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The role of re-design for Additive Manufacturing on the process environmental performance

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Abstract

At present, economic and technological design criteria for products and processes should be matched with the minimization of environmental impact objectives. Manufacturing, material production, and product design are strictly connected stages. The choice of a production system over another could result in significant material and energy/resource savings, particularly if the component has been properly designed for manufacturing. In this scenario, Additive Manufacturing, which has been identified as a potential disruptive technology, gained an increasing interest for the creation of complex metal parts. The paper focuses on the tools, based on the holistic modelling of additive and subtractive approaches, which could be used to identify the production route allowing the lowest energy demand or CO_2 emissions. The models account for the main process variables as well as the impacts due to the re-design for AM for the creation of components made of Ti-6Al-4V.

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Keywords: Sustainability; Additive Manufacturing; Life Cycle Assessment; Energy demand

1. Introduction

The potential of Additive Manufacturing (AM) for the production of end-use objects is nowadays well recognized. In order to fully exploit the available technologies, the design phase has to be reimagined as a function of the layer-by-layer component creation. In general, the literature highlights some pre-conditions directing the choice towards AM instead of traditional manufacturing processes, as machining. The part should be complex, requiring a labour-intensive and expensive production by means of conventional techniques. The surface quality should not be a critical issue, in order to minimize the post-AM processing steps. Low production volumes or small batch sizes have to be generally preferred [1, 2]. Klahn et al. [3] presented selection criteria to identify the components worth to be produced via AM, with respect to (*i*) the reduction of the number of parts to be assembled, (*ii*) the satisfaction of the customer needs by enhancing the product individualization, (*iii*) the possibility of the economic manufacturing of individual parts, since no tools and fixtures are required, and (*iv*) the weight reduction potential coupled with a more efficient design. Being the identified component capable to take advantages of the AM process, a re-design phase is needed. In this context, since the increase in shape complexity does not represent a constrain for the additive-based approach, the topology optimization has been widely applied. In such a way, high-strength and low-mass structural parts could be obtained [4, 5]. However, the choice of a manufacturing approach over another affects the environmental impact per produced part. Following the idea of creating decision-support tools for the selection of additive instead of subtractive manufacturing approaches [6], in this paper a methodology recently proposed by the authors [7] is extended and adapted to a typical case study. The main aim is to verify to what extent the re-design for AM could play a role in energy demand and carbon dioxide emission reduction.

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2. Methodology

Two different production approaches (in Figure 1), based either on machining or additive manufacturing, have been assessed. A cradle-to-grave analysis (recalled in the following) has been adopted to quantify the primary energy demand and the CO_2 emissions related to the life cycle of the components. A single part has been assumed as functional unit. The impacts of material production, part manufacturing, use, and disposal have been included [7]. The transportation-related impact has been excluded, even if logistics, volumetric and handling differences between the considered approaches are expected. However, the energy and CO_2 penalties for conventional transportation types (e.g., $0.94 \cdot 10^{-3}$ MJ/kg·km and $0.067 \cdot 10^{-3}$ kg/kg·km, respectively, for a 32-t diesel-engine truck [8]) provide a negligible contribution on a per-part based evaluation when small-to-medium moved weights and travelled distances are considered [9]. The methodological assumptions are discussed hereafter by accounting for the variability in Life Cycle Inventory data.

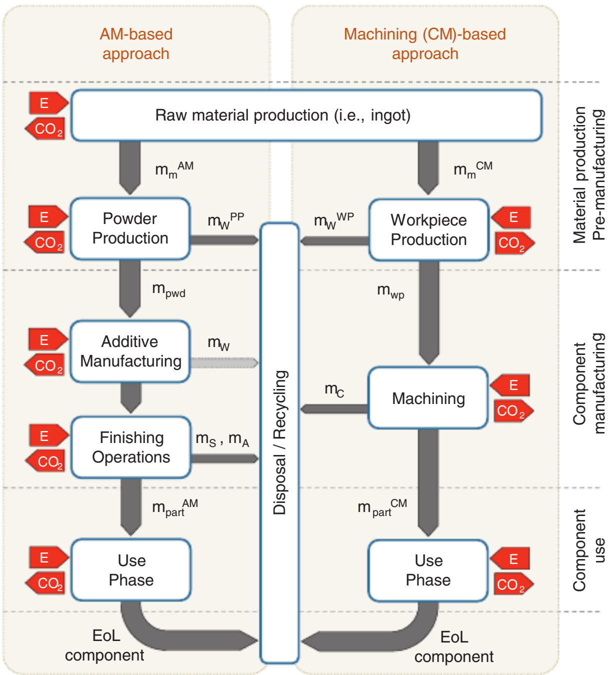

Figure 1. Energy, CO_2 emissions, and material qualitative flows for the AM- (*left*) and machining- (*right*) based approaches.

2.1. Material flows

The amount of raw material needed for both the AM-based (m_m^{AM}) and the machining-based (m_m^{CM}) approach has to be produced by means of primary and/or secondary routes (i.e., recycling), as depicted in Figure 1. Afterwards, each manufacturing approach requires a specific material input, and additional powder and workpiece production processes have to be considered, together with their resulting material wastes (m_W^{PP} and m_W^{WP}). In powder-bed AM processes, the unused powder could be reused in subsequent prints [10, 11]. Therefore, the mass of powder required for AM (m_{pwd}) has to compensate for the mass of component (m_{part}^{AM}) plus the mass of material wastes. During Electron Beam Melting (EBM), the in-process material losses (m_W) could be associated with sieve filtering of reused powder, residues accumulated in the system filters, emissions of aerosols, and platform separation operations [12]. The in-process material losses, amortized per each produced part, have been assumed to be negligible in the present study. Then, post-AM operations are needed to remove the support structures (weighing m_S) and, when necessary, to achieve a smoother surface finish. In this research, a material removal (i.e., milling) process has been supposed to guarantee the surface quality of coupling surfaces, and a machining allowance (m_A) has been considered. No other finishing processes were assumed. For the conventional machining approach, the exceeding material is removed from the workpiece (weighing m_{wp}) in the form of chips (m_C) to obtain the finished part. One of the key differences between the two approaches could be traced back to the masses of produced parts. The re-design for AM could lead to a reduction of the mass of the additively manufactured component while ensuring the same in-work performance of conventionally machined products. Therefore, a k factor (defined as the ratio of m_{part}^{AM} and m_{part}^{CM}) accounting for the light-weighting has been introduced in the analysis.

2.2. Environmental impact assessment

With respect to Figure 1, the total primary energy demand for the AM-based approach (E^{AM}, in MJ/part) could be computed according to Equation 1.

$$E^{AM} = \overbrace{m_m^{AM} \cdot E_E}^{Material\,production} + \overbrace{m_m^{AM} \cdot E_A}^{Powder\,production} + \overbrace{m_{pwd} \cdot E_{AM}}^{AM\ \ process} + \underbrace{m_S \cdot E_{SR} + m_A \cdot E_{FM}}_{Finishing\,operations} + E_{use}^{AM} \qquad (1)$$

where:

- m_m^{AM} : mass of raw material for the AM-based approach (kg);
- E_E : embodied energy of the raw material (MJ/kg);
- E_A : energy demand for atomization (MJ/kg);
- m_{pwd} : mass of powder needed for the AM-based approach (kg);
- E_{AM} : energy demand per unit weight of deposited material (MJ/kg);
- m_S : mass of the support structures (kg);
- E_{SR} : energy demand to remove the support structures (MJ/kg);
- m_A : mass of the machining allowance (kg);
- E_{FM}: energy demand for finish machining operations (MJ/kg);
- E_{use}^{AM}: energy demand for the use phase of the AM part (MJ/part).

The total primary energy demand for the machining-based approach (E^{CM}, in MJ/part) could be similarly quantified, as shown in Equation 2.

$$E^{CM} = \overbrace{m_m^{CM} \cdot E_E}^{Material\,production} + \overbrace{m_m^{CM} \cdot E_F}^{Workpiece\,production} + \underbrace{m_C \cdot E_M}_{Machining\,process} + E_{use}^{CM} \qquad (2)$$

where:

- m_m^{CM} : mass of raw material for the machining-based approach (kg);
- E_E : embodied energy of the raw material (MJ/kg);
- E_F : energy demand for workpiece forming (MJ/kg);
- m_C : mass of the machined chips (kg);
- E_M : energy demand per unit weight of removed material (MJ/kg), accounting for raw machining (E_{RM}) and finish machining (E_{FM});
- E_{use}^{AM} : energy demand for the use phase of the machined part (MJ/part).

According to the assumptions presented in Section 2.1, the masses of the material required for each approach could be written as in Equations 3 and 4, where the yield value (which represents the input material weight necessary to obtain 1 kg of output material) for powder production (y_A) and workpiece forming (y_F) has been introduced to account for the material losses in the pre-manufacturing stage.

$$m_m^{AM} = y_A \cdot m_{pwd} = y_A \cdot \left(m_{part}^{AM} + m_S + m_A\right) \quad (3)$$

$$m_m^{CM} = y_F \cdot m_{wp} = y_F \cdot \left(m_{part}^{CM} + m_C\right) \quad (4)$$

The masses of the produced components can be correlated according to the k factor (Equation 5). Moreover, it could be useful for practical purposes to quantify the process scraps m_S, m_A, and m_C as a fraction of the masses of finished parts, according to Equations 6-8.

$$m_{part}^{AM} = k \cdot m_{part}^{CM} \quad (5)$$

$$m_S = \alpha \cdot m_{part}^{AM} = \alpha \cdot k \cdot m_{part}^{CM} \quad (6)$$

$$m_A = \beta \cdot m_{part}^{AM} = \beta \cdot k \cdot m_{part}^{CM} \quad (7)$$

$$m_C = \gamma \cdot m_{part}^{CM} \quad (8)$$

The light-weighting attainable by means of the re-design for AM could result in energy savings, particularly during the use phase if the component is part of, or carried by, a transportation system. Therefore, the ΔE_{use} could be modelled by multiplying the weight reduction by a coefficient (C_{LW}, in MJ/kg) that quantifies the energy savings achievable per unit of reduced weight [13, 14], as in Equation 9.

$$\Delta E_{use} = E_{use}^{CM} - E_{use}^{AM} = m_{part}^{CM} \cdot (1-k) \cdot C_{LW} \quad (9)$$

The two approaches require the same primary energy (i.e., $E^{AM} = E^{CM}$) if Equation 1 is equated to Equation 2. The k^* target value allowing for that specific condition can be mathematically obtained according to Equation 10 (intermediate steps have been omitted for sake of brevity).

$$k^* = \frac{C_1 \cdot \gamma + C_2}{C_3 \cdot \alpha + C_4 \cdot \beta + C_5} \quad (10)$$

where:

- $C_1 = y_F \cdot (E_E + E_F) + E_M$
- $C_2 = y_F \cdot (E_E + E_F) + C_{LW}$
- $C_3 = y_A \cdot (E_E + E_A) + E_{AM} + E_{SR}$
- $C_4 = y_A \cdot (E_E + E_A) + E_{AM} + E_{FM}$
- $C_5 = y_A \cdot (E_E + E_A) + E_{AM} + C_{LW}$

The same procedure could be implemented to evaluate the CO_2 emissions. In such a case, in order to compute the k^* value of Equation 10, each specific primary energy demand has to be substituted by the associated carbon footprint, as already detailed in [7]. This methodology could be applied as a tool for assessing whether the light-weighting gained through the re-design for AM is enough to achieve benefits in terms of environmental impact throughout the component's life cycle. The C_i constant coefficients are mainly influenced by the type of material and by the specific energies (or carbon footprints) of the adopted production system. Therefore, they do not depend on the re-design stage. The geometrical product specifications of the conventionally manufactured component are usually known a priori, as well as the masses of the scraps that would be obtainable by means of a machining process. Prior to the re-design, k, m_S (or α), and m_A (or β) are usually unidentified variables, since they depend on the topological/ topographic optimization results, the component geometry, the orientation of the component inside the build space of the AM machine, the number of functional surfaces requiring finishing operations. A case study will be defined in Section 3 to clarify the applicability of the proposed methodology.

3. Case study

General Electric (GE) proposed in 2013 a competition for the sustainable re-design of a titanium lifting bracket for a jet aircraft engine, generating over 700 entries [15]. The results of the challenge have been the source of inspiration for the environmental impact comparison discussed in this paper.

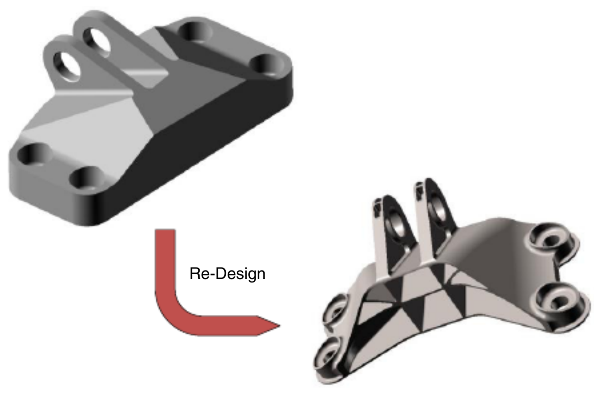

Figure 2. Original and re-designed components considered as case study.

The original design envelop was hypothesized to be the part to be obtained by means of a machining process. Among all the optimized solutions, a re-designed component (suitable for an EBM process) allowing a weight reduction higher than

80% (in Figure 2) has been chosen. The open-source CAD geometries have been obtained from the GrabCAD website [16]. This case study is adequately representative of the weight-saving achievable by mathematical techniques, such as topology optimization, that optimize the material distribution within the design space under specific loading conditions.

4. Data Inventory

The life cycle inventory needed for the empirical models in Section 2 is here reported. Data have been extracted from either commercial databases or recent literature.

4.1. Material production and recycling benefit awarding

The eco-properties for a cast Ti-6Al-4V alloy have been obtained from the CES Selector 2017 (v. 17.2.0) software [17]. The values of embodied energy (E_E) and carbon footprint (CO_{2E}) to be considered (*i*) for the sole primary material production or (*ii*) when including also the recycling benefit awarding are listed in Table 1. The so-known 'recycled content approach' and 'substitution method' have been both applied, as defined by Hammond and Jones [18] for the materials with no losses in inherent properties (as metals). The full benefits of material recycling are allocated to the input side by the first criterion, and to the end of life (EoL) by the second one. The recycle fraction in the current supply has been assumed to be 0.22 [17]. The EoL recyclability has been supposed as high as 0.80 [19], and equal for both process scraps and component material in the absence of specific indications in literature.

Table 1. Eco-properties for material production and pre-manufacturing.

Eco-Property	Min	Max
Embodied energy, E_E (MJ/kg), primary production	653.0	720.0
CO_2 footprint, $CO_{2\,E}$ (kg/kg), primary production	38.3	42.2
Embodied energy, recycling (MJ/kg)	82.6	91.3
CO_2 footprint, recycling (kg/kg)	6.5	7.2
Embodied energy, E_E (MJ/kg), recycled content appr.	527.5	581.7
CO_2 footprint, $CO_{2\,E}$ (kg/kg), recycled content appr.	31.3	34.5
Embodied energy, E_E (MJ/kg), substitution method	196.7	217.0
CO_2 footprint, $CO_{2\,E}$ (kg/kg), substitution method	12.9	14.2
Energy demand for powder atomization, E_A (MJ/kg)	30.1	70.0
CO_2 footprint for powder atomization, $CO_{2\,A}$ (kg/kg)	1.6	3.8
Energy demand for workpiece forming, E_F (MJ/kg)	14	15
CO_2 footprint for workpiece forming, $CO_{2\,F}$ (kg/kg)	1.1	1.2

4.2. Pre-manufacturing

Metal powder for AM has to be produced by means of different techniques [20]. For the production of 1kg of Ti-6Al-4V powder for an EBM process, Paris and colleagues have quantified a consumption of 6.6 kWh of electricity and 5.5 m^3 of Argon, with a process efficiency of 97% (i.e., y_A = 1.03) [21]. The specific energy consumption for Argon production by separating inert gases from air (quantified to be 0.672 kJ/l by Weir and Muneer [22]) has been neglected. The primary energy demand (E_A) and the related CO_2 emission (CO_{2A}) for Ti-6Al-4V powder atomization due to the consumption of electric energy have been computed to be equal to 70.0 MJ/kg and 3.8 kg/kg respectively (for an electric grid characterized by CES = 0.16 kg/MJ and η = 0.34) [7]. Baumers et al. [23] mentioned that the energy consumed for the gas atomization route of Ti-6Al-4V could range from 30.1 to 33.3 MJ/kg. Such data variability has been considered in this research (Table 1). As far as the workpiece production is concerned, the specific energy for material deformation (E_F) and the carbon footprint (CO_{2F}) were assumed to vary from 14 to 15 MJ/kg and from 1.1 to 1.2 kg/kg, respectively [8]. The bulk forming process efficiency was supposed to be 94% (y_F = 1.06), on the basis of the values available for analogous processes [24].

4.3. Component production

The specific electric energy demand for the Electron Beam Melting of Ti-6Al-4V has been quantified within the range 60-177 MJ/kg (for an Arcam machine) by Baumers and colleagues [23, 25]. After the build completion, finishing operations are needed to disconnect the parts from the plate and to remove the support structures. Electrical Discharge Machining (EDM) or mechanical means are common alternatives [12]. The specific electric energy demand for wire-EDM could be as high as 142.5 MJ for a full build [14], while the traditional mechanical removal causes an almost negligible energy consumption [12]. The latter system was assumed for the present study. A further (post-AM) finish machining operation was also supposed, as above mentioned.

For the machining-based approach, the mass of the chips has been hypothesized to be removed under both raw (85% of m_C) and finish cutting (15% of m_C) conditions. Data have been obtained from the CES Selector 2017 software [17]. All the life cycle inventory data for component production are listed in Table 2. The specific electric energy consumption has been converted into primary energy demand where needed (with η = 0.34). The CO_2 emissions have been obtained by assuming a CES value of 0.16 kg/MJ. The lifespans of the EBM and milling machines have been left out of the boundaries of the study.

Table 2. Data for additive and subtractive manufacturing.

Eco-Property	Min	Max
Energy demand for EBM, E_{AM} (MJ/kg)	176.5	520.6
CO_2 footprint for EBM, $CO_{2\,AM}$ (kg/kg)	9.6	28.3
Energy demand for raw machining, E_{RM} (MJ/kg)	2.28	2.52
CO_2 footprint for raw machining, $CO_{2\,RM}$ (kg/kg)	0.17	0.19
Energy demand for finish machining, E_{FM} (MJ/kg)	18.5	20.4
CO_2 footprint for finish machining, $CO_{2\,FM}$ (kg/kg)	1.39	1.53

4.4. Use phase

The application of the component both in a short- and a long-distance aircraft has been envisaged. Average values for energy and CO_2 savings achieved by light-weighting are equal to 150,000 or 200,000 MJ/kg and 10,200 or 13,600 kg/kg, respectively, according to [7] and references therein.

5. Results and discussion

The original component weighs 2.04 kg (m_{part}^{CM}), and could be obtained from a workpiece weighing 5.13 kg (m_{WP}) by means of the machining-based approach. The resulting γ value is 1.52. On the basis of this information, and with respect to the specific material and process data collected in Section 4, it would be possible to compute the k^* factor (according to Equation 10), as a function of α and β, for which the machining-based and the AM-based approaches demand the same primary energy or produce the same CO_2 emissions. Figure 3 plots the results obtained (*i*) by considering the average values of the data listed in Tables 1 and 2, and (*ii*) by neglecting the benefits of light-weighting during the use phase (i.e., by considering a cradle-to-gate plus end-of-life boundaries conditions). It is worth underlining that the same graphs could be generated by considering the best and/or worst case for machining and/or EBM. For a given k^* value plotted in Figure 3, all the combinations of α and β defining a point below the line make the AM-based approach favourable.

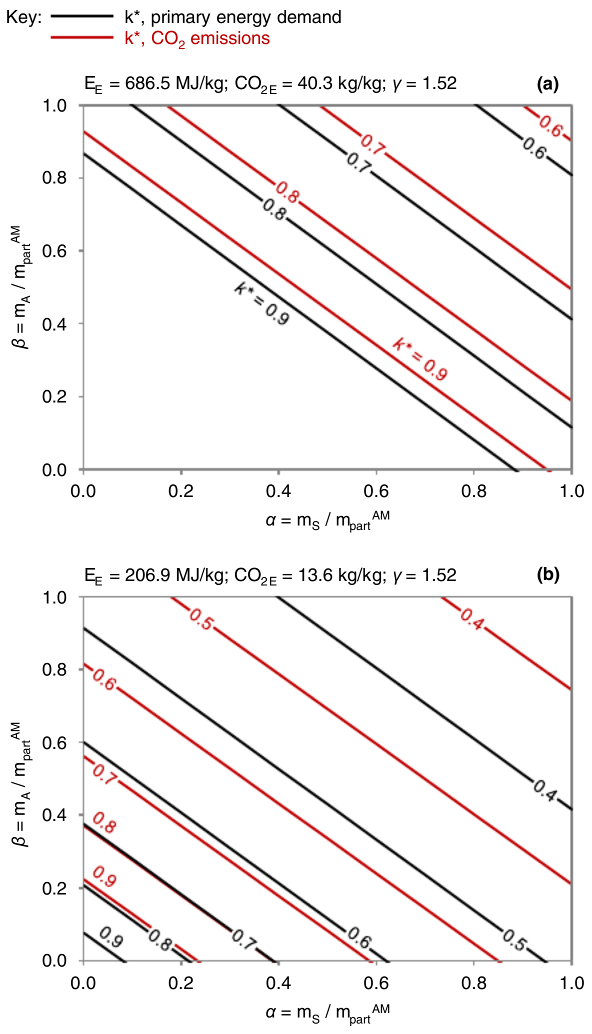

Figure 3. k^* values as a function of α and β, for $\gamma = 1.52$, while neglecting (*a*) or accounting for (*b*) the benefits due to material recycling.

In Figure 3*a*, the production of raw material from primary resources was considered, while in Figure 3*b* the benefits of recycling have been accounted for by means of the substitution method. The recycled content approach provides intermediate results (according to data in Table 1).

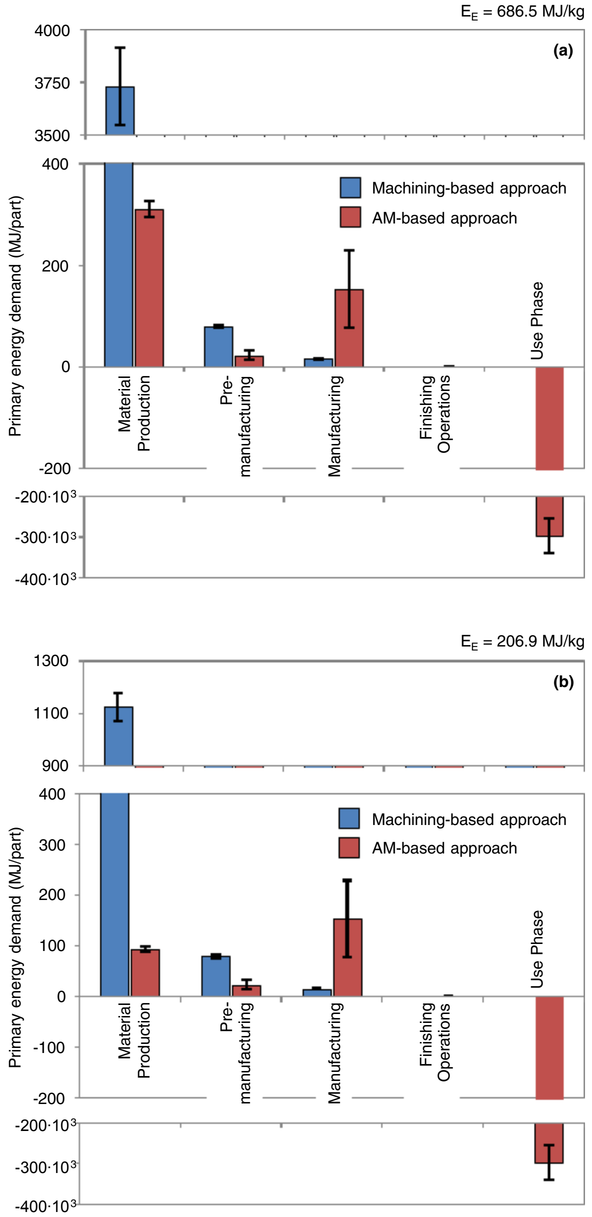

Figure 4. Primary energy demand results for the considered case study, while neglecting (*a*) or accounting for (*b*) the benefits due to material recycling.

The re-designed component weighs 0.34 kg (m_{part}^{AM}), therefore k is equal to 0.17. For this k value, according to the graphs in Figure 3, the machining-based approach would be preferred only for high values of α and β, definitely unrealistic for an EBM process. Therefore, AM appears to be the best choice even while the use phase is not accounted for. The higher specific energy demand of the AM process is compensated by the higher savings in material use. The masses of support structures and machining allowance could be supposed equal to 20% [14] and 10% of the additively manufactured component, respectively. In such a case, the subsequent $k*$ values (for the cradle-to-gate plus EoL boundaries) are listed in Table 3. When assuming the raw material production from sole primary sources, theoretical values of $k*$ higher than 1 imply that AM is the best choice, (for that combination of α, β, and γ) even to produce the as-is part. Vice versa, the results prove that a light-weighting of at least 25% is needed when recycling benefits are considered.

Table 3. $k*$ values computed for the case study (assuming $\alpha = 0.2$, $\beta = 0.1$, and $\gamma = 1.52$), while neglecting or accounting for the material recycling.

Recycling benefit awarding method	Metric: Primary energy demand	Metric: CO_2 emissions
None	1.30	1.35
Substitution method	0.75	0.86

For the case study in Figure 2 (with $k = 0.17$), the primary energy demand results are plotted in Figure 4. The values that are reported in the histogram are the average ones for each phase contribution, while the range bars specify the maximum and the minimum range (according to Tables 1 and 2). The variability in input data does not affect the conclusions. Moreover, the energy savings during the use phase dominate the entire picture, as expected for the components that are part of, or carried by, a transportation system [7].

6. Conclusions

A methodology for comparing the environmental impact of additive manufacturing (EBM) and subtractive (machining) processes has been extended and refined in this paper. The methodology has been applied to assess the life-cycle burden of a jet-engine component, which has been also re-designed by adopting the 'think additive' perspective. The main results confirm that AM could be an environmental-friendly choice when allowing (*i*) the same in-use performance, (*ii*) a better efficiency in raw material usage, (*iii*) benefits due to light-weighting during the use phase, particularly for components designed for transportation systems. The research aims to push forward the debate about the proposal of new environmental-conscious decision-support tools, in addition to those based on productivity and costs, to be integrated at the production design phase.

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