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Giuseppe Ingarao [a] and Paolo C. Priarone [b, *]

[a] University of Palermo, Engineering Department, Viale delle Scienze, 90128 Palermo, Italy

[b] Politecnico di Torino, Department of Management and Production Engineering, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

* Corresponding author (P.C. Priarone)
Email: paoloclaudio.priarone@polito.it
Ph.: (+39) 011 0907259
Fax: (+39) 011 0907299

Abstract

The applicability domain of Additive Manufacturing (AM) processes, apart from technological and quality results, relies on environmental and cost performance. These aspects still need to be better understood. To this aim, comparative analyses with conventional manufacturing routes are needed. In this paper, empirical cost and energy requirement models are suggested to assess subtractive- (machining) and additive- (Electron Beam Melting) based manufacturing approaches for the production of Ti-6Al-4V components. A life-cycle perspective is adopted, and all the steps from the input material production to the post-AM processing operations and the use phase are included. The analyses have been carried out considering the shape of the component, the light-weighting capabilities and the utilization time as the main factors of influence. The proposed modelling effort has allowed different decision-support charts, which are suitable for identifying the most energy-efficient or economically-advantageous manufacturing approach, to be obtained. The results have revealed that, for the considered case study, EBM could be a more energy-efficient approach than conventional machining, even without re-designing the component, due to the higher efficiency in raw material usage. As far as cost is concerned, the additive-based approach only becomes the preferable solution when the cost savings during the use phase are accounted for.

Keywords: Sustainable manufacturing; Additive manufacturing; Machining; Cost; Energy demand; Decision support chart

1. Introduction

The technological suitability of Additive Manufacturing (AM) for the production of end-use components is by now well known. Moreover, AM approaches have proved to enable advanced functionalities on the product and can provide further added value to the manufacturing sector [1]. Additive Manufacturing has moved quickly from prototyping to manufacturing over the last few years [2]. In order to achieve the actual disruptive effect AM technologies are claimed of, two aspects still require a better understanding: the production cost and the environmental performance with respect to conventional manufacturing routes [3]. The AM process category is characterized by certain features which, in theory, should enable both cost and environmental impact savings, including: (*i*) the absence of dedicated tooling; (*ii*) components can be produced in a single step (thus avoiding multiple manufacturing and assembling steps); (*iii*) material waste is generally reduced; (*iv*) very complex geometries can be manufactured, thereby enabling a weight reduction; and (*v*) the supply chain may be compressed drastically. In spite of these positive aspects, AM processes suffer from some drawbacks: (*i*) AM machines usually require a higher specific energy than conventional subtractive or mass conserving processes; (*ii*) the process rate is slow [4]; (*iii*) the input material (e.g., the metal powder) can be characterized by high embodied energy and costs; (*iv*) process wastes may occur as the support structures have to be additively manufactured and removed at the end of the process. All these aspects should be included when implementing cost and environmental analyses.

A few researches aimed at computing and modelling AM production costs have already been presented [5]. One of the first cost estimations concerning polymer processing was presented by Hopkinson and Dickens [6], who quantified the cost of three different polymer-based AM technologies (namely: Stereolithography, Fused Deposition Modelling and Selective Laser Sintering). They compared their results with conventional injection molding process results while varying the production volume, and they identified the break-even points (i.e., the number of parts). Ruffo et al. [7] improved the model by including more details concerning the production and administration overheads, and by also making it available for low production volumes. All the costs in their model were divided into direct and indirect costs. Only material-related costs were considered as direct costs, whereas machine-related costs, production labour, as well as administrative and production overheads were counted among the indirect costs. Their results highlighted, for the laser sintering processes, the relevance of the costs related to the amortization of the investment for purchasing the machine as well as of the maintenance costs. The same authors [8] further extended the model to the case of parallel production (the simultaneous manufacturing of different components on the same machine). The results emphasized the importance of efficiently filling the building space to obtain a reduction in the cost per part. A comprehensive cost model for the Mask Image Projection Stereolithography has recently been proposed by Yang and Li [9], who evaluated the cost performance of the process of simultaneously fabricating several mixed geometries. Moreover, Chan et al. [10], who proposed an integration between machine learning approaches and manufacturing cost estimation modelling, introduced an approach to predict the costs, starting from historical data for Fused Deposition Modelling.

As far as metal-based AM platforms are concerned, one of the earliest cost estimations was presented by Atzeni and Salmi [11], who compared a conventional high pressure die cast approach with Direct Metal Laser Sintering (DMLS) for the production of an aircraft component made of aluminium alloy. The capabilities, due to the re-designing of the part for AM, were considered. The results revealed that the AM approach can be economically preferable for small-to-medium batch sizes. Rickenbacker et al. [12] developed a detailed model for the cost assessment of Selective Laser Melting (SLM) that included all the pre-and post-processing steps. Baumers et al. [13] applied a cost model to DMLS for 17-4 PH steel manufacturing, and assessed the unit cost and energy demand variations when the floor area occupied by the build volume of the machine was changed. Manogharan et al. [14] pointed out the need to include the finishing operations that are necessary to turn the components released by the AM platform into net-shape components. Subtractive approaches are often needed to obtain the desired accuracy and surface finish. These extra process steps have been included in cost models and applied to case studies on Electron Beam Melting (EBM) processes. Manoharan et al. [15] applied cost models to compare two different metal-based additive manufacturing approaches, namely powder bed fusion and binder jetting.

Baumers et al. [16] adapted the model proposed by Ruffo et al. [7] to quantify the production costs of EBM and DMLS processes. Among others, machine productivity was identified as one of the main cost drivers. Baumers et al. [17] conducted a first comparative analysis between DMLS processes and a conventional machining plus a joining approach. Although the cost model for the subtractive approach was not dealt with in detail (since industrial estimations were considered), the benefits enabled by the re-designing for AM during the use phase (i.e., a better energy efficiency of the blower) were highlighted. Laureijs et al. [18] established cost estimations for both EBM and SLM processes, whereby they compared the obtained results with the costs of conventional forging for the same part production. The complete production cycle was considered, including part removal and finishing operations. An analysis regarding an engine bracket for the aerospace sector was presented, and the benefits, in terms of fuel saving during the use phase, due to the light-weighting enabled by the AM approach, were quantified. The results revealed that, when the part re-design for AM and the associated lifetime fuel savings are taken into account, the additively manufactured part was cheaper than the forged one for a wide range of scenarios. Kamps et. al [19] presented both cost and life-cycle energy demand analyses for the production of steel gear wheels. They compared three different manufacturing approaches: (*i*) Laser Beam Melting (LBM), (*ii*) pure milling, and (*iii*) milling plus hobbing. LBM was identified to be a worthy alternative for low production volumes. Moreover, the authors emphasized the cost and energy efficiency improvements of LBM that could be achieved with the adoption of a light-weight design.

Although the environmental performance analysis of manufacturing processes is a more recent research topic than cost estimation, two comprehensive review papers have already been released. One was presented at the ASME International Manufacturing Science and Engineering Conference in 2013 [20], and the other at the CIRP General Assembly in 2012 [21]. These review papers presented the state of the research at different levels, namely: the unit process level, the manufacturing system level, up to the whole supply chain level. The papers covered a good portion of the metal shaping process, such as mass conserving or material removal, and additive-based approaches were also included. An environmental performance characterization that is suitable for subtractive and additive manufacturing processes can be found in [22, 23] and [24-26], respectively. As additive manufacturing has clearly caught the attention of both scientists and industrialists over the last few years, several process variants have been developed. Hence, researchers have started to compare the environmental performance of different additive manufacturing processes. Jackson et al. [27] proposed an energy consumption comparison between wire-based and powder-based additive/subtractive manufacturing. Chan et al. [28] developed a full sustainability comparison (where environmental, economic and social impacts were analysed) between a wire-based Direct Energy Deposition process and the Selective Laser Melting of titanium components. As far as the environmental performance of AM processes with respect to conventional machining is concerned, it has been proved to be affected by the amount of material that has to be removed/deposited [29, 30], the eco-properties of the materials [31, 32] and, above all, the extent of light-weighting enabled by AM [33].

The analysis of the literature has allowed the following knowledge gaps to be identified:

- only a few papers have focused on comparative analyses between AM and conventional manufacturing. Most of the available comparative approaches concern mass conserving processes, which rely on dies and tools for the part manufacturing, and take advantage of the economy of scale. All the already published results show that AM outperforms mass conserving processes when small batch sizes have to be manufactured, while the latter are the cheaper solution for medium-to-big batch sizes. Subtractive approaches, like AM ones, are instead hardly affected by the batch size. In this respect, comparative analyses are more interesting and challenging for low production volumes;
- the effect of part complexity and light-weighting enabled by the re-designing of the part for AM on the cost assessment should be investigated in more depth;
- simultaneous environmental and economic sustainability analyses have rarely been carried out. There is a lack of decision support tools for the selection of the optimum manufacturing approach while varying the process variables from multiple perspectives and under different constraints.

The present paper has had the aim of contributing to filling the aforementioned research gaps. Cost and primary energy demand models for subtractive- (turning) and additive- (EBM) based approaches for the manufacturing of Ti-6Al-4V parts are proposed. A life-cycle perspective, including all the steps from the feedstock material production to the use phase and the end of life, is adopted. With respect to the existing literature, which is often focused on specific case studies or cradle-to-gate assessments, efforts are made to account for the variability in the shape of the component, the light-weighting capabilities and the utilization time as the main factors of influence. The here proposed methodology, which can be easily extended and adapted to other combinations of processes and materials, allows cost- and energy-wise decision support charts to be drawn up and applied while varying the main process design variables. The results permit suitable application domains to be identified (both in terms of cost reduction and energy efficiency) for each manufacturing approach. The methodology, in which all the unit-processes and the main material flows considered for modelling purposes are highlighted, is presented in Section 2. A case study is proposed in Section 3. The equations used to quantify the cumulative energy demand and the total cost per produced part are detailed in Section 4 and Section 5, respectively. The data that have to be applied in the empirical models are summarized in the Life Cycle Inventory of Section 6. The results are discussed in Section 7, whereas the conclusions and outlooks are given in Section 8.

2. Comparative approach

A model that accounts for the main factors of influence on the primary energy demand for different manufacturing routes has recently been developed [32]. The main unit processes for pure machining and additive-subtractive integrated manufacturing approaches were planned as shown in Figure 1. All the significant material flows are labelled and defined, together with the main drivers for the cost and energy requirements. All the pre-manufacturing and manufacturing steps were modelled in detail. The functional unit was the single manufactured part. The contributions due to transportation were overlooked, as they have proved to be negligible on a per-part basis [30-33]. Moreover, the comparison was made under the assumption that both of the manufacturing approaches are suitable for producing parts that comply with the imposed geometrical product specifications.

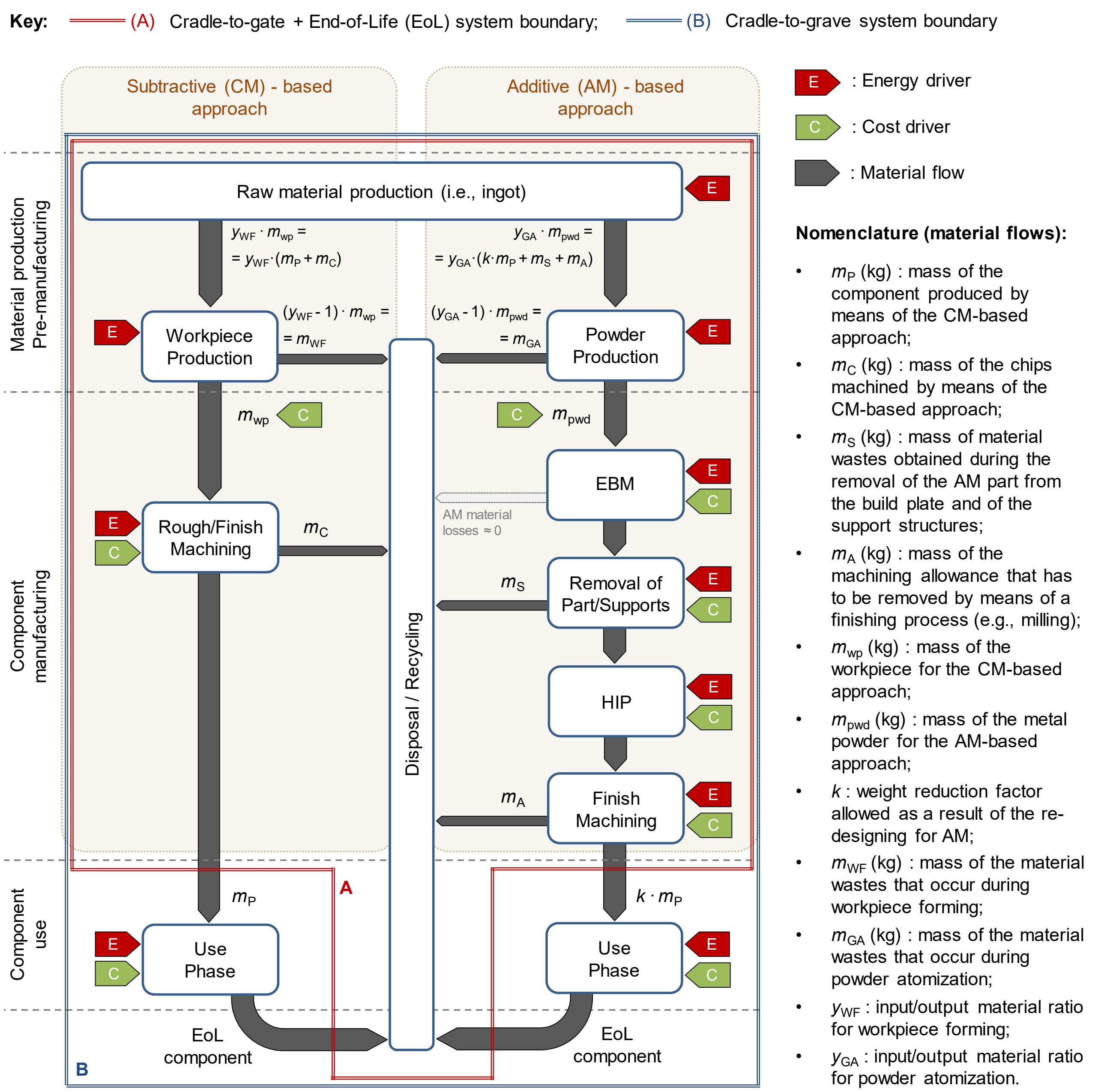

Figure 1. Flowchart of the main unit processes and qualitative material for a pure subtractive approach (*left*) and an integrated EBM-subtractive approach (*right*).

The here presented research focuses on the production of components made of Ti-6Al-4V. The AM-based approach hinged on an EBM process, as it is applied extensively to manufacture parts in titanium alloys, layer after layer [34, 35]. The modelling of the pre-manufacturing steps, together with their resulting material wastes, allowed the differences in cost and energy demand for the feedstock materials (i.e., the bar for machining or the metal powder for EBM) to be highlighted. Then, as far as the subtractive-based approach is concerned, a turning process was assumed. Apart from the pure deposition phase, obtained by means of EBM, the additive-based approach included (*i*) the separation of the part from the build plate and of the support structures from the part itself, (*ii*) Hot Isostatic Pressing (HIP), and (*iii*) a finish machining process [18]. The analyses were developed considering two scenarios. First, a comparison was made considering cradle-to-gate plus end-of-life system boundaries, leaving out the differences that were observed during the use phase (according to the system boundary identified as 'A' in Figure 1). Second, system boundary 'B' was considered, and the use phase was taken into due account. This choice was driven by the desire to consider the light-weight potential of AM approaches. It is worth noting that the re-design options provided by the intrinsic capabilities of AM allow a substantial weight saving to be made [36]. Such a weight reduction could lead to significant fuel savings, if the component is assembled in a transportation system [37]. In the present research, the light-weighting potential was modelled by means of the k factor (which is defined as the ratio between the mass of the part produced by means of the additive-based approach and that of the subtractive-based approach). When k = 1, no weight reduction is achieved, while the weight reduction increases as the k value decreases [31, 33]. The impact assessment performed on the cradle-to-grave system boundary (B) is expected to provide a wider perspective to the results of the comparative analysis.

3. Case study

The efficiency of raw material usage plays a crucial role when assessing subtractive and additive-based approaches [30]. One of the purposes of this type of research is to develop comparative analyses while varying the amount of machined-off material. A case study has been considered. The component shown in Figure 2a is axisymmetric, and can be drawn by rotating its cross-section around the central axis by 360°. The geometry of the rotational part was inspired by the one adopted by Watson and Taminger [38]. In this respect, the Solid-to-Cavity Ratio (SCR) was applied as a single parameter to characterize the geometrical features of the components being produced. Morrow et al. [39] defined SCR as the mass of the final part divided by the mass that would be contained within the bounding volumetric envelope of the part itself. Consequently, the SCR value for the here considered case study was computed as the ratio between the mass of the final part and the mass of the workpiece needed for the turning process (including the machining allowances). In order to cover a wide portion of Solid-to-Cavity Ratios, the inner radius value (R_i) was assumed to range from 23 mm (SCR = 0.78) to 2 mm (SCR = 0.13), while the other dimensions were kept constant (Figure 2b). Therefore, a small value of the SCR ratio identifies a geometry characterized by a large amount of machined-off material when the subtractive-based approach is used (as shown in Figure 2c), as well as a small amount of material deposited by means of the AM-based approach (Figure 2d). The machining allowance that had to be removed after the EBM process was 1-mm thick, and the mass of the material wastes, due to the removal of the part from the build plate and of the support structures (which, in turn, depend on the complexity of the part and its orientation in the build chamber of the machine), was cautiously assumed to be equal to 20% of the mass of the part [40].

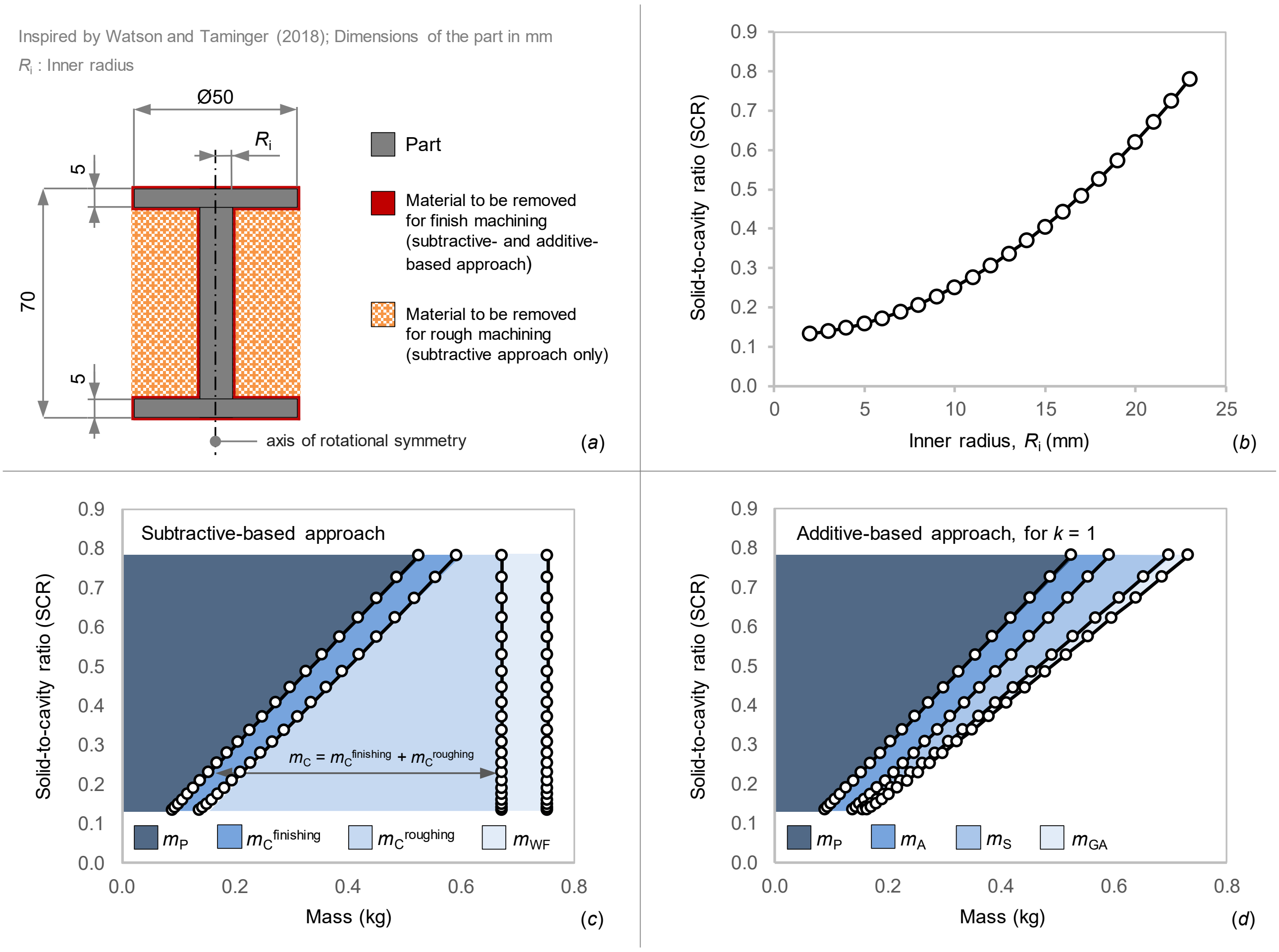

Figure 2. Case study description. The masses are labelled with reference to the nomenclature provided in Figure 1.

4. Models used to quantify the cumulative energy demand per produced part

The energy demand for the manufacturing of a given part (E_{part}, in MJ/part) was computed by identifying the main contributions related to the (*i*) material production, (*ii*) manufacturing, and (*iii*) use phases. Primary energy was selected as the performance metric to sum up, at the same energy level, the different shares due to the resource/material flows and the electric energy flows, according to Frischknecht et al. [41]. The energy demands of the pre-manufacturing stages (namely, workpiece forming or powder production) were added to the embodied energy of the raw material, and material wastes were accounted for. These processes are required to turn the raw, in-stock material (e.g., an ingot for metals) into either a workpiece that has to be machined or a powder that has to be deposited via AM. The energy benefits that arise from material recycling were accounted for. The Cumulative (primary) Energy Demand (CED) models have been enhanced in the present research with respect to the already published researches [30-33]. The energy contributions during idle operational modes were accounted for [42], and post-AM operations, such as the separation of the part and support structures as well as the Hot Isostatic Process (HIP), were included. As far as the conventional machining (CM) process is concerned, a more accurate modelling of roughing and finishing operations is here reported and the contributions of cutting tools and cutting fluids have been included.

4.1. Additive/subtractive (AM-based) integrated approach

The total primary energy per part manufactured by means of the AM-based integrated approach (E_{part}^{AM}), as shown in Figure 1, was obtained by adding the primary energy requirement for powder production (E_{PWD}) to that of the manufacturing of the part (E_{MFG}^{AM}), according to Equation 1,

$$\begin{aligned} E_{part}^{AM} &= \overbrace{y_{GA} \cdot \overbrace{\left(k \cdot m_P + m_S + m_A\right)}^{m_{pwd}} \cdot \left(E_E + E_A\right)}^{E_{PWD}} + \\ &\underbrace{+ \frac{3.6}{\eta} \cdot \left(\overbrace{P_{\mathrm{stb}}^{\mathrm{AM}} \cdot t_{\mathrm{s}}^{\mathrm{AM}}}^{E_{\mathrm{idle}}^{\mathrm{AM}}} + \overbrace{SEC^{\mathrm{AM}} \cdot m_{pwd}}^{E_{\mathrm{deposition}}^{\mathrm{AM}}} \right) + E_{SEP} + E_{HIP} + E_{FM}}_{E_{MFG}^{AM}} \end{aligned} \qquad (1)$$

where:

- m_j (kg): the *j*-th material flow, as defined in Figure 1;
- E_E (MJ/kg): embodied energy of the raw material;
- E_A (MJ/kg): energy demand for powder atomization;
- η (-): primary-to-secondary energy conversion factor;
- E_{idle}^{AM} (kWh): energy consumption of the AM machine when idling;
- $E_{deposition}^{AM}$ (kWh): energy consumption of the AM machine during deposition;
- P_{stb}^{AM} (kW): standby power of the AM machine;
- t_s^{AM} (h): standby time of the AM machine;
- SEC^{AM} (kWh/kg of deposited material): specific energy consumption of the AM machine during deposition;
- E_{SEP} (MJ/part): energy for separating the part from the build plate and for the removal of the supports;
- E_{HIP} (MJ/part): energy for Hot Isostatic Pressing;
- E_{FM} (MJ/part): energy for finish machining.

The energy contributions, E_{SEP} and E_{HIP}, are reported in Equation 1 on a per part basis. As these terms may be geometry dependent, the Specific Energy Consumption (SEC) approach can be applied, as shown in Section 6.1. Moreover, the energy required for finish machining (E_{FM}) can be computed as detailed in Section 4.2.

4.2. Machining (CM-based) approach

The total primary energy per part manufactured by means of the CM approach (E_{part}^{CM}) was computed (as reported in Priarone et al. [42]) by adding the primary energy requirement for the production of the workpiece (E_{WP}) to that of the manufacturing of the part (E_{MFG}^{CM}), according to Equation 2,

$$E_{part}^{CM} = \overbrace{y_{WF} \cdot \overbrace{(m_P + m_C)}^{m_{wp}} \cdot (E_E + E_F)}^{E_{WP}} + \overbrace{\overbrace{\frac{3.6}{\eta} \cdot E_{MT}}^{Machine\ tool} + \overbrace{\sum_{i=1}^{n} \left(E_{\mathrm{tool}_i} \cdot \frac{t_{\mathrm{c}i}}{T_i} \right)}^{Cutting\ tool} + \overbrace{E_{\mathrm{lub}} \cdot q_{\mathrm{L}} \cdot t_{\mathrm{c}}}^{Cutting\ fluid}}^{E_{MFG}^{CM}} \tag{2}$$

where, for all the n needed operations (i.e., per each i-th of the roughing, semi-finishing and finishing operations):

- m_j (kg): the j-th material flow, as defined in Figure 1;
- E_E (MJ/kg): embodied energy of the raw material;
- E_F (MJ/kg): energy demand for workpiece forming;
- E_{MT} (kWh): electric energy consumption of the machine tool;
- E_{tool} (MJ/tool): embodied energy of the cutting tool;
- E_{lub} (MJ/kg): embodied energy of the cutting fluid;
- q_L (kg/h): consumption rate of the cutting fluid;
- t_c (h): cutting time;
- T (h): tool life.

It is worth underlying that, when machining, the cutting fluid is collected, filtered and re-circulated several times through the flood cooling system of the machine tool. The term labelled as q_L in Equation 2 quantifies the consumption rate of the portion of cutting fluid that is unrecoverable (i.e., due to the vapour waste stream dispersed in the surrounding environment and the liquid waste stream created through fluid coating on the chips or the machined parts). The electric energy consumption of the machine tool (E_{MT}) can be computed according to Equation 3 [42],

$$E_{MT} = \overbrace{P_{\mathrm{stb}}^{\mathrm{CM}} \cdot t_{\mathrm{s}}^{\mathrm{CM}}}^{E_{idle}} + \sum_{i=1}^{n} \left(\overbrace{SEC_i^{\mathrm{CM}} \cdot m_{\mathrm{c}i}}^{E_{cutting}} + \overbrace{P_{\mathrm{stb}}^{\mathrm{CM}} \cdot t_{\mathrm{tc}i} \cdot \frac{t_{\mathrm{c}i}}{T_i}}^{E_{tool\ change}} \right) \tag{3}$$

where:

- P_{stb}^{CM} (kW): standby power of the machine tool;
- t_s^{CM} (h): standby time of the machine tool;
- SEC^{CM} (kWh/kg of removed material): specific energy consumption of the machine tool when cutting;
- t_{tc} (h): time necessary for a tool change.

5. Models used to quantify the total cost per produced part

The total cost of manufacturing a given part (C_{part}) was computed as the sum of the (*i*) indirect costs, (*ii*) labour costs, (*iii*) material costs, and (*iv*) processing costs. The same modelling structure was adopted for both of the here considered manufacturing approaches (AM-based and machining-based). The indirect costs were allocated through the total part processing time (including the idle time) and include production and administrative overheads as well as consumables, maintenance and purchase costs of the machine. The labour costs were modelled by multiplying the labour charge rate and the working time of the machine operator(s), which was assessed by hypothesizing (*i*) a full employment during set-up / post-processing activities (i.e., when the machine is in idle operational mode) and (*ii*) a partial employment for process supervision activities during the automated production of the part. The material costs, which are driven by market rules, were considered to quantify the purchase costs of the incoming feedstock for each process. The processing costs accounted for the electricity costs, the consumables (e.g., the cutting tools for machining) and all the post-processing operations, when needed. The implemented cost models for the AM-based approach and the CM-based approach are given in the Sections 5.1 and 5.2, respectively.

5.1. Additive/subtractive (AM-based) integrated approach

The total cost per part manufactured by means of the AM-based approach (C_{part}^{AM}, in €/part), as shown in Figure 1, was obtained according to Equation 4,

$$C_{part}^{AM} = C_{pwd} \cdot m_{pwd} + \overbrace{C_{ind}^{AM} \cdot \left(t_{idle}^{AM} + t_{build}\right) + C_{op}^{AM} \cdot \left(t_{idle}^{AM} + \gamma^{AM} \cdot t_{build}\right) + C_{EE} \cdot \left(E_{idle}^{AM} + SEC^{AM} \cdot m_{pwd}\right)}^{C_{EBM}} + \\ + C_{SEP} + C_{HIP} + C_{FM} \tag{4}$$

where:

- C_{pwd} (€/kg): purchase cost of the metal powder;
- m_{pwd} (kg): mass of the material (i.e., powder) that has to be deposited;
- C_{EBM} (€/part): total cost for the EBM process;
- C_{ind}^{AM} (€/h): indirect cost rate for Additive Manufacturing (AM);
- t_{idle}^{AM} (h): idle time for the AM process;
- t_{build} (h): build time;
- C_{op}^{AM} (€/h): labour charge rate for the AM machine operator;
- γ^{AM} (-): rate of employment of the AM machine operator, with $\gamma^{AM} \leq 1$;
- C_{EE} (€/kWh): cost of the electric energy;
- E_{idle}^{AM} (kWh): electric energy consumption of the AM machine when idling;
- SEC^{AM} (kWh/kg): specific energy consumption of the AM machine during deposition;
- C_{SEP} (€/part): total cost for the removal of the part / support structures;
- C_{HIP} (€/part): total cost for Hot Isostatic Pressing;
- C_{FM} (€/part): total cost for the finish machining operations (to be computed as described in Section 5.2).

It is worth mentioning that AM generally requires certain post-processing operations. These phases, which have often been neglected in literature, have been included in this paper by considering the costs related to (*i*) the removal of the part from the build platform and the support structures, if any (C_{SEP}), (*ii*) Hot Isostatic Pressing (C_{HIP}), as well as (*iii*) the finish machining operations (C_{FM}). These cost drivers all account for indirect, direct and labour costs.

5.2. Machining (CM-based) approach

Unlike AM-based approaches, conventional subtractive machining processes are suitable for obtaining a net-shape part with satisfactory surface quality and strict tolerances. Therefore, no further post-CM processing operations have been envisaged in this paper. Roughing, semi-finishing and finishing machining operations are usually carried out. These process steps, which are performed considering different process parameters (cutting speed, feed, depth of cut, et cetera), imply a different Material Removal Rate (MRR) and tool life performance. The total cost per part manufactured by means of the CM-based approach (C_{part}^{CM}, in €/part) was computed according to Equation 5 [42],

$$C_{part}^{CM} = C_{wp} \cdot m_{wp} + C_{ind}^{CM} \cdot \left(t_{idle}^{CM} + t_{mach}\right) + C_{op}^{CM} \cdot \left(t_{idle}^{CM} + \gamma^{CM} \cdot t_{mach}\right) + C_{EE} \cdot E_{MT} + \\ + \sum_{i=1}^{n} \left(C_{\mathrm{tool}_i} \cdot \frac{t_{\mathrm{c}i}}{T_i} \right) + C_{\mathrm{lub}} \cdot q_{\mathrm{L}} \cdot t_{\mathrm{c}} \tag{5}$$

where, for all the *n* needed operations (i.e., per each *i*-th of the roughing, semi-finishing and finishing operations):

- C_{wp} (€/kg): purchase cost of the workpiece;
- m_{wp} (kg): mass of the workpiece;
- C_{ind}^{CM} (€/h): indirect cost rate for Conventional Machining (CM);
- t_{idle}^{CM} (h): idle time for the CM process;
- t_{mach} (h): total machining (i.e., cutting plus tool change) time;
- C_{op}^{CM} (€/h): labour charge rate for the machine tool operator;
- γ^{CM} (-): rate of employment of the machine tool operator, with $\gamma^{CM} \leq 1$;
- C_{EE} (€/kWh): cost of the electric energy;
- E_{MT} (kWh): electric energy consumption of the machine tool (computed as in Equation 3);
- C_{tool} (€/tool): cost of the cutting tool;
- C_{lub} (€/kg): cost of the cutting fluid;
- q_L (kg/h): consumption rate of the cutting fluid;
- t_c (h): cutting time;
- T (h): tool life.

The cutting times (t_c) were computed as the ratio between the mass of the chips that had to be removed and the MRRs. This simplified definition does not consider the transients or the positioning movements of the tool (i.e., all the times when the tool is not effectively removing material, as it is not in contact with the workpiece). However, this definition was assumed to be adequate for the purposes of the current discussion. The total machining time (t_{mach}) is the total of the cutting time and the tool changing times. The costs related to the consumables in machining were here limited to the cutting tools and the cutting fluid, and were computed according to their specific consumption.

6. Life Cycle Inventory (LCI)

The main eco-properties and the costs regarding the material production and the pre-manufacturing phases for the Ti-6Al-4V alloy are listed in Table 1. The embodied energy of the raw material was quantified by assuming two scenarios: (*i*: the worst case) where there is no material recycling, or (*ii*: the best case) where the energy credits are due to the downstream flow of recyclable materials. The so-called 'substitution method' was applied for the latter case. The equations proposed by Hammond and Jones [43] were implemented in the model, under the following hypotheses: (*i*) the recycled materials did not suffer from inherent property losses, (*ii*) the end-of-life recyclability was the same for both the material wastes and the bulk components, (*iii*) the energy necessary for disposal was negligible. Average values were obtained for each variable from the most recent literature. Unless otherwise specified, the energy demand values refer to primary energy sources. The data inventory for the processing phases is explained in detail in the following sub-sections.

Table 1. Data inventory for material production and pre-manufacturing.

Variable	Value	Source
Embodied energy, primary material (i.e., ingot) production (MJ/kg)	685.0	[44]
Embodied energy, recycling (MJ/kg)	87.0	[44]
End-of-life recyclability	0.8	[45]
Embodied energy of the raw material, E_E (MJ/kg)	685.0 or 206.6	[43, 44]
Energy demand for workpiece forming, E_F (MJ/kg)	29.1	[44]
Energy demand for powder atomization, E_A (MJ/kg)	70.0	[31]
Input/output material ratio for workpiece forming, y_{WF} (-)	1.12	[44]
Input/output material ratio for powder atomization, y_{GA} (-)	1.05	[46]
Workpiece cost, C_{wp} (€/kg)	28.0	Market quotation
Powder cost, C_{pwd} (€/kg)	175.0	Market quotation

6.1. Electron Beam Melting

The specific electric energy consumption of the EBM machine (SEC^{AM}) was quantified as 16.7 kWh/kg of deposited material, according to Baumers et al. [47]. The SEC value accounts for the pre-heating, production and cooling-down phases. The machine was assumed to work at full machine capacity, according to the best industrial practices. The specific primary energy consumption resulted to be 176.8 MJ/kg, when a primary-to-secondary energy conversion factor (η) of 0.34 was assumed [31]. The power demand of the EBM machine when idling (P_{stb}^{AM}) was assumed to be 1.09 kW [47]. If an average setup time (t_s^{AM}) of 0.3 h/job is considered (handling the data of Laureijs et al. [18]), the electric energy demand during setup would result to be 0.327 kWh/job (with a primary energy demand of 3.5 MJ/job). Since several parts may be produced in a single job (i.e., under the hypothesis of full machine capacity utilization), the impact of the setup operations on the cumulative (primary) energy demand and on process costs was assumed to be negligible on a per-part basis. The deposition rate was fixed at 0.127 kg/h. This value was obtained from Baumers et al. [47], to be consistent with the assumed SEC value.

As far as the EBM process costs are concerned, an indirect cost rate (C_{ind}^{AM}), ranging from 11.2 €/h (best case) to 38.4 €/h (worst case), was presumed. This range was computed according to Baumers et al. [48], assuming: (*i*) the cost per year of an EBM machine (including purchase cost and maintenance costs, over a depreciation period of 8 years) within the range of 37,615 - 165,000 €/year [16, 18]; (*ii*) an annual operating time of 5000 h/year (i.e., utilization rate: 57%) [16] or 6570 h/year (i.e., utilization rate: 75%) [19]; (*iii*) administrative and production overhead rates of 0.35 €/h and 5.08 €/h, respectively (adapted from Ruffo and Hague [8]). The cost of the electric energy (C_{EE}, including taxes) for an Italian company was 0.15 €/kWh. An average labour charge rate (C_{op}^{AM}) of 27.0 €/h was assumed, in order to take into account the salary of a specialized Italian technician. The working time of the operator was obtained by hypothesizing full employment during the setup/post-processing activities, and this cost was increased by 5% of the productive time, due to supervision operations, according to Kamps et al. [19]. Wire-Electrical Discharge Machining (wire-EDM) operation was hypothesized for the removal of the parts from the build plate and of the support structures. The specific primary energy consumption for wire-EDM was taken as 37.0 MJ/kg and its cost (accounting for indirect, direct and labour costs) was 34.85 €/kg [18]. A HIP process was considered for Ti-6Al-4V, with a specific primary energy demand of 122.0 MJ/kg and a cost (which accounts for indirect, direct and labour costs) of 10.86 €/kg of HIPed material [18]. The finish machining energy and costs depend on the final part shape, and were calculated by applying the equations outlined in Sections 4.2 and 5.2, under the assumptions declared in Section 6.2.

6.2. Turning process

Empirical models that correlate the specific electric energy consumption (SEC) with the Material Removal Rate (MRR) when turning are available in literature. The electric energy consumption of all the machining processes planned in Figure 1 was computed according to the SEC (kJ/cm^3) = 1.494 + 2.191/MRR (cm^3/s) equation [50]. In addition, the standby power (P_{stb}^{CM}) was 1.75 kW [50], and an idle time (t_s^{CM}) of 10 min (0.17 h) was assumed. Standard carbide cutting inserts were identified for machining [51]. The here assumed MRR was 0.5 cm^3/s (7.9 kg/h) for roughing and 0.1 cm^3/s (1.6 kg/h) for the finishing operations, with resulting SEC^{CM} values of 0.4 kWh/kg and 1.5 kWh/kg, respectively. A tool life (T) of 0.17 h was considered for roughing and 0.50 h for finishing. The tool change time (t_{tc}) was 2 min (0.03 h). The finishing cutting conditions were kept unvaried for both of the manufacturing approaches so as to make the result comparison consistent. The contributions of the consumables to the primary energy demand and costs are listed in Table 2.

Table 2. Data inventory of the consumables in machining processes (according to Priarone et al. [51] and references therein).

Variable	Value
Embodied energy of the cutting tool, E_{tool} (MJ/edge)	1.38
Cost of the cutting tool, C_{tool} (€/edge)	1.50
Embodied energy of the cutting fluid, E_{lub} (MJ/kg)	1.37
Cost of the cutting fluid, C_{lub} (€/kg)	0.93
Consumption rate of the cutting fluid, q_L (kg/h)	0.48

The hypotheses regarding the machine utilization rate (57% or 75%) and the depreciation time (8 years) declared in Section 6.1 were maintained for the cost assessment, and the CNC machine cost per year was evaluated within the € 18,750 - 72,500 range. As a result, the indirect cost rate for machining (C_{ind}^{CM}) was within the 8.3 €/h (best case) to 19.9 €/h (worst case) range. The average labour charge rate for the CNC machine operator (C_{op}^{CM}) was assumed as 27.0 €/h (like that of the EBM machine operator). The working time of the operator was obtained by hypothesizing full employment during the setup/post-processing activities (which lasted 0.17 h), and was increased by 30% of the productive time due to supervision operations.

7. Results and discussion

The results concerning the case study presented in Section 3 are analysed in this Section. The results for the (cradle-to-gate plus end-of-life) system boundary labelled 'A' in Figure 1 are presented considering two different scenarios in which light-weighting enabled by means of the re-designing for the additive/subtractive integrated approach is either neglected (as in Section 7.1) or included (as in Section 7.2). The results for the (cradle-to-grave) system boundary labelled 'B' in Figure 1 are discussed in Section 7.3. It is worth remarking that, according to the life cycle inventory outlined in Section 6, the main sources of variability of the cumulative (primary) energy demand and of the total costs are due to the differences in estimating the recycling benefit awarding and the indirect cost rates, respectively. The worst case involves not considering material recycling and maximizing the indirect cost rate over the identified range. On the other hand, the embodied energy of the material was computed by means of the 'substitution method' and the indirect cost rate was minimized in the best case scenario.

7.1. Results of system boundary 'A', with no light-weighting (k = 1)

In this section, the two different manufacturing approaches (either the pure subtractive approach or the additive/subtractive integrated approach) have been hypothesized to have been applied to produce the same type of component. This implies that no light-weighting benefits, due to re-designing for AM, are accounted for, and the *k* value is set at 1. The results, in terms of Cumulative (primary) Energy Demand (CED) and total costs, are shown in Figure 3 and Figure 4, respectively. A worst case and a best case were identified, according to the Life Cycle Inventory phase.

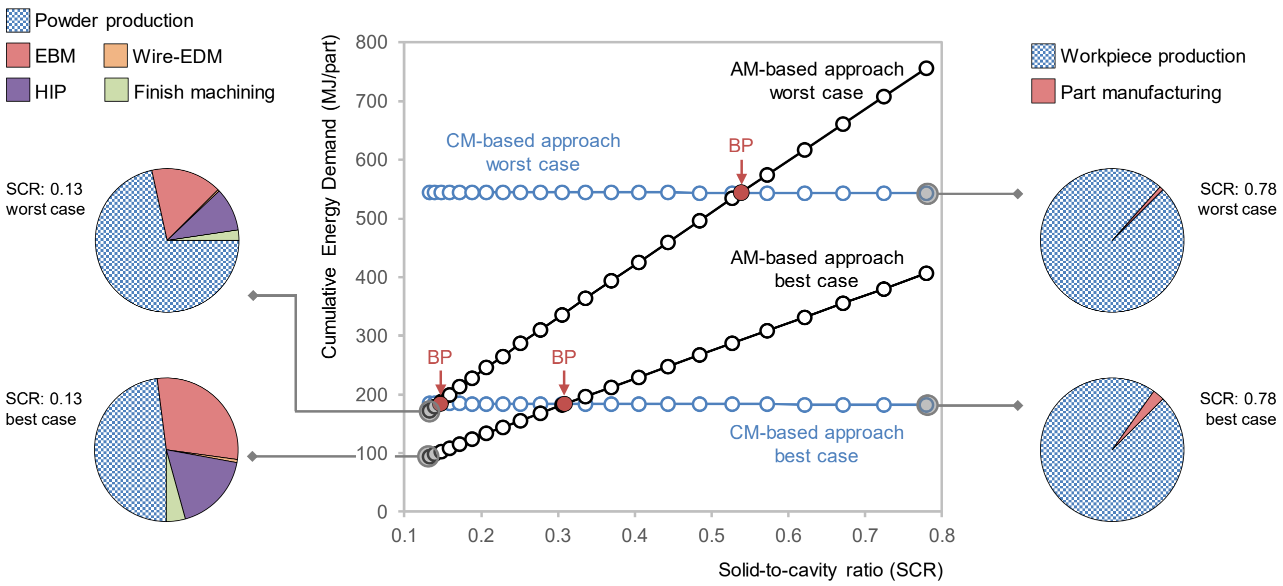

Figure 3. Comparative results for the Cumulative Energy Demand (CED) per produced part.

The CED for the AM-based approach decreases when the SCR ratio decreases, due to the lower consumption of powder (and, thus, of raw material) and of manufacturing energy. The break-down analyses for the CED of the AM-based integrated approach show that the powder production and manufacturing shares are balanced and almost constant when the SCR value changes. Moreover, the primary energy requirements for powder production account for approximately three fourths or one half of the total demand when recycling benefit awarding is neglected or included, respectively. The only variation in CED for the CM-based approach is due to the higher energy required to machine a higher amount of chips at lower SCR ratios, since the mass and the primary energy embodied in the workpiece are constant, regardless of the considered SCR (as shown in Figure 2). The energy consumption for machining for the considered case study represents a small share compared to the energy necessary for workpiece production. Hence, this justifies the slight slope of the CED curve versus

SCR for the subtractive approach. These results are consistent with other researches carried out by the authors [30-32]. When the curves intersect for a given SCR value, a break-even point (BP) can be identified. When the SCR value is higher than the BP, the conventional machining approach results to be the most energy-efficient choice, while the AM-based approach is preferable when the SCR value is lower. Under the hypothesis of no light-weighting, SCR is the only factor that affects the comparative results. Therefore, the graphs in Figure 3 can be used as a decision support chart to identify the most advantageous manufacturing route. The inherent differences in the break-even (BP) values echo the modelling criterion assumed for the assessment of the primary energy embodied in the feedstock materials. The higher the embodied energy is (i.e., if no environmental benefits are due to material recycling), the more beneficial the AM-based approach, because of its higher material-usage efficiency. On the other hand, when material recycling is included (best case) in both of the manufacturing approaches, the BP moves toward lower SCRs and the machining application domain increases. Similar results were found by Paris et al. [46], who compared an EBM-based approach with subtractive processes to manufacture turbines made of titanium alloys. Paris et al. [46] assumed the geometry of the part to be the same for both the manufacturing approaches, and the comparison was made while varying the SCR (which was named 'shape factor' in their paper). Concerning other metals, to the best of the authors' knowledge the only paper accounting for the effect of SCR on the results of comparative analyses is the research published in 2007 by Morrow and colleagues [39], who assessed three different case studies (i.e., moulds and dies made of AISI H13 steel) and proved that DMD has to be preferred for components with low solid-to-cavity ratios.

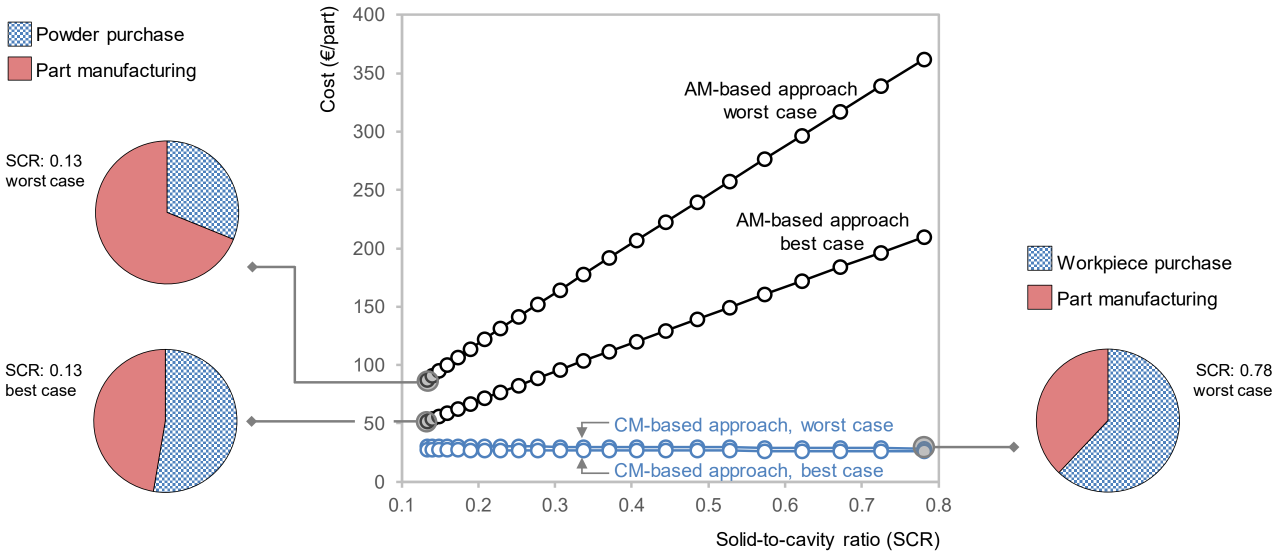

Figure 4. Comparative results for the total costs per produced part.

The total cost per part (in Figure 4) for the EBM-based approach decreases when the solid-to-cavity ratio (SCR) decreases, as the amount of powder that is first acquired and then deposited decreases, together with the related costs. The total cost for the machining approach instead increases only slightly when SCR decreases, due to the increase in manufacturing costs linked to the increase in the amount of material that has to be machined-off. The share due to the manufacturing costs (including EBM, separation of the part/support structures, HIP and finish machining) is dominant for the AM-based approach, and in particular for the worst case scenario (i.e., when higher indirect cost rates are assumed), despite the high purchase cost of the Ti-6Al-4V powder. Break-even points cannot be identified for the considered case study when the total cost is considered as a process metric for comparative purposes, and the CM-based approach always appears to be preferable [52].

The role of the utilization rate of the machine deserves a special mention. The above presented results (in Figure 3 and Figure 4) refer to full build utilization, which corresponds to an SEC value of 16.7 kWh/kg of deposited material. The energy consumption of the EBM process appears to be driven by a cross-sectional area and hence by an overall part mass, and does not exhibit any direct link between energy consumption and shape complexity. The choice of full capacity operation (which was assumed in this paper) is an industrial best practice, and results in a reduction of the specific energy consumption of the EBM process [47]. An SEC of 49.2 kWh/kg can be extrapolated from the results of Baumers et al. [53] for the production of a single part for the same machine. If this latter value is considered (all the other parameters being equal), the CED and total cost versus the solid-to-cavity ratio curves are shifted upward, as shown in Figure 5. This leads to a worsening of the performance of the additive-subtractive integrated approach, particularly from the energy demand perspective.

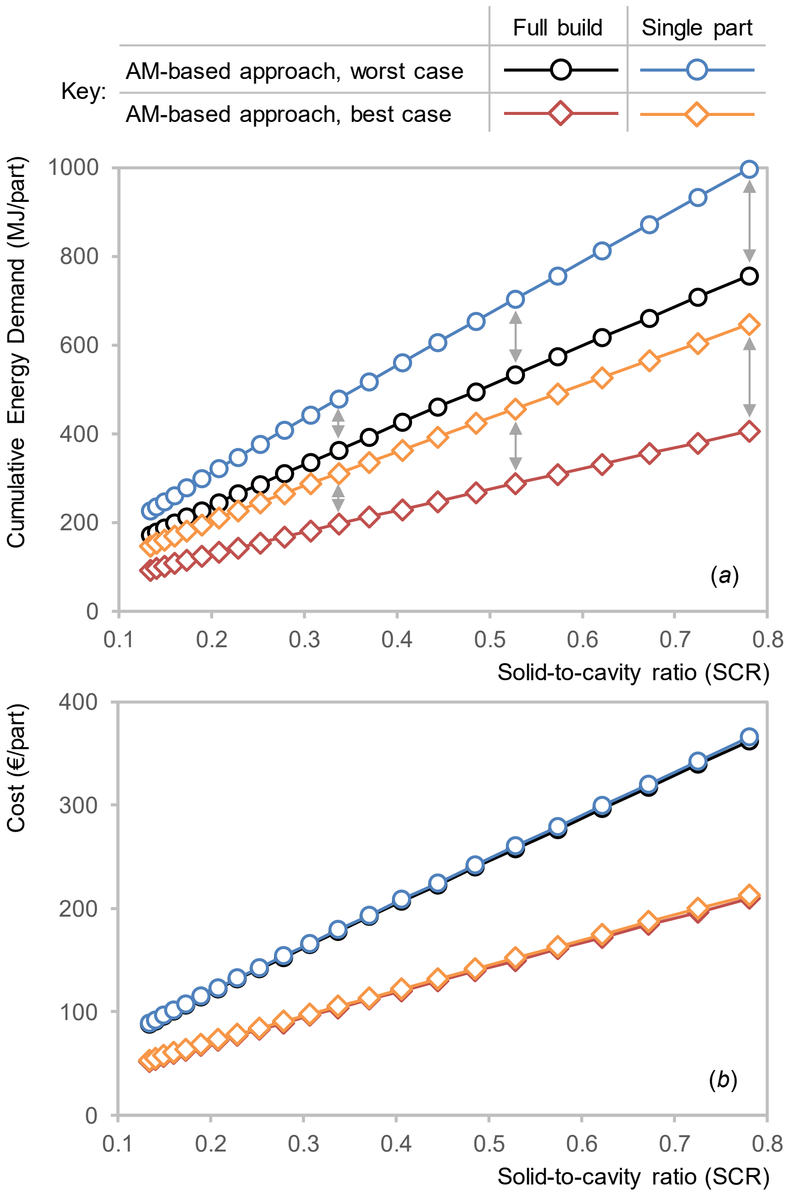

Figure 5. Impact of build chamber utilization on CED (*a*) and cost (*b*) per part.

7.2. Results of system boundary 'A', with light-weighting (k < 1)

The selective deposition nature of AM processes enables component re-designing by means of topographical or topological optimization techniques. A weight reduction results in less material having to be produced and deposited. Therefore, the costs and the cumulative energy demand decrease. The results of the comparative analyses depend on both the SCR value and the extent of the weight reduction. As mentioned above, the extent of light-weighting was modelled in this paper by introducing a *k* factor, which was defined as the ratio between the mass of the part produced by means of the AM-based approach and that of the CM-based approach. The weight reduction increases as the *k* value decreases. A minimum *k* value equal to 0.1 (which corresponds to a 90% weight reduction) was hypothetically considered as the lower limit. For a given SCR value of the CM-based approach, it is possible to identify a *k** value for which the considered process metric (either the CED or the cost) is equal for both of the manufacturing approaches [31]. The *k** values were computed by applying the models proposed in Sections 4 and 5 to the case study while varying the SCR value for the CM-based approach. The results are plotted in Figure 6. All the combinations of *k** and SCR that fall below the curve define a specific condition that is suitable for the AM-based approach.

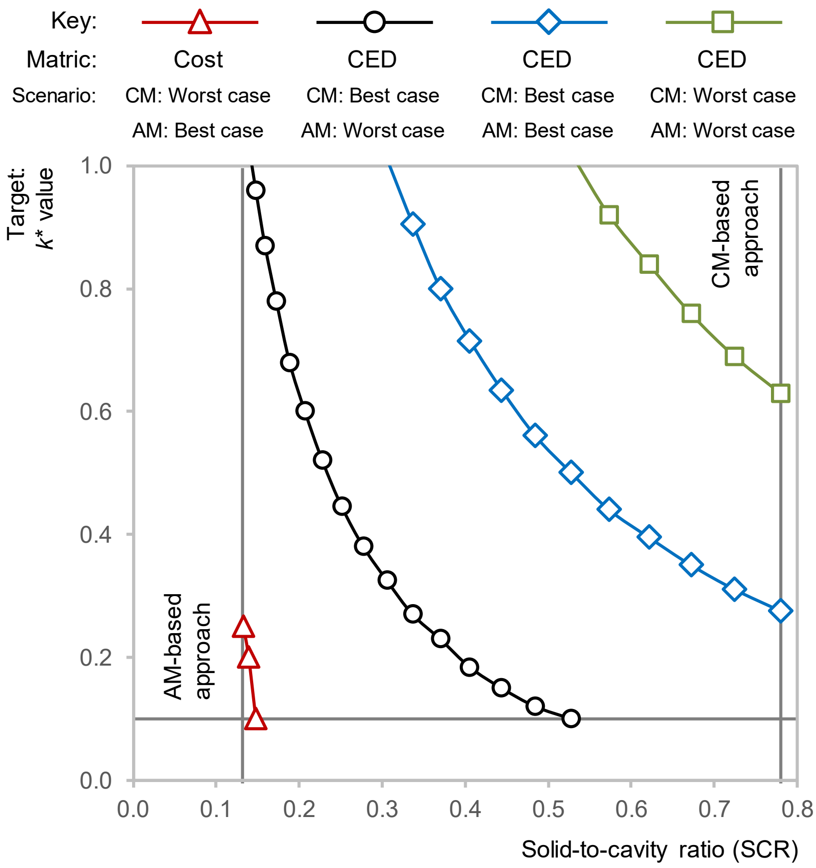

Figure 6. A two-factor decision support chart that accounts for material-usage efficiency and light weighting.

For instance, if a component produced via the CM-based approach and characterized by an SCR equal to 0.6 is considered, the AM-based approach should be chosen if the *k** value achievable by means of the re-design is lower than (*i*) 0.41, when material recycling is accounted for in both of the approaches, or (*ii*) 0.87, when material recycling is not envisaged. The material recycling policy affects the results to a great extent, as mentioned above. This highlights the need of a manufacturing route with a higher material-usage efficiency when the energy recovery due to recycling is neglected. In addition, the CM approach should always be preferred for SCR = 0.6 (*i*) if material recycling is not applied to the AM-approach only, and (*ii*) for cost reasons. In fact, for the here assumed case study, the AM-based approach generally appears to be the most expensive one, even though the cradle-to-gate economic benefits of light-weighting were included in the assessment. The graph reported in Figure 6 can be considered as a two-factor decision support chart that allows energy- and cost-wise processes to be selected while varying the shape of the component as well as the extent of the light-weighting. Additive Manufacturing allows substantial energy savings with respect to conventional manufacturing routes when the light-weighting of the part is enabled by means of re-design techniques. In fact, even when leaving the use phase out of the boundaries of the study, Figure 6 shows large areas where the EBM of titanium alloys is preferable over machining. The here discussed results are consistent with the analyses presented by Huang et al. [36], who adopted a cradle-to-gate approach to compare five different case studies made of either titanium alloys or aluminium alloys. They considered different AM platforms, depending on the material being analysed, and each case study was characterized by a mass reduction ranging from 35% to 65% when choosing the AM approach. Huang et al. [36] stated that "the AM pathway led to significantly lower cradle-to gate primary energy use compared to the CM pathway" and the energy savings were "primarily due to the reductions in resource production energy use attributable to the lower buy-to-fly ratios of AM processes and the reduced mass associated with the AM components' advanced lightweight geometries". When compared with subtractive processes, AM approaches do not appear to be a cost-effective solution within the analysed boundaries. Nevertheless, better results were found in literature when AM approaches either concern other materials or are compared with mass conserving ones. Kamps et al. [19] proved that Laser Beam Melting processes can be a cost-efficient process (when compared to subtractive processes) for a 16MnCr5 gear wheel with a weight reduction as high as 54%. Moreover, Atzeni and Salmi [11] demonstrated the economic benefits of Direct Metal Laser Sintering (DMLS) for the small-to-medium batch size production of an aircraft component made of aluminium alloy which was re-designed for AM.

7.3. System boundary 'B'

Weight reduction can provide even higher returns for AM-based approaches when the use phase is included in the model [32]. This statement is particularly true when the component has to be assembled in a transportation system, since light-weighting results in a reduction in fuel consumption [36]. Therefore, further energy and cost reductions are achievable, and higher cradle-to-gate impacts of the AM-based approach might be compensated for by the advantages that arise over the use phase of the component. Under this assumption, three factors of influence affect the comparative analyses: the SCR, the *k* value and the extent of the use phase (i.e., the amount of driven distance and/or the utilization time).

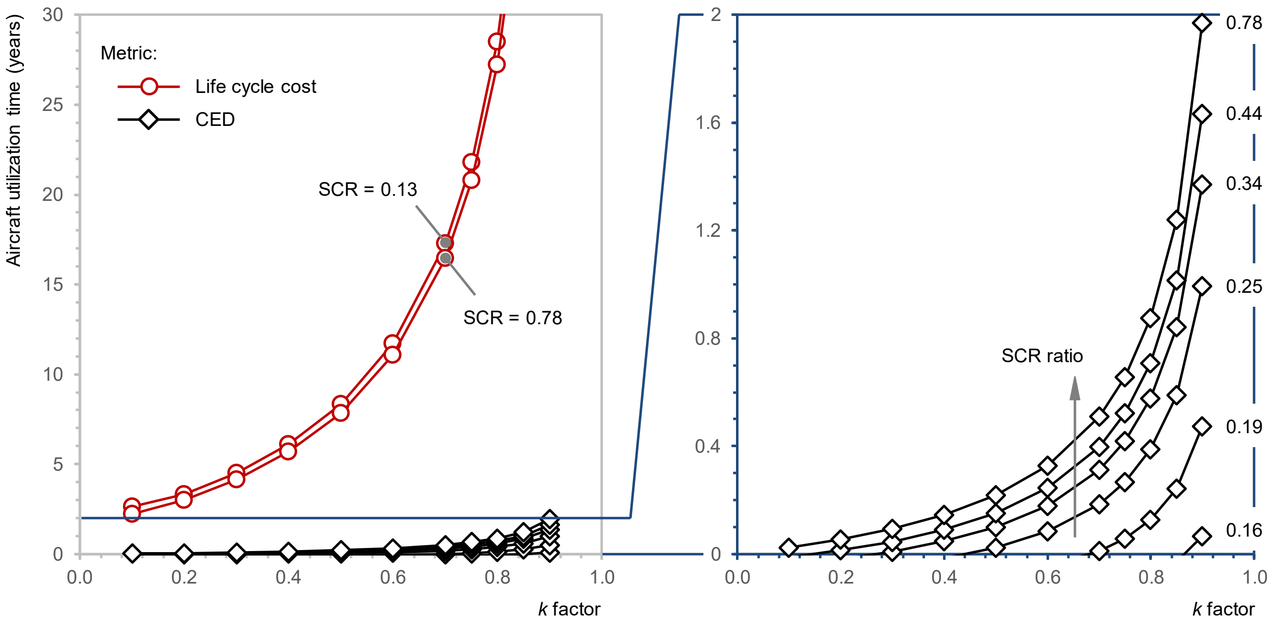

Figure 7. A decision support chart that accounts for material-usage efficiency, light weighting and use-phase benefits.

To better clarify the impact of the use phase on the achievable results, it was assumed that the here considered components were assembled on a short distance aircraft. The saved primary energy per kilogram of reduced mass and per year was assumed to be 5000 MJ/kg·year [36]. A saved cost of 93.8 €/kg·year was obtained, handling the data published by Baumers et al. [17]. The utilization times whereby the extra energy or cost due to the AM-based approach (in the cradle-to-gate scenario) is counterbalanced by the savings during the use phase were calculated while varying the SCR (i.e., the component shape for the CM-based approach) and the *k* value (i.e., the extent of light-weighting). The results are plotted in Figure 7, in which the maximum gap between the worst case for the AM-based approach and the best case for the CM-based one was assumed. If the break-even value computed in terms of utilization time is lower than the expected lifetime of the component, then the AM-based approach could be chosen, even when the production of the component (including the pre-manufacturing phases) is economically and energetically more expensive. The life expectancy of an aircraft has been estimated as 30 years [36]. The breakeven points occur before 2 years for CED, despite the considered SCR / k combination, thus highlighting that the AM-based approach provides significant environmental benefits, even when a limited light-weighting is achieved by the re-designing. Moreover, a lower *k* value than 0.8 (i.e., a higher light-weighting than 20% of the mass of the conventionally manufactured component) leads to economic paybacks prior to the expected lifetime of the aircraft. The latter statements can be confirmed when the life expectancy of the component is equal to that of the aircraft (e.g., if no component replacement is needed). It is worth remarking that the effects of SCR variation on the results can be traced back to the counteracting trends already presented in Figure 3 and Figure 4. The graphs in Figure 7 can be used as decision support charts for the selection of the manufacturing approach. For instance, when a component produced via the CM-based approach and characterized by a SCR value of 0.78 is considered, and if a *k* value of 0.6 is achieved via re-designing for AM, the payback period is equal to 0.3 years and to 11.1 years for the CED and the total costs, respectively. Since these values are lower than the expected lifetime of the component (under the above mentioned hypothesis), the AM-based approach would be preferable. Vice versa, the CM-based approach would be the best choice. The here-presented models confirm the results achieved by Laureijs et al. [18], who compared the cost of an EBM approach with conventional forming to produce an engine bracket made of Ti-6Al-4V. Their study was one of the few available researches including the cost saving during the use phase of a transportation system, and it was highlighted that a “lighter design provides significant savings to the part end user” because of the fuel consumption reduction over the use phase. Moreover, as far as stainless steel is concerned, a use phase benefit was pointed out by Baumers et al. [17], who compared a DMLS process and a conventional machining plus joining approach for the manufacturing of a stainless steel blower. A unit-cost saving of 37.5% was due to a better in-use efficiency when switching from the conventional pathway to the AM-based route.

8. Conclusions

Empirical models used to compare the total costs and the cumulative energy demand for both subtractive and additive/subtractive integrated approaches have been presented in the paper. The main phases of the life cycle were assessed by including post-AM processing operations (such as the removal of the part and support structures, Hot Isostatic Pressing and the finish machining of the functional surfaces). A more detailed modelling effort than that found in the existing literature was attempted, and decision support charts for the concurrent economic and environmental selection of the preferable manufacturing route were introduced. The production of components made of a Ti-6Al-4V alloy was considered to better clarify the applicability of the here proposed methodology. Different scenarios were assumed, and decision support charts were developed to be applied when: (*i*) identical components are manufactured by means of subtractive and additive-based approaches; (*ii*) the components produced by AM are characterized by a weight reduction that has a negligible impact on the use phase; (*iii*) the components produced by AM allow use-phase benefits related to light-weighting to be introduced. The comparative analyses were carried out while varying two main factors of influence, namely the geometry of the component (through the solid-to-cavity ratio) and the extent of light-weighting enabled by AM (through the *k* factor). Overall, the decision support charts allowed the suitable domains of application of each manufacturing approach to be identified. However, it is probably unfair to a priori label one of the two routes as being the most environmentally or economically sustainable. The outcomes are affected by the factors of influence related to the (eventually re-designed) geometry of the part, the end-use application of the component, as well as the policy regarding the recycling/recyclability of the materials. AM has proved to be a preferable choice for the presented case study from the energy demand perspective, in which the material-usage efficiency of the process or the benefits due to light weighting affect the outcomes to a great extent. Moreover, although the production costs are often higher, AM is expected to guarantee other advantages (which have here been neglected) over the entire value chain. The applicability of the here proposed empirical models and decision support charts has a general validity [54]. Further developments in this research field should concern the development of decision support charts for other combinations of materials and AM processes, in order to provide a more comprehensive picture about the sustainability of AM. However, variability and uncertainty of the input data could lead to significantly different conclusions, which are purely case specific.

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