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A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case

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Abstract

Additive Manufacturing (AM) technologies revolutionized the common understanding of manufacturing with their layer-by-layer building principle. However, the literature has documented their high energy requirements, which is not in-line with the current policies of energy and emission reduction. This ambivalence of AM opens the question for the research community about the wise choice of the manufacturing process to be adopted. This paper proposes a comparative LCA method to select the best manufacturing technology between Conventional Manufacturing (CM) and EBM plus Finish Machining (EBM+FM). The Life Cycle Assessment (LCA) is conducted under cradle-to-gate boundaries. Three metrics, namely the Cumulative Energy Demand (CED), cost and CO_2 emissions are considered. Characterization of unit processes is done by using the recent findings in the literature which are included in the model for both process technologies. The Specific Energy Consumption (SEC) is connected to the Material Removal Rate (MRR) and to the average Deposition Rate (DR_a), respectively for machining and EBM. The main finding of this research is the description of breakeven surfaces, which separate the regions of validity between machining and EBM, as function of the Solid-to-Cavity Ratio (SCR) and the DR_a. Moreover, the presented methodology gives the possibility to compare the goodness of the different sets of design rules that can be chosen for EBM, thanks to the proper evaluation of the SEC parameter. Finally, a sensitivity analysis is conducted to assess the effect of the remaining key variables.

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Keywords: Additive manufacturing; Machining; Cumulative energy demand; Cost; CO_2 emissions.

1. Introduction

Recently published papers proposed a methodology to assess the Cumulative Energy Demand (CED), the costs and the carbon dioxide emissions through the life cycle of a product manufactured by means of additive- or subtractive-based approaches [1-3]. Priarone and Ingarao [1, 3] proposed breakeven surfaces allowing the most sustainable manufacturing route between conventional machining (CM hereafter) and integrated AM-based approaches (AM + FM) to be identified. As far as the feedstock material production is concerned, due attention should be given to the energy embedded in the raw material, especially for machining, since it usually starts from massive workpieces [2]. Focusing on the AM-based integrated approach, the methodology should include, beside finish machining operations, the unit-processes related to the removal of support structures (i.e., by means of wire-EDM) and the thermal treatments [3]. The evaluation of practical case studies showed that the manufacturing phase can count for around 30-55% of the CED for a titanium lifting bracket for a jet aircraft engine realized with EBM [4]. A higher predominance (85-95%) of the manufacturing share on the CED was shown for a L-PBF technique applied to realize an airplane bearing bracket, due to the low energy efficiency of the laser source [5].

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Nomenclature

C_{EE} (€/kWh): cost of electric energy;
C_{gas} (€/kg): specific cost of the gas (EBM);
C_{Ind}^{CM} (€/h): indirect cost rate for the machine tool;
C_{Ind}^{EBM} (€/h): indirect cost rate for the EBM machine;
C_{lub} (€/kg): specific cost of the cutting fluid;
C_{Mat}^{CM} (€/kg): feedstock material cost (workpieces);
C_{Mat}^{EBM} (€/kg): feedstock material cost (powder);
C_{Mfg}^{FM} (€): cost contribution of finish machining (EBM+FM);
CO_{2E} ($kgCO_2$/kg): carbon footprint of the raw material;
CO_{2gas} ($kgCO_2$/kg): carbon footprint of the gas (EBM);
CO_{2lub} ($kgCO_2$/kg): carbon footprint of the cutting fluid;
CO_{2Mfg}^{FM} ($kgCO_2$): CO_2 emissions of finish machining (EBM+FM);
$CO_{2Pre\text{-}mfg}^{CM}$ ($kgCO_2$/kg): carbon footprint of workpiece forming;
$CO_{2Pre\text{-}mfg}^{EBM}$ ($kgCO_2$/kg): carbon footprint of powder atomization;
CO_{2tool_i} ($kgCO_2$): carbon footprint of the cutting tool, with i = RM, FM;
C_{Op}^{CM} (€/h): labour charge rate of the machine tool operator;
C_{Op}^{EBM} (€/h): labour charge rate of the EBM machine operator;
C_{tool_i} (€): cost of the cutting tool, with i = RM, FM;
E_E (MJ/kg): embodied energy of the raw material;
E_{gas} (MJ/kg): embodied energy of the gas (EBM);
E_{lub} (MJ/kg): embodied energy of the cutting fluid;
E_{Mfg}^{FM} (MJ): energy demand of finish machining (for EBM+FM);
$E_{Pre\text{-}mfg}^{CM}$ (MJ/kg): specific energy demand for workpiece forming;
$E_{Pre\text{-}mfg}^{EBM}$ (MJ/kg): specific energy demand for powder atomization;
E_{tool_i} (MJ): embodied energy of the cutting tool, with i = RM, FM;
m_A (kg): mass of allowances to be removed from the EBM-ed components by means of finish machining;
m_B^{CM} (kg): mass of the batch produced by means of the CM route;
m_B^{EBM+FM} (kg): mass of the batch produced by means of the EBM+FM route;
m_{Ci} (kg): mass of the chips to be removed, with i = RM, FM;
m_{Feed}^{CM} (kg): mass of the feedstock material for the CM route;
m_{Feed}^{EBM+FM} (kg): mass of the feedstock material for the EBM+FM route;
m_S (kg): mass of the support structures for the EBM-ed components;
m_W^{CM} (kg): material waste stream produced during the workpiece forming;
m_W^{EBM} (kg): material waste stream produced during the EBM process;
m_W^{EBM+FM} (kg): material waste stream produced during the powder atomization;
P_{np}^{CM} (kW): power demand of the machine tool in non-productive mode;
P_{np}^{EBM} (kW): power demand of the EBM machine in non-productive mode;
q_G (kg/h): consumption rate of the gas (EBM);
q_L (kg/h): consumption rate of the cutting fluid;
SEC_i^{CM} (kWh/kg): specific energy consumption of the machine tool when cutting, with i = RM, FM;
SEC^{EBM} (kWh/kg): specific energy consumption of the EBM machine during the printing phase;
t_c (h): overall cutting time;
t_{ci} (h): cutting time, with i = RM, FM;
t_G (h): gas insufflation time (EBM);
T_i (h): tool life, with i = RM, FM;
t_{np}^{CM} (h): non-productive time of the machine tool;
t_{np}^{EBM} (h): non-productive time of the EBM machine;
t_{Mfg}^{CM} (h): total manufacturing time for machining (i.e., considering both non-productive and productive times);
t_{Mfg}^{EBM} (h): total manufacturing time for EBM (i.e., considering both non-productive and productive times);
t_{SR} (h): time for removal of support structures;
t_{tc} (h): tool change time;
y^{CM} (-): input/output material ratio for workpiece forming;
y^{EBM} (-): input/output material ratio for powder atomization;
δ^{CM} (-): rate of employment of the operator ($\delta \leq 1$) of the machine tool;
δ^{EBM} (-): rate of employment of the operator ($\delta \leq 1$) of the EBM machine;
η (-): primary-to-secondary energy conversion factor;
λ (-): ratio between the total output mass flow from the EBM+FM route (i.e., m_B^{EBM+FM}) and that from the CM route (i.e., m_B^{CM})

These results are mainly due to the typical magnitude of the Specific Energy Consumption (SEC) for AM processes, which can be two orders of magnitude higher than that of subtractive processes [6]. Therefore, the manufacturing step plays a key role when performing a LCA for a product realized by means of AM. Moreover, the LCA studies available in literature lack a precise evaluation of the manufacturing step for both CM and AM + FM approaches, and average values achieved from database are often applied. This issue can be problematic particularly when multiple AM scenarios are compared. Considering the manufacturing step, recently published works found an empirical law to assess the SEC parameter of the different processes. For subtractive technologies, Kara and Li [7] correlated the SEC parameter with the Material Removal Rate (MRR). On the other hand, the energy efficiency of (*i*) an entire AM process (i.e., considering productive plus non-productive phases) and (*ii*) the printing phase only was related to the average Deposition Rate (DR_a) for EBM and FDM [8, 9]. The MRR quantifies the amount of material removed from a workpiece in the unit time, according to the main process parameters for machining [7]. Instead, the DR_a quantifies the amount of material deposited in a precise process window. Therefore, being the DR_a an average value, it connects the time efficiency of the given AM process to the geometrical features of the components being printed (i.e., to the complexity of the printed job) and to the process parameters [8, 9]. A proper evaluation of the SEC parameter would give an added value to the LCA study of AM-based manufacturing routes, allowing to consider the implications of the different product and process design rules for AM in terms of CED, costs and CO_2 emissions.

1.1. Aim of the paper

This paper performs a comparative LCA under cradle-to-gate boundaries (i.e., neglecting the use phase), as shown in Figure 1. Considering the manufacturing scenarios and the models already reported in [1-4], the Conventional Milling from a massive workpiece (CM) is compared with EBM plus subsequent Finish Machining (EBM+FM). Breakeven surfaces are proposed for the CED, cost and CO_2 emission metrics, as in

[1, 3]. The SCR variable is kept as main input driver for the subtractive approach, as in [3]. The SCR has been defined as the mass of the final part divided by the mass that would be theoretically enclosed in the bounding volumetric envelope of the part itself [10]. The aim of this paper is to better address the additive manufacturing (i.e., EBM) step in Figure 1 due to the integration of the hyperbolic model proposed in [8] for the quantification of the SEC parameter as a function of the DR_a. Therefore, in this research, the breakeven conditions are investigated in a tridimensional space, using the SCR and the DR_a as variables of the input domain.

2. Methodology

The AM systems, due to their layer-by-layer building principle, could simultaneously print several components. In this paper, the functional unit of the analysis is extended from the single manufactured part to a generic batch of components, in order to fully exploit the empirical SEC model for the EBM technology which was proposed in [8]. However, it is assumed that the manufactured batch is made of a fixed number of replicas of the same component. This choice allows simplifying the formulas referring to the other phases of the LCA.

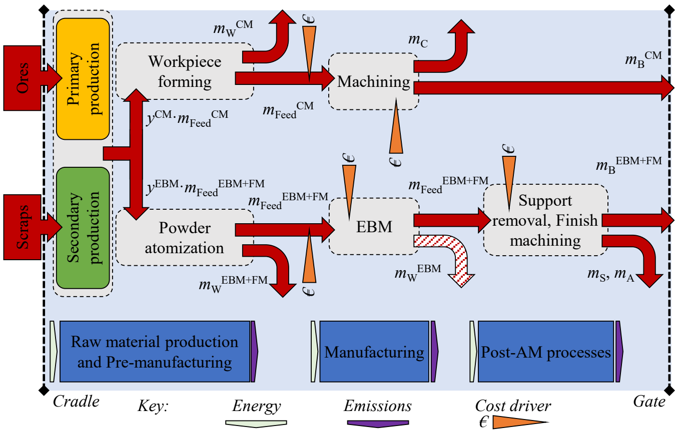

Fig. 1. Flows of energy, resources and emissions for CM and AM+FM [1-3].

2.1. Material production and pre-manufacturing

The raw material production and the pre-manufacturing stages are included in the analysis to characterize the feedstock material flows [1-3]. The embodied energy and the CO_2 emissions account for the benefits due to the upstream flow of recycled material in the current supply by applying the so-called 'recycled content approach' [11]. The cost per unit mass of the feedstock materials was multiplied by the process input flows to evaluate the material purchase costs [2, 3].

2.2. Rough and finish machining

The mass of the chips is the amount of material removed when rough (RM) and finish (FM) machining. The SEC_i^{CM} values (in kWh/kg) are determined by using the empirical law reported in [7], i.e., $SEC^{CM} = C_0^{CM} + C_1^{CM}/MRR$. The power demand during the non-productive mode of the machine tool is included in the analysis to evaluate the energy consumption in idle operational modes [2]. The energy shares due to the consumables (such as cutting tools and cutting fluids) are considered [2]. The Carbon Emission Signature (CES) is applied to convert the electric energy demand of the machine tool into carbon dioxide emissions [12]. Considering the main cost drivers, the indirect cost rate of the machine tool and the labour charge rate are computed as proposed in [13] and [2], respectively.

2.3. Electron Beam Melting and post-EBM processes

Baumers et al. [14] verified that the saturation of the build capacity leads to a reduction of the SEC value, especially for metal AM processes. Similarly, the saturation of the build chamber reduces the cost per part due to the optimization of the long non-productive times, such as the pre-setting and cooling phases, but also the powder layer distributions during the printing phase. The number of components in the chamber is up to the machine capacity, and is related to the features of the parts being printed as well as their orientation [5]. But how to address the variation of the SEC value and the costs due to these phenomena? For instance, the authors in [8] demonstrated that the presence of support and lattice structures slows down the DR_a, together with the higher height of the components in the chamber. Similarly, the same batch of components can be placed into the build chamber with different orientations, each one with a specific DR_a that implies a specific energy demand. Therefore, in this work, the SEC^{EBM} value which refers to the EBM printing phase is computed by using the empirical law obtained in [8], i.e., $SEC^{EBM} = C_0^{EBM} + C_1^{EBM}/DR_a$. The power demand during the non-printing phases of the EBM machine is also included to evaluate the non-productive contributes.

The powder losses during the EBM process (m_W^{EBM}) are omitted from the analysis, since the powder is melted under vacuum with a low pressure of inert helium gas, and the un-melted powder can be re-used. The energy contribution due to the gas consumption should be included to complete the assessment at the unit-process level. Therefore, the embodied energy of the inert gas (helium) is multiplied for its consumption rate and for the overall insufflation time [2]. The cost assessment can be carried out as for the machining unit process [2]. The thermal treatment is neglected, due to the usual lack of residual stresses on EBM components [15]. The energy and the CO_2 contributions of support removal are omitted since manual tools are considered for this task. However, its cost contribution is taken into account due to the high labour cost rate of the operator. Milling finishing operations are considered for the 3D printed parts to remove the allowance masses. Their energy, cost and CO_2 contributes can be assessed as discussed in Section 2.2 for the machining unit process.

2.4. Comparative LCA method

The evaluated metrics can be computed as the sum of the contributes discussed in Sections 2.1, 2.2 and 2.3 for either the CM or the EBM+FM manufacturing approach [1-4]. Then, per each metric, the ratio between the results for the CM approach and the ones for the EBM+FM approach can be written. This ratio can be set equal to 1, as shown in Equations 1-3, to evaluate the breakeven surfaces, and the characteristic λ factor (here defined as the ratio m_B^{EBM+FM} / m_B^{CM} allowing the equation to be satisfied) can be mathematically obtained. In order to better clarify this point, as far as the CED is considered, a λ^{CED} equal to 5 means that, for the same batch size, the total (output) mass of components manufactured by means of the EBM+FM route should be 5 times higher than that of the CM approach to achieve the same cumulative energy demand. All the conditions which give a λ lower than the threshold λ^{CED} (computed under the same production scenario, i.e., process parameters and batch size), would underline that the EBM+FM route should be preferred for the CED metric. This methodology could be applied for each value of the investigated domain of the input variables SCR and DR_a.

2.5. Data inventory

The material considered in this research was a Ti-6Al-4V alloy, with average eco-properties for E_E and CO_{2E} of 556.2 MJ/kg and 33.0 $kgCO_2/kg$ [16]. Moreover, the upstream flow of recycled material in the current supply was assumed to be 22% [16]. The best estimation for $E_{Pre\text{-}mfg}^{CM}$ and $E_{Pre\text{-}mfg}^{EBM}$ was 14.5 MJ/kg [17] and 70.0 MJ/kg [18], respectively, with related CO_2 emissions of 1.2 $kgCO_2/kg$ [17] and 3.8 $kgCO_2/kg$ [1]. The input/output material ratios y^{CM} and y^{EBM} were set to 1.05 [16] and 1.03 [18], respectively. The model for quantifying the electric energy consumption of the cutting process was $SEC^{CM°}$(kWh/kg) = 0.19 + 2.02 / MRR (kg/h) [7], whereas the model concerning the electric energy consumption of the EBM process during the printing phase (for an Arcam A2X system) was SEC^{EBM} (kWh/kg) = 2.82 / DR_a (kg/h) [8]. The secondary-to-primary energy conversion factor was 0.38 [5]. The CES of the electric grid was 0.447 $kgCO_2/kWh$ [2]. The here-analysed ranges of variation of the MRR were 1.6-2.2 kg/h for rough machining (RM, which removed 80% of m_C) and 0.1-0.2 kg/h for finish machining (FM, which removed 20% of m_C) [19]. On the other hand, the range for the DR_a of EBM was 0.02-0.12 kg/h, according to [8, 14]. The term P_{np}^{CM} was fixed at 2.2 kW [2], while P_{np}^{EBM} was 1.6 kW for the vacuum generation phase or 1.4 kW for the machine settings and the cooling phase [8]. The cutting tool life (T) of 30 min and the tool change time (t_{tc}) of 2 min were obtained from [2]. The embodied energy of the carbide material was 400 MJ/kg, while its carbon footprint was 47.3 $kgCO_2/kg$ [20, and references therein]. The contribution of the cutting fluid was also considered (E_{lub} = 1.4 MJ/kg, CO_{2lub} = 0.11 $kgCO_2/kg$ and q_L = 0.48 kg/h [20, 21]). The E_{gas} and the CO_{2gas} for helium were computed as 1.58 MJ/kg and 0.08 $kgCO_2/kg$, with reference to the extraction from natural gas [22]. Moreover, according to the machine datasheet, q_G was 1 L/h during the printing phase, while 50-75 L were needed for the cooling phase. As far as the cost assessment is concerned, C_{Mat}^{CM} was assumed to be 28.0 €/kg, and the powder purchase cost was 175.0 €/kg [23]. C_{Ind}^{CM} of the milling machine was equal to 12.5 €/h [2]. For the evaluation of C_{Ind}^{EBM}, the following data were considered [13]: a depreciation period of 8 years, 5000 working hours per year, a maintenance cost equal to the 6% of the machine purchase cost and 5.46 €/h for production and administration overheads. On the basis of these assumptions, a value of C_{Ind}^{EBM} equal to 31.4 €/h was computed for the Arcam A2X system (considering the machine purchase cost from [24]). An average labour charge rate of 21.7 €/h was hypothesized [2], with a rate of employment for the operator of 10% for machining and 5% for EBM. The cost of the electric energy was set to 0.15 €/kWh [2]. The terms C_{tool}, C_{lub} and C_{gas} were assumed to be 20 €/tool [2], 0.93 €/kg [20, 21] and 13.76 €/kg [25], respectively.

3. Results and Discussion

The breakeven surfaces for the CED, costs and CO_2 emissions are plotted in Figure 2 as a function of DR_a and SCR. For the sake of clarity, the following variables were used for the computation of the surfaces: (*i*) m_B^{CM} = 3 kg; (*ii*) MRR_{RM} = 1.90 kg/h, (*iii*) MRR_{FM} = 0.15 kg/h, (*iv*) masses of allowances and support structures both equal to 10% of m_B^{EBM+FM}.

$$\frac{CED^{\mathrm{CM}}}{CED^{\mathrm{EBM+FM}}}=\frac{\left[\left(E_{\mathrm{E}}+E_{\mathrm{Pre-mfg}}{}^{\mathrm{CM}}\right)\cdot y^{\mathrm{CM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{CM}}\right]+\frac{3.6}{\eta}\cdot\left[P_{\mathrm{np}}{}^{\mathrm{CM}}\cdot t_{\mathrm{np}}{}^{\mathrm{CM}}+\sum_{\mathrm{i=RM,FM}}\left(SEC_{\mathrm{i}}{}^{\mathrm{CM}}\cdot m_{C_{\mathrm{i}}}+P_{\mathrm{np}}{}^{\mathrm{CM}}\cdot t_{\mathrm{tc}}\cdot\frac{t_{c_{\mathrm{i}}}}{T_{\mathrm{i}}}\right)\right]+\left[\sum_{\mathrm{i=RM,FM}}\left(E_{\mathrm{tooli}}\cdot\frac{t_{c_{\mathrm{i}}}}{T_{\mathrm{i}}}\right)+E_{\mathrm{lub}}\cdot q_{\mathrm{L}}\cdot t_{\mathrm{c}}\right]}{\left[\left(E_{\mathrm{E}}+E_{\mathrm{Pre-mfg}}{}^{\mathrm{EBM}}\right)\cdot y^{\mathrm{EBM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{EBM+FM}}\right]+\frac{3.6}{\eta}\cdot\left[P_{\mathrm{np}}{}^{\mathrm{EBM}}\cdot t_{\mathrm{np}}{}^{\mathrm{EBM}}+\left(SEC^{\mathrm{EBM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{EBM+FM}}\right)\right]+E_{\mathrm{gas}}\cdot q_{\mathrm{G}}\cdot t_{\mathrm{G}}+E_{\mathrm{Mfg}}{}^{\mathrm{FM}}}=1 \tag{1}$$

$$\frac{Cost^{\mathrm{CM}}}{Cost^{\mathrm{EBM+FM}}}=$$

$$\frac{\left[C_{\mathrm{Mat}}{}^{\mathrm{CM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{CM}}\right]+\left[\left(C_{\mathrm{Ind}}{}^{\mathrm{CM}}+\delta^{\mathrm{CM}}\cdot C_{\mathrm{Op}}{}^{\mathrm{CM}}\right)\cdot t_{\mathrm{Mfg}}{}^{\mathrm{CM}}\right]+C_{\mathrm{EE}}\cdot\left[P_{\mathrm{np}}{}^{\mathrm{CM}}\cdot t_{\mathrm{np}}{}^{\mathrm{CM}}+\sum_{\mathrm{i=RM,FM}}\left(SEC_{\mathrm{i}}{}^{\mathrm{CM}}\cdot m_{C_{\mathrm{i}}}+P_{\mathrm{np}}{}^{\mathrm{CM}}\cdot t_{\mathrm{tc}}\cdot\frac{t_{c_{\mathrm{i}}}}{T_{\mathrm{i}}}\right)\right]+\left[\sum_{\mathrm{i=RM,FM}}\left(C_{\mathrm{tooli}}\cdot\frac{t_{c_{\mathrm{i}}}}{T_{\mathrm{i}}}\right)+C_{\mathrm{lub}}\cdot q_{\mathrm{L}}\cdot t_{\mathrm{c}}\right]}{\left[C_{\mathrm{Mat}}{}^{\mathrm{EBM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{EBM+FM}}\right]+\left[\left(C_{\mathrm{Ind}}{}^{\mathrm{EBM}}+\delta^{\mathrm{EBM}}\cdot C_{\mathrm{Op}}{}^{\mathrm{EBM}}\right)\cdot t_{\mathrm{Mfg}}{}^{\mathrm{EBM}}\right]+C_{\mathrm{EE}}\cdot\left[P_{\mathrm{np}}{}^{\mathrm{EBM}}\cdot t_{\mathrm{np}}{}^{\mathrm{EBM}}+\left(SEC^{\mathrm{EBM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{EBM+FM}}\right)\right]+C_{\mathrm{gas}}\cdot q_{\mathrm{G}}\cdot t_{\mathrm{G}}+C_{\mathrm{Op}}{}^{\mathrm{EBM}}\cdot t_{\mathrm{SR}}+C_{\mathrm{Mfg}}{}^{\mathrm{FM}}}=1 \tag{2}$$

$$\frac{CO_2{}^{\mathrm{CM}}}{CO_2{}^{\mathrm{EBM+FM}}}=\frac{\left[\left(CO_{2\mathrm{E}}+CO_{2\mathrm{Pre-mfg}}{}^{\mathrm{CM}}\right)\cdot y^{\mathrm{CM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{CM}}\right]+CES\cdot\left[P_{\mathrm{np}}{}^{\mathrm{CM}}\cdot t_{\mathrm{np}}{}^{\mathrm{CM}}+\sum_{\mathrm{i=RM,FM}}\left(SEC_{\mathrm{i}}{}^{\mathrm{CM}}\cdot m_{C_{\mathrm{i}}}+P_{\mathrm{np}}{}^{\mathrm{CM}}\cdot t_{\mathrm{tc}}\cdot\frac{t_{c_{\mathrm{i}}}}{T_{\mathrm{i}}}\right)\right]+\left[\sum_{\mathrm{i=RM,FM}}\left(CO_{2\mathrm{tooli}}\cdot\frac{t_{c_{\mathrm{i}}}}{T_{\mathrm{i}}}\right)+CO_{2\mathrm{lub}}\cdot q_{\mathrm{L}}\cdot t_{\mathrm{c}}\right]}{\left[\left(CO_{2\mathrm{E}}+CO_{2\mathrm{Pre-mfg}}{}^{\mathrm{EBM}}\right)\cdot y^{\mathrm{EBM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{EBM+FM}}\right]+CES\cdot\left[P_{\mathrm{np}}{}^{\mathrm{EBM}}\cdot t_{\mathrm{np}}{}^{\mathrm{EBM}}+\left(SEC^{\mathrm{EBM}}\cdot m_{\mathrm{Feed}}{}^{\mathrm{EBM+FM}}\right)\right]+CO_{2\mathrm{gas}}\cdot q_{\mathrm{G}}\cdot t_{\mathrm{G}}+CO_{2\mathrm{Mfg}}{}^{\mathrm{FM}}}=1 \tag{3}$$

According to each breakeven condition, the value of m_B^{EBM+FM} can be obtained directly from m_B^{CM} by applying the λ^{CED}, λ^{Cost} and λ^{CO2} values reported in Figure 2. As far as the CED and CO_2 emissions are concerned, the results show a predominance of λ higher than one for a large area of the investigated domain. Since high reductions in energy and CO_2 emissions can be achieved when high DR_a are applied [8], the breakeven condition between CM and EBM+FM can be reached only when the processed mass flow of the EBM+FM route increases. On the other hand, the cost result shows that the EBM+FM route (under the above-mentioned assumptions) does not show clear advantages over CM. This is due to the low productivity of EBM, which implies an increase in the indirect cost contribution. Values of λ^{Cost} lower than 1 are evident almost for the entire domain, meaning that from the economic point of view the EBM-based approach should be chosen only if a mass reduction can be achieved. The capability to create lightweight structures, when using EBM, by means of topology optimization procedures appears to be unavoidable to obtain λ values lower than one. Moreover, Figure 2*b* highlights negative values of λ^{Cost} for SCRs higher than 0.6. In these cases, the cost of the CM approach is so low in comparison to that of EBM+FM, that the overall output mass of the latter approach should be negative, which is a meaningless condition.

3.1. Sensitivity analysis

A sensitivity analysis was conducted by considering the effects of: (*i*) the masses of support structures and allowance, (*ii*) the MRR (for RM and FM), and (*iii*) m_B^{CM}. The average value of each parameter was initially fixed at: (*i*) masses of support structures and allowance = 50% of m_B^{EBM+FM}, (*ii*) MRR_{RM} = 1.90 kg/h, (*iii*) MRR_{FM} = 0.15 kg/h, (*iv*) m_B^{CM} = 3 kg. In order to investigate the effect of the variation of each parameter at once, the other variables were kept to their average value. The best-case scenario for EBM was evaluated under the following conditions: (*i*) masses of support structures and allowance = 0% of m_B^{EBM+FM}, (*ii*) MRR_{RM} = 1.60 kg/h, (*iii*) MRR_{FM} = 0.10 kg/h, (*iv*) m_B^{CM} = 5 kg. For the worst-case, the following values were used: (*i*) masses of support structures and allowance = 100% of m_B^{EBM+FM}, (*ii*) MRR_{RM} = 2.20 kg/h, (*iii*) MRR_{FM} = 0.20 kg/h, (*iv*) m_B^{CM} = 0.5 kg. The results are plotted in Figure 3 as a function of the SCR (with DR_a = 0.07 kg/h) and DR_a (with SCR = 0.5). All the analyses focused on the 0-1 range for the λ parameter, in order to account for the production of lighter EBM-ed components. The increase of the SCR reduces the applicability of EBM+FM (area below the curves), since a higher material-usage efficiency is gained by means of the CM approach [3]. The opposite behavior is appreciable when increasing the DR_a values, since a higher time- and energy-efficiency of the printing process is achieved. The masses of support structures and allowance strongly affect the investigated metrics because they rise the energy related to the material flows and slow down the time efficiency of the EBM process [8]. The sensitivity analysis conducted on the MRR shows a low effect on CED and CO_2 emissions (due to the low SEC required by machining). Instead, it slightly influences the cost results, since a variation in the cutting time is achieved. More in detail, the applicability of the EBM+FM approach is reduced for high MRRs, due to the higher cutting efficiency of the CM route. This effect is particularly visible for low SCRs. Considering the effect of m_B^{CM}, for the m_B^{CM} = 5 kg scenario, the long non-productive phases of the EBM machine gain a higher amortization on the printed mass, giving a larger area of applicability to the EBM+FM approach.

4. Conclusions and outlooks

The increase of the time efficiency is a crucial driver for the environmental and economic sustainability of EBM. This paper could help in understanding the competitiveness of EBM, since the breakeven surfaces showed λ^* ratios higher than one for a large area of the investigated domain. Moreover, the presented methodology, which is based on a modelling background well-established in literature, could give the opportunity to compare the goodness of the different sets of design rules that can be chosen for a given component. This study could also help to better define the sustainability borders between the two approaches. Future studies should focus on L-PBF techniques, which are negatively affected by the low energy efficiency of the laser source.

Declaration of Conflict Interest

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

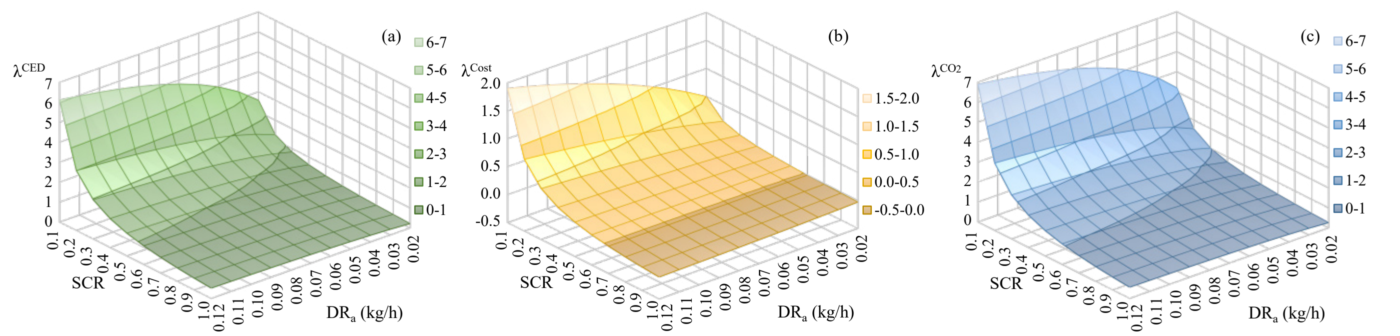

Fig. 2. Breakeven surfaces for (a) CED, (b) Cost and (c) CO_2 emissions.

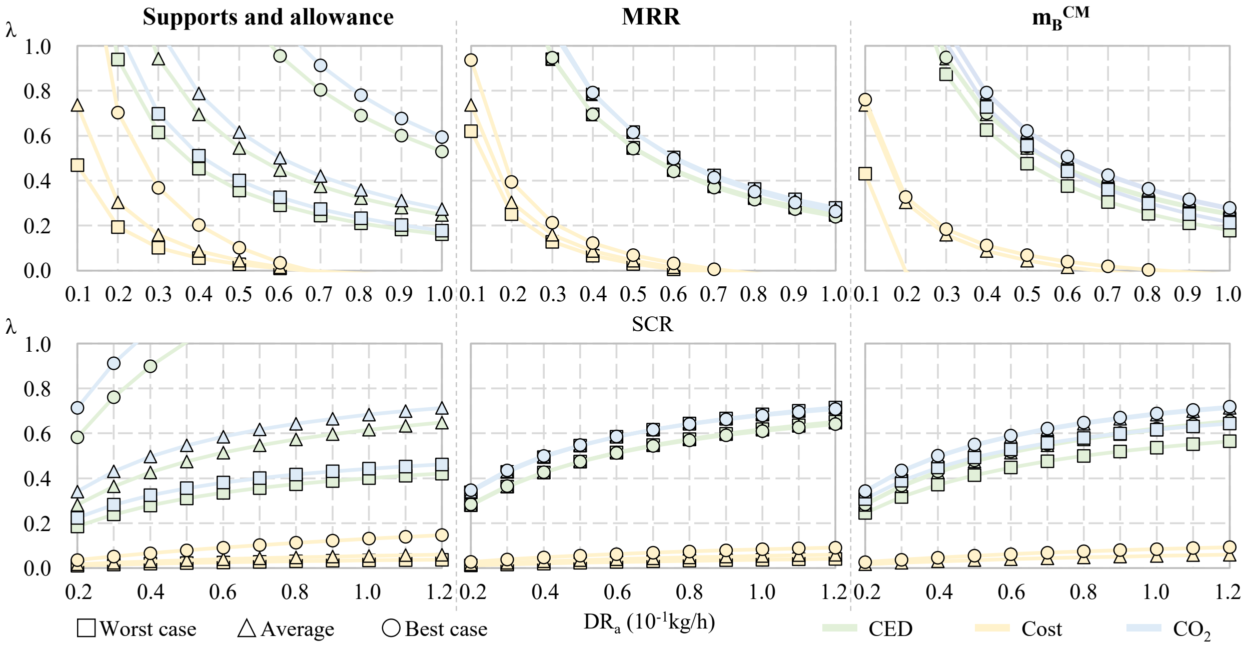

Fig. 3. Sensitivity analysis: effect of main variables.

CRediT authorship contribution statement

Vincenzo Lunetto: Formal analysis, Conceptualization, Methodology. **Paolo C. Priarone:** Conceptualization, Supervision. **Sami Kara:** Conceptualisation, Supervision. **Luca Settineri:** Funding acquisition, Supervision.

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