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Laser powder bed fusion (L-PBF) additive manufacturing: On the correlation between design choices and process sustainability

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Abstract

The specific energy consumption of Additive Manufacturing (AM) unit processes for the production of metal parts could be much higher than that of more traditional manufacturing routes, such as machining. However, AM, due to its intrinsic process peculiarities, including the flexible realization of (almost) any kind of complex shape, has a great potential for improving the material use efficiency, with positive environmental impact benefits from the material production to the product use and disposal at the end of first life. Aim of this paper is to assess the role of the design choices on the environmental AM process sustainability. An integrated design methodology (accounting for the product re-design via topological optimization, the design of support structures, and the design of allowances and features for post-AM finishing operations) for components produced by means of laser powder bed fusion processes is considered. One resource (the cumulated energy demand) and one emission (carbon dioxide) are assumed as metrics for the impact assessment across the product life cycle. The results demonstrate the importance of a proper design for AM to improve the overall energy and emission saving potential.

Keywords: Additive Manufacturing; Sustainability; Design

1. Introduction

Additive Manufacturing (AM) is nearly to be broadly adopted in industrial production. The strategic analyses of the Boston Consulting Group (BCG) show that the growth rate of AM market is exponential. In 2015 it had already reached about 5 billion dollars; today an annual raise of almost 30% is expected up to 2020. Hypothetically, if by 2035 AM will be adopted by at least 1.5% of the manufacturing market, the AM market alone would exceed 350 billion dollars [1]. Especially, metal-based AM technologies constitute an increasingly important market share. The current scenario shows that metal powder bed fusion (PBF) processes are the leading AM technologies for the production of industrial metallic components. Among the PBF technologies, Laser-based PBF (L-PBF) processes are currently able to produce metal parts with a complex shape suitable for high demanding applications in space, aerospace, medical, and racing fields [2, 3]. The range of materials available for L-PBF processes is in continuous growth and the mechanical properties of AM components are comparable with those of analogous parts fabricated with conventional technologies [4]. However, from an economic point of view, AM parts are often more expensive than conventional ones. Thus, the designers should take full advantage of the new opportunities given by L-PBF processes, creating added value for the products. This objective can be achieved by designing

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parts capable to improve functionality and reduce weight at the same time, without losing sight of the technical requirements [5]. The re-design offering functional advantages during the product use has proved to be beneficial also from the environmental perspective, as reviewed in Kellens et al. [6]. The higher unit material and manufacturing impacts of AM can be compensated by energy and emissions savings in the use phase, making AM an environmental friendly strategy for some domains. The aim of this paper is to verify, for a specific case study, to what extent a re-design approach has an effect on the environmental performance across the life cycle of a product.

2. Case study description

The case study is a bearing bracket whose geometry has been taken from the GrabCAD Airplane Bearing Bracket Challenge [7]. The component is supported by a high stiffness plate and fastened with four #10-32 high strength bolts. The component (Figure 1) is loaded at the center of the bearing case with three different load cases: a horizontal load of 1,300 N, a vertical load of 2,500 N, and a 45-degree inclined load of 2,000 N. The design material is an EOS Aluminium AlSi10Mg, that is assumed to be isotropic and linear elastic. The selection of this case study is expected to influence the outcomes of the research.

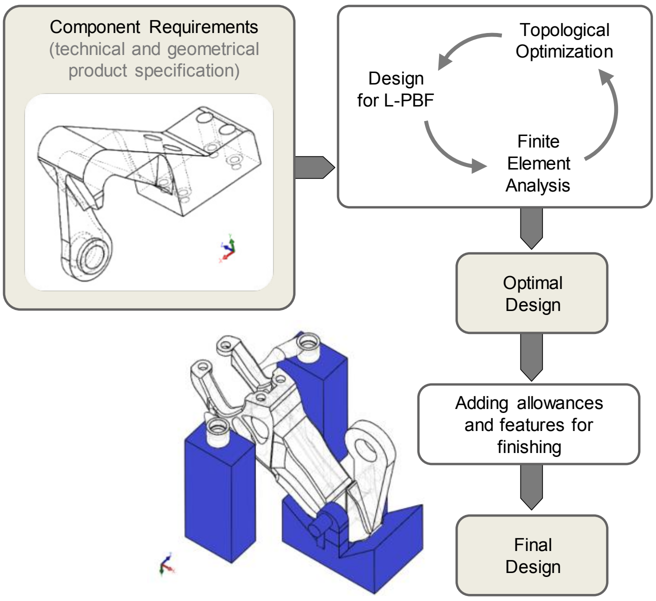

Figure 1. Main steps of the re-design procedure. Adapted from [8].

3. Product re-design

The component is re-designed for minimizing its mass. The re-design approach is illustrated in Figure 1 and brings together Topology Optimization (TO) techniques, designing rules for L-PBF, Finite Element Analysis (FEA) and finishing requirement considerations in order to maximize the AM benefits. Starting from the component requirements, the optimal geometry of the bracket is achieved after performing three loops of TO, design for L-PBF, and FEA [8]. The goal of the TO task is to minimize the mass while considering as a constraint that the maximum Von Mises stress must remain below the yield strength. Then, the optimal design of the bracket is edited in order to optimize the building phase, taking into consideration process variables such as orientation and supports, and to add allowances and features for finishing. In this way, the final design of the component is obtained. Further details can be found in [8].

4. Environmental impact assessment

A model for quantifying, under cradle-to-grave boundaries, the energy requirements and carbon dioxide emissions in an integrated additive-subtractive manufacturing approach was recently proposed by Priarone and Ingarao [9]. Such a model was already applied to assess the environmental impact of additively manufactured (by means of an EBM process) and finish machined components made of Ti-6Al-4V, focusing on either the material-usage efficiency [10] or the influence of the re-design for AM [11]. The same methodology is exploited in the present paper to evaluate the correlation between the product / process design choices (as discussed in Section 3) and the sustainability of the L-PBF-based integrated approach when manufacturing an AlSi10Mg component. The considered flows of material, energy, and CO_2 emissions (regarding the metal powder production, part production, use, and disposal phases) are recalled in Figure 2. The data inventory through the entire life cycle of a single re-designed component, which is here assumed as functional unit for the assessment, is detailed in the following. The impact of transportation is left out of the boundaries of the analysis, since it could be neglected on a per-part basis evaluation [10, 11].

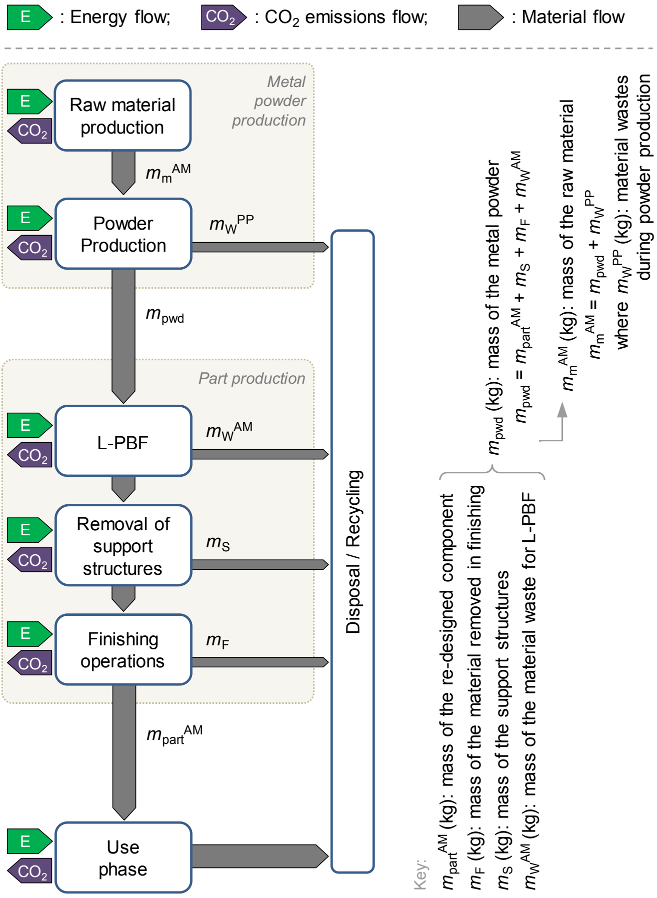

Figure 2. Energy, CO_2 emissions, and material qualitative flows for the L-PBF plus finish machining approach. Adapted from [9-11].

Regarding the flow of material, the mass of the component (m_{part}^{AM}) was determined by the re-design strategy. Also, the mass of allowances and datum / sacrificial features for post-AM machining operations (m_F) hinged on the designer's choice and on the geometrical product specifications. The mass of the support structures (m_S) is related to the orientation of the part within the working volume of the L-PBF machine, and three scenarios were considered for the present case study [8].

Table 1. Main material flows for the case study.

Mass	Value
- of the re-designed component, m_{part}^{AM} (kg)	0.105
- of the material removed in finishing, m_F (kg)	0.011
- of the support structures, m_S (kg)	*(i)* 0.248; *(ii)* 0.032; *(iii)* 0.047
- of the metal powder, m_{pwd} (kg)	*(i)* 0.364; *(ii)* 0.148; *(iii)* 0.163
- of the raw material, m_m^{AM} (kg)	*(i)* 0.382; *(ii)* 0.155; *(iii)* 0.171

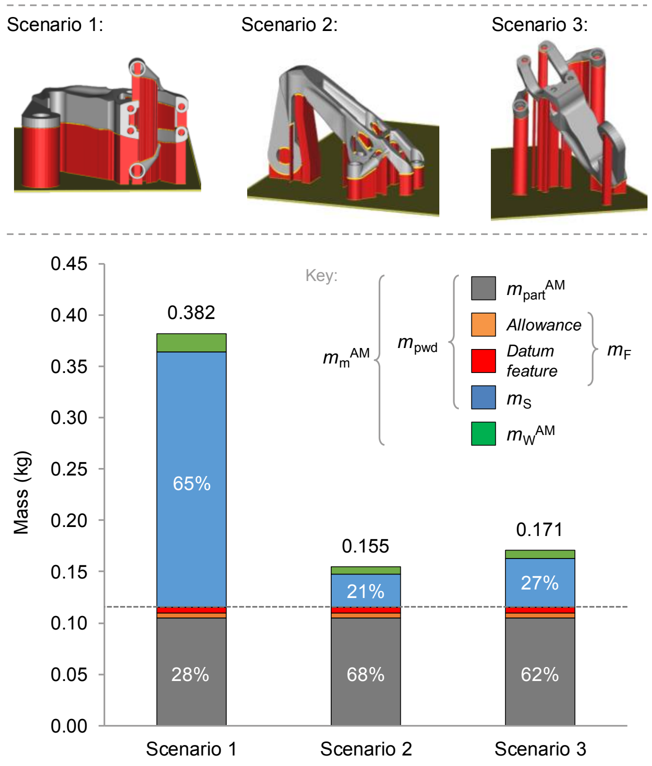

Figure 3. Material flows as a function of the considered scenario. The pictures have been adapted from Salmi et al. [8].

The amount of material waste during the AM process was overlooked ($m_W^{AM} \approx 0$), being that (*i*) the unused aluminium powder can be reused in subsequent jobs, and (*ii*) the material losses due to residues accumulated in the system filters, emissions of aerosols, and sieve filtering of reused powder can be assumed to be negligible, as mentioned in Faludi et al. [12]. Therefore, the amount of AlSi10Mg powder (m_{pwd}) accounts for the volume lost to print the part ($m_{part}^{AM} + m_F$) and the support structures (m_S) [11]. As for the pre-manufacturing phase, the metal powder has to be produced from the raw material by means of a gas atomization process. In order to account for the material wastes during powder production (m_W^{PP}), a yield value (representing the input material weight necessary to obtain 1 kg of output material) of 1.05 was assumed, according to Lavery et al. [13]. The main material flows are quantified in Table 1 and plotted in Figure 3. The different densities of printed part and support structures have been taken into due account.

4.1. Powder production

The average eco-properties of the aluminium alloy were obtained from the CES Selector 2017 database [14]. The 'substitution method' and 'recycled content approach' (as defined by Hammond and Jones [15]) were both applied to compute the recycling benefit awarding. The same methodologies were exploited by the authors in previous research studies (e.g., [9-11]), particularly when the impact assessment of the material usage has been a factor of utmost interest. The recycle fraction in the actual material supply and the end-of-life recyclability (of both process scraps and component material) were fixed to 0.43 and 0.90, respectively [14, 16]. The powder production by atomization was modelled by adding 8.1 MJ/kg of embodied energy to that of the raw material, and this energy was assumed to come from natural gas burned in an industrial furnace [12], as listed in Table 2. The embodied energy and the carbon footprint arising from the inert gases used during the powder production were neglected, with particular reference to [12, 17].

Table 2. Eco-attributes of the AlSi10Mg material.

Eco-Property	Average
Embodied energy, primary production (MJ/kg)	189.0
CO_2 footprint, primary production (kg/kg)	12.1
Embodied energy, recycling (MJ/kg)	32.7
CO_2 footprint, recycling (kg/kg)	2.6
Energy demand for powder atomization (MJ/kg)	8.1
CO_2 footprint for powder atomization (kg/kg)	0.5

4.2. L-PBF additive manufacturing

Values for the Specific Energy Consumption (SEC) of the L-PBF additive manufacturing process could be obtained from the data published by Faludi and colleagues [12], who measured the electric energy consumption when selective laser melting an AlSi10Mg alloy. In the maximum energy efficiency condition, which corresponds to the full build configuration [18], a specific electric energy consumption (including ancillaries, active processing phase and non-processing modes) of approx. 566 MJ/kg of deposited material could be supposed. To allow the comparison of embodied energies and processing energies at the same energy level, the electrical energy was corrected back to the primary energy by assuming a conversion efficiency value, which was set at the European average of 0.38 [19]. The related consumption of fossil fuels and the CO_2 emissions are country-specific. An average carbon intensity of electricity consumed at low voltage for the EU 28 member states was assumed to be 0.12 kg/MJ [20]. In general, it is permissible to ignore the impact of protective gases during build, according to [12].

4.3. Post-AM finishing operations

After the build completion, the support structures (weighing m_S) were manually removed. In such a case, the contribution of support removal to energy demand and carbon emissions can be neglected, although all the activities requiring an operator have a significant impact on cost assessment [8]. It is worth remarking that the environmental assessment of the removal of support structures becomes non-negligible if EDM systems are employed [12]. CNC milling was envisaged in order to achieve the imposed tolerances and surface quality in coupling surfaces, and a machining allowance was added, where needed, during the part design phase. Fine machining average energy and CO_2 emissions (per unit weight removed) were estimated to be 6.6 MJ/kg and 0.40 kg/kg [14]. Moreover, it was assumed that the removal of datum / sacrificial features can be manually done. The environmental impact of CNC tooling and fixtures is also insignificant on a per-part basis assessment when a batch of several units has to be produced. The finishing operations ended with a shot peening process. Overall, given the modest consumption of the equipment and the limited process time, the electric energy demand for this latter operation was negligible when compared to all the other contributions.

4.4. Use phase

The fuel consumption of a transportation system depends on its weight, and light-weighting can heavily contribute to the reduction of energy consumption and carbon emissions. The saving estimates for aircrafts can hardly be expressed by a single coefficient, according to Helms and Lambrecht [21], who quantified the use phase primary energy savings for a 100 kg-weight reduction in the range between 10 - 20 TJ or 20 - 30 TJ for short- or long-distance aircrafts, respectively, over a lifespan of 30 years. The reduction in CO_2 emissions are directly related with the carbon footprint of the fuel (i.e., 0.068 kg/MJ for kerosene [19]). Some industrial data are also available. In the case of an Airbus A340-600, Lufthansa estimated fuel savings of 47 tons per aircraft and year for a weight reduction of about 900 kg. In the same report, it has been stated that one kg less on all aircrafts of Lufthansa German Airlines saves 30 tons of kerosene per year [22]. Another study from SKF shows how a weight reduction of 110 kg on an aircraft holds potential for a reduction in emissions of $CO_{2\text{-eq}}$ of nearly 33 tons per year [23].

4.5. AM versus conventional production

In order to evaluate the environmental performance of the AM-based manufacturing approach, the subtractive approach can be considered as a benchmark for process comparison [11].

Table 3. Eco-attributes of the Al 7075 (T6) material.

Eco-Property	Average
Embodied energy, primary production (MJ/kg)	193.5
CO_2 footprint, primary production (kg/kg)	13.2
Embodied energy, recycling (MJ/kg)	33.3
CO_2 footprint, recycling (kg/kg)	2.6
Energy demand for workpiece forming (MJ/kg)	11.2
CO_2 footprint for workpiece forming (kg/kg)	0.8
Energy demand for machining (MJ/kg)	5.1
CO_2 footprint for machining (kg/kg)	0.4

The same component, made of an Al7075 T6 alloy and designed for milling, would have a weight of 0.279 kg and could be obtained by removing 0.851 kg of chips from a workpiece weighing 1.130 kg (with a buy-to-fly ratio of approx. 1:4). Table 3 lists the average eco-properties of the material, which were extracted from the CES Selector software [14]. As for the recycle fraction in the current supply and the EoL recyclability, the values already defined in Section 4.1 were confirmed. A forming process was considered for the workpiece pre-manufacturing phase [9-11], assuming a yield value of 1.25 [16]. The energy demand and the carbon footprint for machining were both calculated by hypothesizing a process undertaken in subsequent roughing (80% of chip removal) and finishing (20% of chip removal) cutting conditions.

5. Results and discussion

The average values collected in Section 4 were used to assess the contribution of each phase of product life to the cumulated energy demand and to the total carbon dioxide emissions.

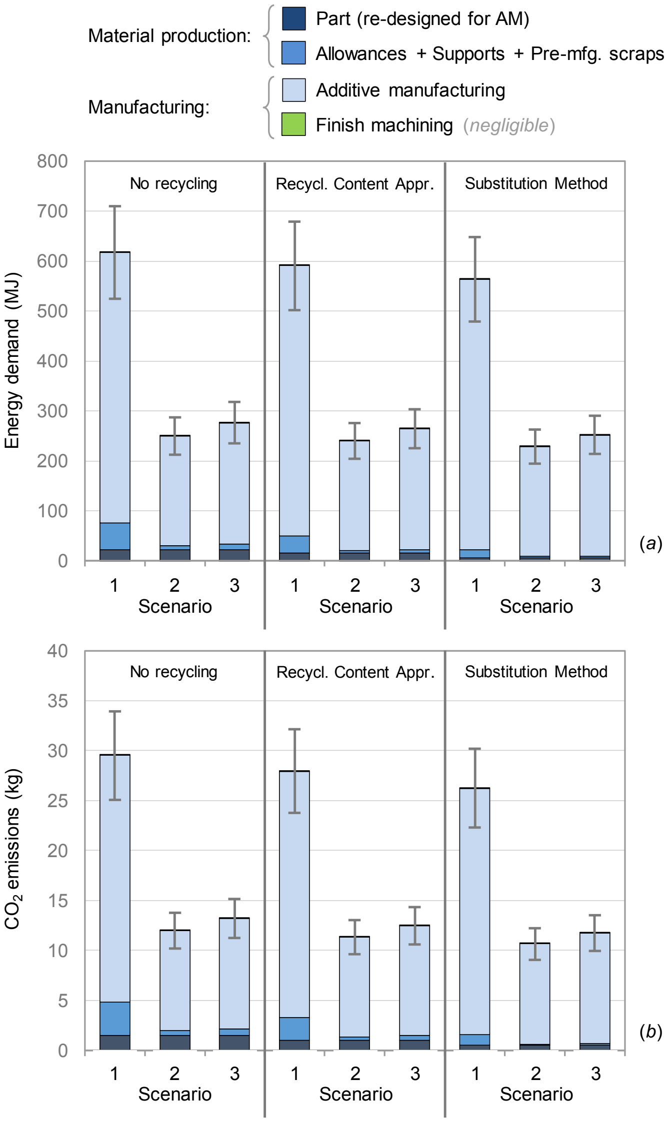

Figure 4. Energy demand (*a*) and CO_2 emissions (*b*), under cradle-to-gate system boundaries, for producing the part via the AM-based approach.

The two metrics were selected for the ease of understanding of the research outcomes [24]. The results, obtained by considering cradle-to-gate plus EoL system boundaries (i.e., by assessing material production - including recycling benefit awarding - and part manufacturing phases) for the AM-based approach and the subtractive approach are plotted in Figure 4 and Figure 5, respectively. Each bar was computed by using the average values of the eco-properties. It is worth to remark that the precision of much eco-data could be low [19]. The aluminium production has proved to be affected by a geographically-dependent variability [16]. A certain process performance variability is also expected due to the different equipment available on the market. A first-attempt ± 15 % range of variation of all the data taken from literature (i.e., all the values listed in Tables 2 and 3 and mentioned in the Sections from 4.2 to 4.4) was supposed to further comment about the reliability of the results. The error bars in Figures 4 and 5 show the variation range of the total results obtainable by considering the input data variability.

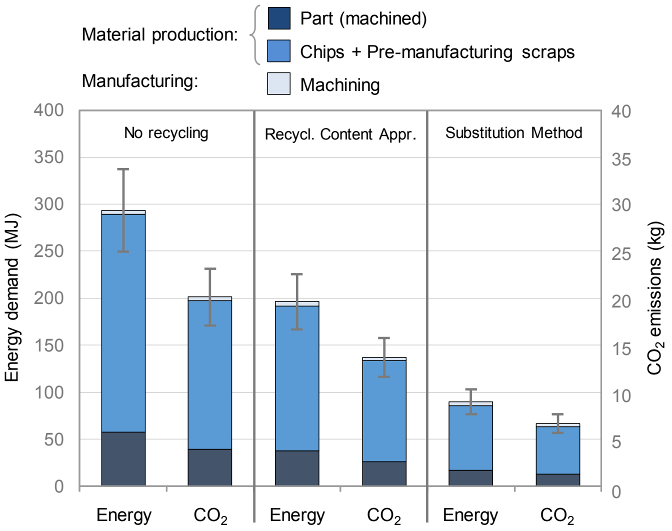

Figure 5. Energy demand and CO_2 emissions, under cradle-to-gate system boundaries, for producing the part via the machining approach.

The results prove that the impacts of the AM-based approach (in Figure 4) were dominated by the high specific energy demand of the additive manufacturing process itself. Vice versa, the share due to the material production was the main contribution for the subtractive approach (in Figure 5), as highlighted in [16]. The choice of the optimal positioning of the part in the chamber of the AM machine was confirmed to be a critical parameter. Moreover, the re-design for AM allowed a weight reduction of the additively manufactured component with respect to the machined one of about 62% (0.105 kg versus 0.279 kg), with a substantial reduction of the raw material needed for the two manufacturing approaches (0.155 kg for the Scenario 2 of the AM-based approach versus 1.413 kg for the subtractive approach). Therefore, the amount of material being recycled and the choice of the model used to quantify the related benefit awarding (i.e., the recycled content approach or the substitution method [15]) both entailed a noticeable variation in the results for machining, while the results for AM underwent a much less significant reduction. Overall, when the results of the best case (Scenario 2) of the AM-based approach are compared with those of the subtractive manufacturing, it can be noticed that: (*i*) if no material recycling processes are considered (i.e., all the raw materials derive from primary production), the AM-based approach allows obtaining results comparable or even better with respect to the conventional manufacturing route; (*ii*) if the embodied energy of the material is computed by using the substitution method, the subtractive approach is the less impacting.

5.1. The role of the use phase

It should be emphasized that the aforementioned comments are valid and limited to the boundaries of the cradle-to-gate plus EoL study. Hence, the benefits deriving from the use phase have not been considered yet. The re-design phase involved a light-weighting on the single part equal to 0.174 kg. Being a component for aeronautical applications, the reduction of the impact in terms of primary energy consumption and CO_2 emissions during the use phase can be quantified.

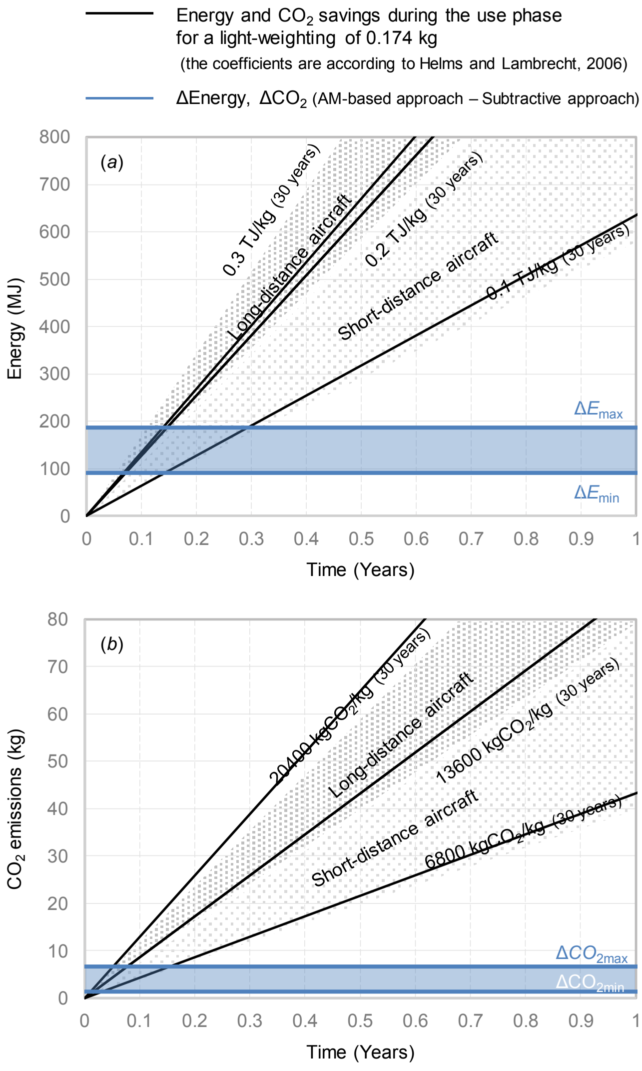

Figure 6. Energy and CO_2 savings during the use phase.

The benefits related to light-weighting can be evaluated for the specific case study as a function of the time of use (on the basis of the different suggestions reviewed in Section 4.4), as shown by the black lines in Figure 6. Therefore, the possible increase in primary energy demand and CO_2 emissions (noticed under cradle-to-gate plus EoL assessment boundaries) which is due to the adoption of the AM-based manufacturing approach instead of a conventional one could be compensated by the in-use fuel savings. A break-even point can be generally identified [16]. In the hypothesis of accounting for the material recycling benefit awarding by means of the substitution method [15], the computed maximum (ΔE_{max} or ΔCO_{2max}) and minimum (ΔE_{min} or ΔCO_{2min}) differences between the additive-based approach (for the Scenario 2) and the subtractive-based one are added (in blue colour) to Figure 6. The results show that, even in the worst case, the break-even point occurs after a few months of component use, allowing an overall saving during the entire life cycle of the product (here assumed to be equal to that of the aircraft), as already highlighted in [11] for another case study. It should be noted that the extent of the benefits obtainable during the use phase due to light-weighting is of such a magnitude that it also compensates for any underestimation of the influencing factors of material production and part manufacturing (such as post-AM processes or stress relieve treatments, which were here neglected). Therefore, these results confirm the evidences already published in the literature [6].

6. Conclusions and outlooks

An integrated design approach for a laser powder bed AM process and an environmental impact assessment method were both applied in this paper, by assuming an airplane bearing bracket as a case study. The two methodologies, which were developed previously and separately by the authors, have proved to complement one another. In fact, the here presented results show that the choices made during the part re-design phase, which shall account for the process setup, not only add value to the additively manufactured component, but also have a significant influence on the cumulated energy demand and the carbon dioxide emissions. It is widely accepted that the specific energy consumption values of AM processes for the production of metal components are considerably higher than those of more traditional processes. However, it is evident that the comparison among different manufacturing routes should not be made for an identical produced component. AM allows achieving a light-weighting due to the capability of realizing (almost) any kind of complex shape. This results in environmental impact savings during both the material production and the use phase (if the component is a part of a transportation system). Overall, the manufacturing route has to be assessed within the wider framework of the entire component's life cycle. It is worth remaking that further experimental experiences are needed to make a more reliable inventory available, which would provide much accurate results.

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