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Simplified primary energy models for the selection of Electron Beam Melting over turning in the production of titanium alloys components

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Abstract

Over the last years two factors have deeply affected research in Manufacturing: the growing interest around Additive Manufacturing (AM) processes and the need to reduce the anthropogenic environmental impact. As result, a large papers concerning the environmental impact performance of AM compared to conventional processes have been published. Specifically, very complex models accounting for the impact of each life cycle stage of AMed components have been released. Results revealed that AM, at present, guarantees energy savings only within some domains, and the potential saving depends on several factors: product complexity, eco-properties of the material, energy intensity of the material deposition, light-weighting enabled by AM approaches and extent of the use phase. Above all, the result of the comparative analysis depends both on the considered factors and on the selected system boundaries. The already proposed models are very complex and many inventory data are needed, this could make them unapplicable at industrial level. In the presented paper, simplified models are proposed and the performances of these are quantified with varying the analyzed scenario (considered factors and selected system boundary). Results revealed that, for given scenarios, simplified models characterized by low computational effort, can provide reliable results. Guidelines for the implementation of different models with varying the system boundary are provided for the cumulative energy comparison of Electron Beam Melting and conventional turning for the production of titanium alloys components.

Keywords: Decision suppport tools; Additive Manuafcturing; Turning; Sustainable manufacturing; CED.

1. Introduction

Additive Manufacturing (AM) processes might have a disruptive impact in the manufacturing sector. However, the industrial applicability is still limited especially if compared to the industrial application shares of conventional manufacturing approaches. The environmental sustainability of such process category is still difficult to be labeled as on one hand lightweight of the components can be obtained by topology optimization, on the other hand the deposition energy is generally quite high contributing in worsening the environmental impact of AM processes.

In this regards Kellens et al [1], after proposing a literature review on sustainability impact of Additive Manufacturing processes, stated that: “from an environmental perspective, AM can be a good alternative for producing customized parts or small production runs as well as complex part designs creating substantial functional advantages during the part-use phase” (such us light-weight component for aerospace sector). Actually, the environmental performance of additive manufacturing processes over conventional manufacturing depends on several factors: Eco-properties of the processed material, energy intensity of the material deposition, light-weighting enabled by AM approaches, the extent of the use phase. Some of the authors of the present papers have performed comparative analyses between additive processes and conventional ones by including these factors [2, 3]. Over the last years, the environmental impact of additive manufacturing processes has been under the spotlight. An extensive and updated state of the art about the developed

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research on environmental sustainability of AM processes was recently released by Kokare et al. [4]. In this paper a systematic literature review of studies analysing the application of LCA methodology to different AM processes was carried out. To be more specific, comparative environmental impact analyses between additive and conventional approaches have been steadily published over the last decade. In this research very complex model are considered including all the factors of influence [5-8]. The main already proposed research studies concerning additive vs traditional manufacturing are gathered and commented on by Jung et al [9].

The presented models, although providing reliable results, are complex to be implemented and, above all, require a large number of inventory data. The idea of the present paper is to explore the possibility to simplify these models still providing reliable environmental impact quantification in comparative analyses. This would make the models easier to be implemented in industrial environment. To this aim the models already developed by some of the authors [2,3] have been simplified and six new models are proposed; the related performance have been compared to those of full and original model. Three different scenarios are analysed, these consider both the wight reduction enabled by the topology optimisation and different use phase impacts.

Results revealed that simplification is possible as reliable results can be obtained reducing the amount of inventory data to collect.

Nomenclature

α	input/output material ratio for powder production;
ε	input/output material ratio for workpiece production;
k	weight reduction factor due to re-design for AM;
r	end-of-life recyclability;
E^{AM} (MJ/part)	energy demand for producing one part by additive manufacturing approach;
E^{CM} (MJ/part)	energy demand for producing one part by conventional machining approach;
E_A (MJ/kg)	energy demand for metal powder atomization;
E_E (MJ/kg)	embodied energy of the material, including the recycling benefit awarding;
E_F (MJ/kg)	energy demand for forming the workpiece (e.g., by hot extrusion);
E_V (MJ/kg)	energy demand for the primary production of the material;
E_R (MJ/kg)	demand for the secondary production of the material;
$E_{USE}{}^{i}$ (MJ/part)	energy demand for the use phase, for i CM or AM;
m_A (kg)	mass of the machining allowance to be removed by a finishing process;
m_C (kg)	mass of the chips machined by means of CM;
m_P (kg)	mass of the component produced by means of CM;
m_S (kg)	mass of the support structures for AM;
$U_E{}^{AM}$ (MJ/kg)	specific energy demand for AM (per kg of deposited material);
$U_E{}^{CM}$ (MJ/kg)	specific energy demand for CM (per kg of deposited material);
E_{HIP} (MJ/part)	energy for Hot Isostatic Pressing
E_{SEP} (MJ/ part)	energy for separating the part from the build plate
$BEPi$	Breakeven point (SCR values) for the model I with i: I, II,…VII

2. Materials and methods

The present paper starts from the findings and the models presented by some of the authors [2,3]. Specifically, in those research studies the authors developed extensive models, under cradle-to-grave perspectives, in order to quantify and compare one another additive and subtractive manufacturing approaches. In those papers all the main steps from raw material production up to End-of-Life steps were modeled for each single approach.

The factors included in these models can be clustered considering two main drivers: material and processing related impacts.

As far as the material impact is concerned, it accounts for the impact due to all the material involved in the component manufacturing, including the process scrap of all the manufacturing steps involved either in the AM approach or in the machining one. Concerning the AM, along with the mass of the part (m_P), the mass of the supports (m_S) and the mass of the allowance (m_A) were also considered in the analysis. Moreover, scrap occurring during pre-manufacturing step was considered: in the case of AM approach the atomization (accounted by including the α factor in the models) was considered.

Following the same approach, for the case of machining the masses included in the models concerned the mass of the part (m_P), the mass of the machined off chips (m_C) and the process scrap occurring during extrusion process (accounted by including the ε factor in the models) here considered as pre-manufacturing step. Concerning the processing energy, for the additive manufacturing the following process chain were considered: atomization, Electron Beam Melting (EBM) deposition, finish machining, part/support removal and Hot Isostatic Pressing (HIP). For each process the primary energy demand was considered along with the process scrap where relevant (as already discussed). As far as the machining approach is concerned, the primary energy of hot extrusion (pre-manufacturing step) and of the machining processes were included in the models.

In this research the comparison was made on the production of a component made of the titanium alloys Ti6Al4V, the inventory was based on the previous research [2, 3] and is reported in table 1.

The main idea of this research is to try to remove elements from these models to have reduced/easier to be implemented models and, at the same time, guaranteeing a good reliability of the models in terms of primary energy quantification.

Table 1. Inventory data [2, 3].

Factor	Inventory data value
E_V (MJ/kg)	683
E_R (MJ/kg)	87
r	0.8
E_E (MJ/kg)	206.2
E_F (MJ/kg)	29.1
E_A (MJ/kg)	70
U_E^{AM} (MJ/kg)	179.4
U_E^{CM} (MJ/kg)	6.5
ε	1.25
α	1.05
$\mathbf{E_{SEP}}$ (MJ/kg)	122
$\mathbf{E_{HIP}}$ (MJ/kg)	37
$\mathbf{m_S}$	20 %m_p or 5% m_p

In this respect six new models were tested as reported in table 2. In table 3, instead, the factors included in each model are reported (please note: V=included X=not included). Including all the factors mentioned above led to the formulation of the models I of table 2. As it is possible noticing, the model I includes all the factors while the model complexity increases moving from model II to model VII.

The model I, therefore, represents the benchmark and the accuracy of the other models will be evaluated by comparing the obtained results with those provided by model I.

Table 2. Analytical formulation of the proposed models.

Model ID	Analytical formulation
I	$\mathbf{E^{AM}} = (k * m_P + m_A + m_S) * \alpha * (E_E + E_A) + (k * m_p + m_A + m_S) * U_E^{AM} + m_A U_E^{CM} + E_{USE}^{AM} + E_{SEP} + E_{HIP;}$
	$\mathbf{E^{CM}} = (m_P + m_C) * \varepsilon * (E_E + E_F) + m_C * U_E^{CM} + E_{USE}^{CM};$
II:	$\mathbf{E^{AM}} = (k * m_P) * (E_E) + (k * m_P) * U_E^{AM};$
	$\mathbf{E^{CM}} = (m_P + m_c) * (E_E);$
III:	$\mathbf{E^{AM}} = (k * m_P + m_A + m_S) * (E_E) + (k * m_P + m_A + m_S) * U_E^{AM};$
	$\mathbf{E^{CM}} = (m_P + m_C) * (E_E);$
IV	$\mathbf{E^{AM}} = (k * m_P) * \alpha * (E_E + E_A) + (k * m_P) * U_E^{AM};$
	$\mathbf{E^{CM}} = (m_P + m_C) * \varepsilon * (E_E + E_F);$
V	$\mathbf{E^{AM}} = (k * m_P + m_A + m_S) * \alpha * (E_E + E_A) + (k * m_P + m_A + m_S) * U_E^{AM}$
	$\mathbf{E^{CM}} = (m_P + m_C) * \varepsilon * (E_E + E_F)$
VI	$\mathbf{E^{AM}} = (k * m_P + m_A + m_S) * \alpha * (E_E + E_A) + (k * m_p + m_A + m_S) * U_E^{AM} + m_A U_E^{CM};$
	$\mathbf{E^{CM}} = (m_P + m_C) * \varepsilon * (E_E + E_F) + m_C * U_E^{CM};$
VII	$\mathbf{E^{AM}} = (k * m_P + m_A + m_S) * \alpha * (E_E + E_A) + (k * m_P + m_A + m_S) * U_E^{AM} + m_A U_E^{CM} + E_{SEP};$
	$\mathbf{E^{CM}} = (m_P + m_C) * \varepsilon * (E_E + E_F) + m_C * U_E^{CM};$

Table 3. Factors included in the models (V=included; X=not included).

Model I.D.	Component material energy	Pre-manufacturing steps (material scrap)	Pre-manufacturing steps (process energies)	Machining process scraps (accounted as material impact)	Additive Manufacturing process scrap (supports + allowance)	Deposition energy	Machining processes energy	Part separation from platform AM	HIP process for AM component
I	V	V	V	V	V	V	V	V	V
II	V	X	X	V	X	V	X	X	X
III	V	X	X	V	V	V	X	X	X
IV	V	X	V	V	X	V	X	X	X
V	V	V	V	V	V	V	X	X	X
VI	V	V	V	V	V	V	V	X	X
VII	V	V	V	V	V	V	V	V	X

To be more specific, the models simplification was developed starting from the models ID I and removing some of the elements of the equations according to what reported in table 3. Some of the factors such as the material impact of the mass component, the amount of chips (in subtractive approach) and the deposition energy are included in all the models as are they are the main contributors in primary energy demand. The other factors are, instead, selectively removed. Looking at both tables 2 and 3 it is, therefore, possible to understand the factors included and neglected by each model.

In order to account for the credits arising from material recycling, the 'substitution [10], was implemented. The embodied energy (E_E, in MJ/kg) reported in models of table was obtained according to equation: $E_E = E_V - r\,(E_V - E_R)$.

2.1. The analyzed case study

Some of the authors of the present paper have already proved [2, 3] that when comparing additive and subtractive approaches the part geometrical complexity plays a significant role. In this paper the expression part geometrical complexity will be used to refer to the amount of material to be machined off to produce a target part via conventional machining. To deal with this aspect the Solid-to-Cavity Ratio (SCR) metric will be used throughout the paper. To be more specific the SCR was defined as [11] the mass of the final part divided by the mass that would be contained within the bounding volumetric envelope of the part itself. The smaller the SCR value the more complex is the component, the larger is the amount of material to be machined off by conventional machining . Concerning the environmental impact comparison with additive manufacturing, it was proved that the more complex is the part to be manufactured the more likely the AM approach could result to be the more environmentally friendly approach.

As the aim of this paper is to analyze the performance of the proposed simplified models with varying the SCR, the same geometry already used [2,3] and reported in figure 1 was considered. By varying the inner radius of the component, different SCR values can be obtained, hence it is possible to cover a large portion of possible part shape complexity. In figure 1, two different examples are reported, characterized by different values of SCR, constant and uniform machining allowance of 1 mm was assumed.

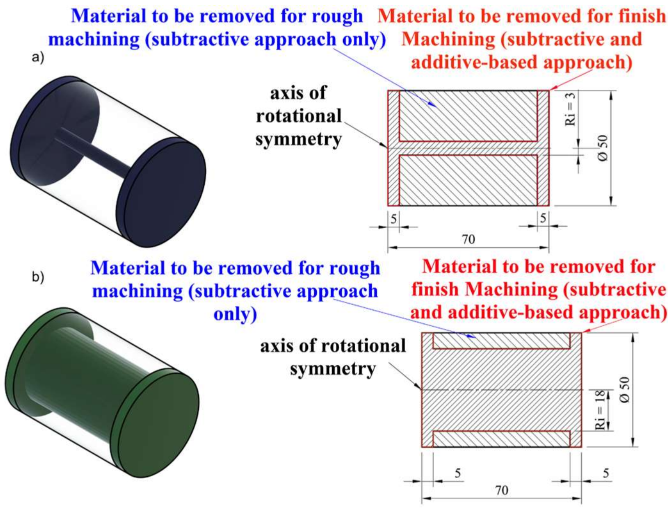

Fig. 1. Analyzed case study (a) high geometrical complexity, SCR=0.59; (b) low geometrical complexity, SCR=0.16.

2.2. The Analyzed scenarios

The performance of the simplified models were tested on three different scenarios as below reported:

- Scenario 1. In this scenario it is assumed that geometrically identical components are manufactured by means of additive-based and subtractive approaches. In this case the use phase is left out of the analysis as the parts have the same geometry and mass and no difference in the use phase would occur.
- Scenario 2. In this scenario the light-weighting enabled by AM approach is considered. Specifically, by the topology optimization substantial mass reduction can be obtained in AM approach with a reduction in the related primary energy demand. Topology optimization, coupled with the free form fabrication characterizing AM approaches, allows a given component to be redesigned, enabling mass reduction [5]. Impact related to both material and deposition phase decrease with decreasing the mass of the AM based component. In the models presented in table 2 the weight reduction is taken into account by introducing the factor k (weight reduction factor due to re-design for AM) that can assume value from 1 (no mass reduction enabled) to 0.15 (85% of mass reduction). In this scenario it is still assumed that the impact of the use phase of the produced component is negligible.
- Scenario 3. In this scenario the component manufactured by AM allows use phase benefits (i.e., energy savings) due to the weight reduction. In other words, the same assumption of Scenario 2 are here included concerning the mass reduction; however, a system boundary expansion is envisaged as the benefit during the use phase is also accounted for. In this respect two different scenarios are analyzed, in fact it is assumed that the manufactured component is assembled either on a gasoline car or on an aircraft. These two different cases allows to consider two different use phase impacts, this difference proved to lead to different results in terms of comparative analyses [3].

3. Analysis of the results

In this section the accuracy of the simplified models will be discussed. For each analyzed scenario, a specific decision support tool is designed, and for each model the performance are compared with those of the reference model I.

3.1. Results for the Scenario 1

In this scenario, as the part manufactured by means of the two different manufacturing approaches is assumed to be identical in geometry and mass, the Solid-to-Cavity Ratio (SCR) is the only factor affecting the results. Overall, it has already been proved [3] that as the SCR decreases, the environmental performance of AM approach improves. For same materials, a given SCR (Break Even Point, BEP) value exists where the AM approach starts equaling the impact of conventional machining; for smaller SCR values the AM outperforms conventional machining approach. From now on, this particular SCR value will be referred to as Break-Even Point (BEP). BEP values actually represent the first decision support tool: for SCR values larger than the identified BEP value, the conventional machining approach is to be preferred, otherwise the AM approach is the more environmentally friendly solution. The differences between the energy demand for the AM approach and the one for the CM approach (i.e., ΔEnergy) with varying the SCR are reported for all the analyzed models in Figure 2 (from model I to model VII of table 2). Positive values of ΔEnergy identify SCR values for which the conventional machining approach demands less primary energy than AM processes. The intercept identify the BEP for a given model. As it is possible to notice, model II and IV do not provide reliable results, while model V, VI VII provide very good results as the curves almost overlap the curve of the reference model (model I). A quantitative analysis of the obtained results is reported in table 4, in this table the obtained BEP (SCR intercept value) values for each model along with BEP Error (%) $((|BEPi - BEP\ I|)/BEP\ I)\%$; where i=II,…,VII) and the Root Mean Square Error (RMSE). The last two metrics are calculated with the aim to quantify the accuracy of each model with respect the refence model.

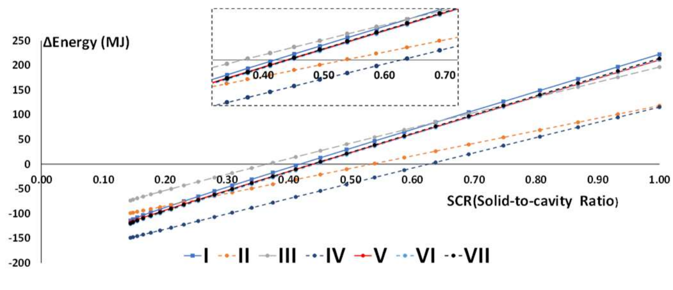

Fig. 2. Models results for Scenario 1 (the dotted box contains an enlargement of the BPs area)

Table 4. Error performance indicators for Scenario 1.

MODEL I.D.	BEP (SCR)	BEP Error (%)	RMSE (MJ)
I	0.424	N.A.	N.A.
II	0.535	26	47.96
III	0.370	13	25.65
IV	0.627	47	68.02
V	0.444	5	7.98
VI	0.449	4	9.69
VII	0.443	4	7.37

Looking at the results it is possible to state that for the Scenario 1, model V is the best solution as it provides the best compromise between prediction accuracy and computational effort. Actually, the errors values are very low and comparable to those of the reference models, at the same time several factors are not included in the model. To be more specific, looking at table 1 the model V includes the energy of all the material involved in the approaches, the energy of the pre-manufacturing processes and the energy of deposition. The energy related to machining operations (both for the pure subtractive approach but also for the finish machining operations of the AM approach) are neglected as well as that of separation and HIP processes. It is worth remarking that, although the errors provided by model III is higher than those of model V, it might represent a choice in case low computational effort is need or inventory data are missing.

3.2. Results for Scenario 2

In this scenario the weight reduction obtainable by applying topological optimization in AM approaches is included. Under these assumptions the results of the comparative analyses still depend on SCR value but also on the amount of reduced weight. For a given SCR of a component to be produced via the CM approach, it has to be a k* value below which the AM approach is the less energy demanding manufacturing route. k* can be considered as a threshold value (for a given SCR); for smaller values the AM approach is more environmentally friendly than the CM one, vice versa the CM approach is to be preferred. In this context the decision support tool is a bidimensional one relying on SCR and k* values. The curves obtained for all the models are reported in figure 3. It is worth highlighting that for a given combination of k and SCR falling below the obtained curve, the AM approach is to be preferred. As it can be noticed, similar results to those shown for Scenario 1 were obtained. Both models II and IV don’t provide reliable results, while models V, VI, VII can be used as simplified models. Also, it is worth highlighting that, although the model III provides a curve more distant that those provided by models V,VI, and VII, the prediction could still be used especially if the limited computational effort is considered. This results was already somehow observed for the Scenario1.

A quantification of the accuracy provided by the different models is reported in table 5. In order to be consistent with the errors provided for the Scenario 1, the average error is reported in terms of SCR. It is possible to see that limited error values were obtained for model V, VI,VII; model III provides acceptable performance, as already discussed.

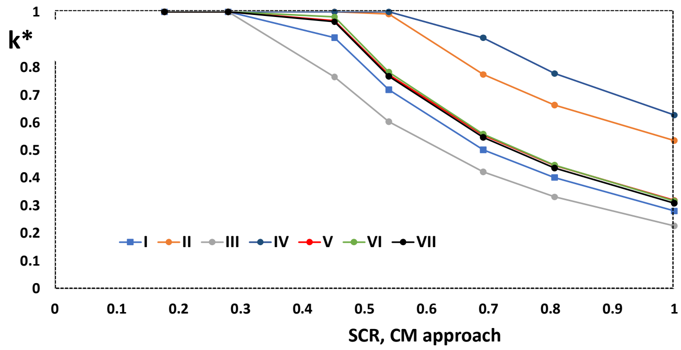

Fig. 3. Models results for Scenario 2

Table 5. Error performance indicators for Scenario 2.

MODEL I.D.	Average error (SCR) (%)	RMSE (SCR)
II	25	0.185
III	8	0.063
IV	35	0.246
V	5	0.040
VI	4	0.039
VII	5	0.031

3.3. Results for Scenario 3

In order to include the energy saving in the use phase enabled by wight reduction of a AMed part in a decision support tool, two different scenarios were included namely the gasoline car and aircraft case study. In this respect the energy saving obtainable per kg of weight reduction for the two transportation systems have been implemented in the models by adopting the coefficients suggested by Helms and Lambrecht [12]. In this scenario the comparative analysis is affected not only by the SCR and the k values but also by the extent of the use phase (i.e., the amount of driven distance in case of a car or the utilization time in case of an aircraft). To be more specific, considering the case of a gasoline car, for a given combination of SCR and k, a break-even point exists in terms of travelled kilometers where the two approaches are characterized by the same primary energy demand. For use phase extension lower that the identified break-even point the conventional machining should be selected, vice versa the AM must be chosen as environmentally friendly solution. The tool, as already presented in the past [2], for a given SCR value is a bidimensional graph reporting BEP against k. In figure 4, the results for SCR=0.75 for all the models for the gasoline car is reported. It is worth remarking that the AM approach is to be preferred for all the combinations of k and travelled distance/utilization time falling above the curves plotted. As it is possible to see, for the gasoline car the performances of model III are comparable to those of models V,VI, and VII. Also, looking at the performance of model III in terms of decision support tool, this model would mistakenly suggest CM over AM for a very small k range equal to about 0.015 as reported in figure 4. This range is similar or even better that those provided by other models, and it is definitely acceptable in terms of prediction accuracy. Similar results can be observed when looking at the case study of an aircraft with SCR=0.75 (see figure 5).

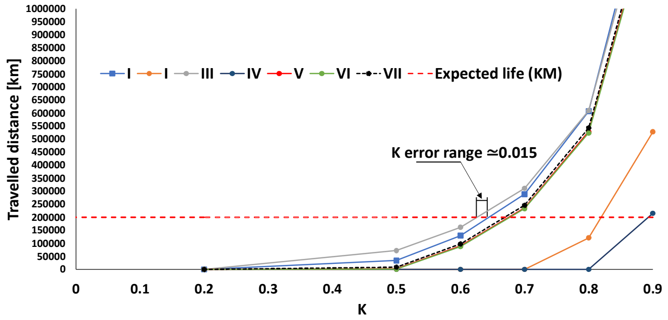

Fig. 4. Models results for Scenario 3 - gasoline car case study.

Although the break-even points occur in less than one year time (very far from the expected life of an aircraft= 30 years), making the AM always the best choice, it is still possible to see how model III provides almost the same trend of the reference model. In scenario 3, it is possible to state that model III is the best choice. These results would facilitate the decision support tool implementation as few pieces of information are required namely, the energy of all the material involved in the two approaches and only the deposition energy of the AM approach, all the other factors are neglected. In order to verify the consistency of the main findings of the present research, the same analyses were developed for a reduced amount of supports mass m_S. It was assumed to be equal 5% m_P (instead of 0.20% m_P as used in the above reported analysis). Results revealed that by reducing the mass of the supports, the performances of the simplified models improve and the model III can be used in all the analyzed scenarios.

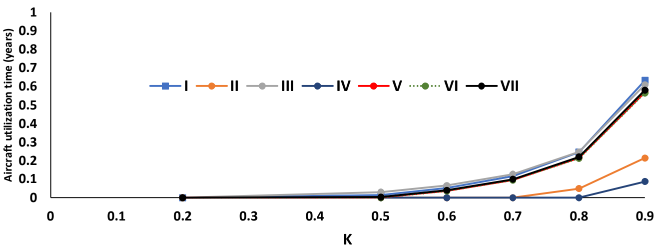

Fig. 5. Models results for Scenario 3-Aircraft case study.

4. Conclusions

In the present paper six new simplified models have been proposed with the aim to compare, with a low computational effort, the environmental impact of additive and conventional manufacturing approaches. The different scenarios were analyzed, and results revealed that simplification is possible.

Overall, model V and III are the best ones, this leads to the conclusion that it is crucial accounting for all the involved masses and for the energy of deposition step. The energy related to machining (both for the CM approach and for the finish machining in AM approach), separation and hipping could be left out. It means that the mass of the support and of allowance should be always taken into account for obtaining reliable predictions (this is proved by the bad performance provided by model II). In the Scenario 2, and above all in scenario 3 (when the use phase is included in the analysis), the model III provides excellent performance. This model requires only the involved mass, the primary energy of the involved material and the energy for deposition (even the pre-manufacturing processes energies are left out).

Further development of the present research will concern the application of this model reduction to other materials and AM technologies. Actually, results might be affected if applied to different AM processes such as Direct Energy Deposition where the impact of finishing operation by machining is higher. In fact, by changing process the extent of machining impact changes as well, questioning the validity of the presented research. The application of this approach to different materials and processes would allow the environmental impact of different AM set up to be quantified easily, providing a wider and clearer picture concerning the environmental performance of AM approaches.

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