of each job after sandblasting. Figure 2 depicts the scheme modeled in GaBi Sphera software, representative of all the scenarios, containing all the processes and fluxes considered. Thus, this work aims, on the one hand, to fill the gap of knowledge existing in the LCA databases in the AM regard, especially on the Powder Bed Fused processes such as the LPBF process, and, on the other hand, to release guidelines useful for decision-making from a sustainability perspective of typical scenarios in AM environments.

2.3 Life Cycle Inventory (LCI)

The second step of the LCA is the life cycle inventory (LCI) definition. It consists of the identification and quantification of the input and outputs of each process modeled within the fixed boundaries. They include energy inputs, materials and resources. Primary data were collected by means of direct measurements, whereas secondary data were taken by the technical documentation or the latest available literature. Cutoff rules were followed to decide whether processes had to be included in the product system. In particular, a cutoff level of 1% is applied in this work, which means that the process is neglected if it reaches less than 1% of the total known mass, primary energy and impact, focusing on uncertain processes during the use phase. Table 3, Tables 4, 5 and 6 contain input and output data used to model LPBF, unpacking, depowdering and sandblasting processes, respectively, within the software. For the LCI, energy consumption and AlSi10Mg parts/powders were experimentally measured, whereas argon, compressed air and sand were estimated by using technical documentation. In the mentioned tables, the label EM indicates that the data are experimentally measured, whereas the label TD indicates that the data are calculated based on a technical datasheet. In particular, according to the SLM500 datasheet (Ref 17), a flow rate of 50 L/min 6 bar was considered for the compressed air and a flow rate of 1 m^3/min of sand for sandblasting.

Table 3 LCI of the printing process

Resources	Data	INPUT (I)/OUTPUT (O)	Measurement unit	JOB 1	JOB 2	JOB 3	JOB 4
AlSi10Mg powders	EM	I	kg	39	44	50	64
Granusafe (silica)	EM	I	kg	6	7	9	9
Energy consumption SLM500	EM	I	MJ	233	311	417	651
Energy consumption chiller (printing)	EM	I	MJ	173	230	310	482
Argon consumption purging	TD	I	kg	125	150	175	200
Argon consumption process	TD	I	kg	375	450	525	600
Compressed air SLM500	TD	I	m^3	136.8	182.4	245.1	381.9
Coolant chiller (R410A) gas	TD	I	kg	36	48	65	100
AlSi10Mg as-built parts + powders	EM	O	kg	39	44	50	64
Waste	EM	O	kg	6	7	9	9

Table 4 LCI of the unpacking (PRS station)

Resources	Data	INPUT, I/OUTPUT, O	Measurement unit	JOB 1	JOB 2	JOB 3	JOB 4
AlSi10Mg as-built parts + powders	EM	I	kg	39	44	50	64
Energy consumption chiller (unpacking)	EM	I	MJ	10	10	10	10
Energy consumption unpacking station	EM	I	MJ	0.5	0.5	0.5	0.5
Argon consumption unpacking	TD	I	kg	80	110	130	150
Compressed air unpacking	TD	I	m^3	4388	4388	4388	4388
Coolant chiller (R410A) gas	TD	I	m^3	2.25	2.25	2.25	2.25
AlSi10Mg as-built parts + excess powders	EM	O	kg	3.9	4.4	5	6.4
AlSi10Mg powders	EM	O	kg	35.1	39.6	45	57.6

Table 5 LCI of the depowdering

Resources	Data	INPUT, I/OUTPUT, O	Measurement unit	JOB 1	JOB 2	JOB 3	JOB 4
AlSi10Mg as-built parts + excess powders	EM	I	kg	3.9	4.4	5	6.4
Energy consumption depowdering	EM	I	MJ	1	1	1	1
AlSi10Mg as-built parts	EM	O	kg	2.48	2.71	3.94	4.24
Powders	EM	O	kg	1.42	1.69	1.06	2.16

Table 6 LCI of the sandblasting

Resources	Data	INPUT, I/OUTPUT, O	Measurement unit	JOB 1	JOB 2	JOB 3	JOB 4
AlSi10Mg as-built parts	EM	I	kg	2.48	2.71	3.94	4.24
Energy consumption sandblasting	EM	I	MJ	0.24	0.24	0.24	0.24
Sand	EM	I	kg	10	10	12	12
Compressed air	TD	I	m^3	100	100	100	100
Waste (sand + AlSi10Mg powders)	EM	O	kg	10.05	10.05	12.08	12.08
AlSi10Mg surface-treated parts	EM	O	kg	2.43	2.66	3.86	4.16

In this regard, it is paramount to underline that technical datasheets contain nominal consumption of the flow rate of both argon and compressed air, which were used in this work for the resource calculations used in the LCI. Nevertheless, in the real case, actually, their flow rate can easily fluctuate over time, being lower than estimated. Thus, a limitation of this work, since technical datasheets were used to estimate the resources' consumption, is that compressed air and argon consumption can be overestimated. That means that the results of the LCA presented in this work represent the worst possible case.

Aside from the previously mentioned assumptions, additional ones had to be made. The power usage during unpacking was deemed equivalent to that of the argon purging process after analyzing the logfiles and overlapping them with the on-site data. During unpacking, power for the vacuum and argon is needed. This process is similar to the argon purging process for the printer where the machine draws constant idle power, and argon flooding takes place. For all the jobs, it has been estimated a 5% powder was eliminated by the depowdering (Ref 18).

3. Results and Discussion

3.1 Life Cycle Impact Assessment (LCIA) and Interpretation

As stated in the previous section, LCA was divided into three life cycle stages: printing, unpacking, depowdering and sandblasting. All the stages included inputs and outputs of all the consumables, which are energy consumption, argon, compressed air and materials. Four scenarios have been compared, considering four different production mixes, as described in Table 2, which are a few medium parts, a few big parts, many medium parts and many small parts. Thus, the functional units are mass printed (parts + supports) and post-processed by sandblasting. As mentioned above, among all the impact categories of the CML method, only the GWP was investigated. Moreover, the CED was calculated and compared as a result of the energy consumption measurements. Figure 3 and 4 illustrates the GWP and CED, respectively, for all the scenarios investigated for all the processes modeled. Printing is the stages producing the greatest amount of kg CO2 eq., followed by unpacking, sandblasting and depowdering. In particular, the printing stage produced 169.81 kg CO_2 eq., 209.76 kg CO_2 eq., 255.4 kg CO_2 eq. and 325.53 kg CO_2 eq. for scenario 1, scenario 2, scenario 3 and scenario 4, respectively. Among all the stages modeled, printing results in about 88% of the total GWP, as observable in Fig. 5(a). That means that printing is the stage under investigation which deserves more attention to find strategies to make it less environmentally impactful. Among all the resources used in printing, unpacking, depowdering and sandblasting, argon is the resource which mostly affects the GWP, followed by the energy consumption, as observable in Fig. 5(b). Thus, strategies should be found to minimize argon consumption during printing. Moreover, CED represents the total energy consumption of all the experimentally monitored subsystems, which are the SLM500, the chiller, the unpacking station, the powder aspirator and the sandblasting machine. Figure 4 and 6 displays the CED values and percentages, respectively, for all the processes/subsystems modeled within the Software. CED for printing and post-processing linearly depends on the time, fixing the power consumption average (Ref 19-21). Thus, as shown in this study, CED can be almost 3 times higher if the total process time is 3 times higher (Fig. 4). Printing is the stage which requires the greatest amount of energy consumption. During this stage, the SLM500 is the subsystem requiring the greatest amount of energy consumption (55%), followed by the chiller (41%). The SLM500 machine integrates different subsystems, such as the laser which mostly affects energy consumption. Power consumption of the laser depends linearly on the laser power, and strategies to optimize process conditions are required to minimize the total energy consumption for printing LPBF parts without sacrificing the quality of the parts (Ref 22-24). Aside from the energy demands for the lasers, energy is also required by a chiller to constantly supply cooling liquid to the lasers. This is necessary to attain a stable and appropriate temperature for melting the substrate; otherwise, the printing quality will fluctuate throughout the part. According to the results, it is very energy-consuming, since it works for the same duration as LPBF. Thus, chillers that are more energy efficient are needed to reduce the overall energy consumption for printing LPBF parts. Even if the total mass of the printed parts (and supports) is very similar among the production mix, the total volume of the printed parts strongly affects the printing duration and so the total energy consumption, as observable in Fig. 7.

3.2 Sensitivity Analysis

After the investigation of the four jobs, a sensitivity analysis was carried out. The sensitivity analysis allows us to examine how changes in resource input, resulting in different scenarios, affect the environmental impact. According to the results obtained and discussed in the 3.1 section, three other scenarios were investigated: scenario 5, scenario 6 and scenario 7. Scenario 5 consists of a 30% reduction in argon during printing, scenario 6 consists of a 30% reduction in the energy consumption of the chiller during printing and scenario 7 consists of a 30% reduction in argon during printing and a 30% reduction in the energy consumption of the chiller during the printing. The job reference chosen is scenario 4. Figure 8 depicts the results in terms of GWP due to the printing as a result of the comparison among scenario 4, scenario 5, scenario 6 and scenario 7. It can be observed that a reduction of 30% in argon consumption during the printing results in up to 18.4% reduction of kg CO_2 eq. (scenario 5), a reduction of 30% in chiller electricity leads to 5% reduction of kg CO_2 eq. (scenario 6), whereas a reduction of both 30% in argon consumption

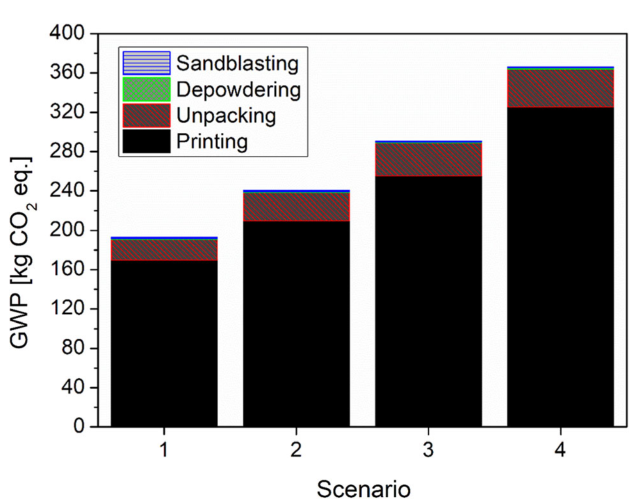

Fig. 3 GWP for all the scenarios and processes modeled

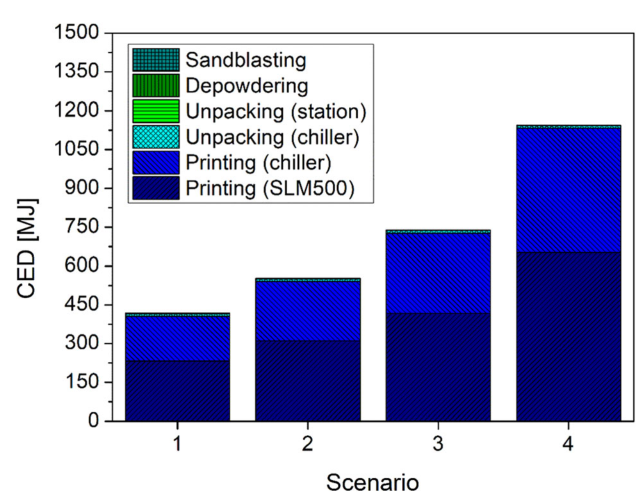

Fig. 4 CED for all the processes/subsystems modeled

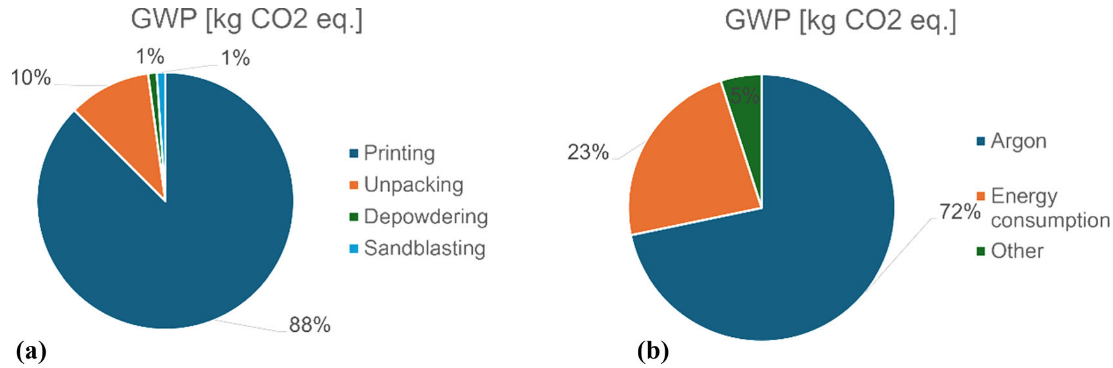

Fig. 5 GWP percentages for all the modeled processes/subsystems (a) and resources (b)

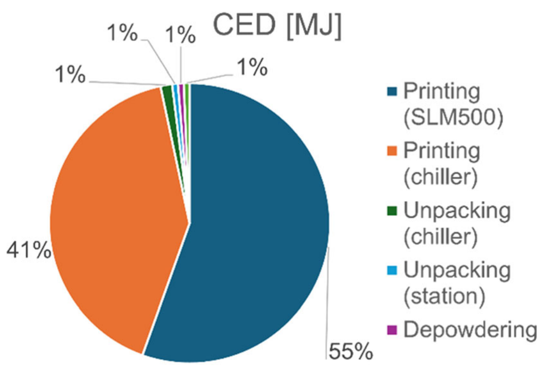

Fig 6 CED percentages for all the resources used for the modeled processes

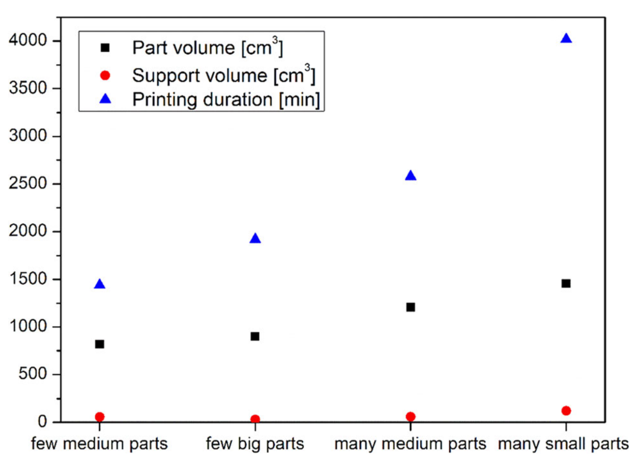

Fig. 7 Part volume, support volume and printing duration for all the scenarios of production mixes investigated

during the printing and 30% in chiller electricity (scenario 7) results in up to 23.3% GWP reduction.

It is clear that the scenario 7 represents the best possible one among those investigated since it provides the reduction of both the 30% in energy consumption and the 30% in the argon consumption during the printing. To realize scenario 7, two aspects should be considered: the first one regards the possible use of a chiller that is more energy efficient, the second one would consist in a more efficient use of the argon during the

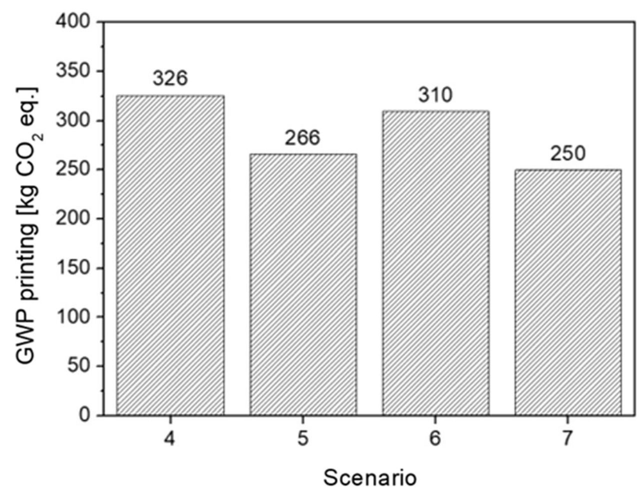

Fig. 8 GWP due to the printing stage: sensitivity analysis results

printing. The power and energy consumption of the chiller were recorded during the printing of all the jobs, so the energy consumption was not overestimated.

As mentioned above, one of the limitations of this work is that compressed air and argon consumption can be overestimated, since technical datasheets of the subsystems used to perform to manufacture and post-process the LPBF parts were used to estimate their resources' consumption.

Especially concerning argon consumption, the literature on this point has been very contradictory. Most of the studies existing in the literature in this regard underestimated the quantity of consumed argon for the process. Moreover, results obtained by comparing the scenarios investigated in this work and by the sensitivity analysis show that effectively the consumption of the argon is very high, and that its reduction could strongly affect the environmental impact of the LPBF process. Nevertheless, further studies should include the use of fluxmeters to experimentally measure and record over time argon consumption, and compressed air as well, for LPBF process. That would be of paramount importance to investigate potential strategies to reduce and optimize their consumption without sacrificing the needed inertization of the processes.

Another point which needs to be considered is the fact the AM process considered in this work, that is the LPBF, is subject to rapid technological evolution. This means that their LCI would potentially need to be updated or outdated in the future. In this regard, the integration of patent analysis should be taken into consideration in future because it could help in the extraction of prospective data, thus making the LCA results more prospective. In fact, to the current state of the art, LCA analyses make use of data extracted from different sources, such as scientific publications, and simulations, as well as direct measurement in laboratory-scale environments or industrial AM factories, like the primary data used in this work. Nevertheless, patents have the additional ability to reveal data about immature technologies, whose analysis and use within LCA software could be useful to forecast and evaluate the future impacts of the new technologies, thus predicting the potential environmental, economic and social impacts, which are the pillars of the sustainability (Ref 25). Currently, patents are not highly used for the LCA but, since their potentialities, should need to be used more in future LCA analyses, especially regarding immature and newly developed technologies/products. It could be also helpful in scaling up them because of their sustainability benefits derived from LCA of patents.

In this work, the same process conditions were used for all the jobs. Literature (Ref 26) showed that energy consumption and specific energy consumption (SEC) depend linearly on the volumetric energy density (VED), which also rules the mechanical properties and the surface roughness of the parts. Because of the different thermophysical properties of the materials, different ranges of VED are suitable for printing different materials. Also, results existing in the literature in this regard showed the Ti-6Al-4 V alloy exhibits low thermal conductivity, while the AlSi10Mg alloy demonstrates high thermal conductivity under certain LPBF conditions (Ref 27). This means that by varying the VED, which can be chosen in a specific range to obtain specific mechanical properties and surface roughness for specific materials, the energy consumption of the LPBF varies, thus affecting the LCI of the LPBF process. Also, another crucial aspect derived from this work is argon consumption. Thus, optimization of the argon consumption is also needed for the most widely used materials in LPBF, including aluminum, titanium and nickel alloys, because it also plays a crucial role in the LCA.

Finally, it is important to underline that in this work the stages before the printing have not been considered for two reasons. First of all, the idea of this work was to compare four different scenarios of LPBF in AM factories to print parts by using the same machines and metal powder alloy, so in the absence of material variation, the results would not have been affected so much by the previous stages in the comparison of the four scenarios. Then, this study aimed to carry out LCA by using mostly experimentally measured data of energy and resources to give added value to the existing literature. Previous stages such as the gas atomization would be of great interest to be experimentally monitored and investigated from the LCA perspective. Thus, further research is required, as well as the availability of sharing process data by the powders' supplier for a clear and precise environmental assessment. The usage of measured data is highly encouraged to reflect reality as closely as possible. For AM factories, it is advised to maximize the usage of their PBF machines, to turn off argon gas as soon as possible, to print with a chamber utilization rate as high as possible and to minimize leakages in the form of argon and compressed air.

4. Conclusions

In this work, gate-to-gate LCAs of typically printed AlSi10Mg LPBF jobs in AM factories have been carried out. Four scenarios of different production mixes have been performed and monitored to be investigated from an LCA perspective. LCA was divided into three life cycle stages: printing, unpacking, depowdering and sandblasting. All the stages included inputs and outputs of all the consumables, which are energy consumption, argon, compressed air and materials. The main conclusions that can be enucleated are the following:

- Printing is the stage producing the greatest amount of kg CO2 eq., followed by unpacking, sandblasting and depowdering. Among all the stages modeled, printing results in about 88% of the total GWP. Printing is also the stage which requires the greatest amount of energy consumption. During this stage, the SLM500 is the subsystem requiring the greatest amount of energy consumption (55%), followed by the chiller (41%).
- Among all the resources used in printing, unpacking, depowdering and sandblasting, argon is the resource which mostly affects the GWP, followed by energy consumption. For printer manufacturers, recycling argon during printing and minimizing the argon needed during flooding would be a solution to mostly reduce the carbon footprint.
- During the printing, the SLM500 is the subsystem requiring the greatest amount of energy consumption (55%), followed by the chiller (41%).
- Even if the total mass of the printed parts (and supports) is very similar among the production mixes, the total volume of the printed parts strongly affects the printing duration and so the total energy consumption.
- From the sensitivity analysis carried out in this work, it has been observed that a reduction of 30% in argon consumption during the printing results in up to 18.4% reduction of kg CO2 eq., a reduction of 30% in chiller electricity leads to 5% reduction of kg CO2 eq., whereas a reduction of both 30% in argon consumption during the printing and 30% in chiller electricity results in up to 23.3% GWP reduction.

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Author Contribution

Ersilia Cozzolino was involved in conceptualization, data curation, formal analysis, methodology, investigation, software, validation, visualization, writing–original draft and writing–review and editing. Ilaria Papa was responsible for writing–review and editing, conceptualization, validation and supervision. Antonello Astarita took part in conceptualization, funding acquisition, supervision, resources and project administration.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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