Guidelines to compare additive and subtractive manufacturing approaches under the energy demand perspective

Original
Guidelines to compare additive and subtractive manufacturing approaches under the energy demand perspective / Ingarao, G., Priarone, P.C., Di Lorenzo, R., Settineri, L.. - In: INTERNATIONAL JOURNAL OF SUSTAINABLE MANUFACTURING. - ISSN 1742-7223. - STAMPA. - 4:2-4(2020), pp. 266-280. [10.1504/IJSM.2020.107126]

Publisher:
Inderscience Enterprises Ltd.

Published
DOI:10.1504/IJSM.2020.107126

Int. J. Sustainable Manufacturing, Vol. X, No. Y, xxxx *1*

Guidelines to compare additive and subtractive manufacturing approaches under the energy demand perspective

Abstract: In order to characterize the environmental performance of Additive Manufacturing (AM) processes, comparative analyses are required. Different manufacturing approaches (such as additive and subtractive ones), besides adopting different equipment, use different kinds and amounts of material. Therefore, the material-related flow has to be followed throughout the entire product life. Differences in environmental impact arise at each step of the life cycle: material production, manufacturing, use, disposal, and transportation. A life cycle-based methodology able to take due account of all the factors of influence on the total energy demand for the production of metal components is given in this paper. Decision support tools for identifying the most sustainable manufacturing route (subtractive versus AM-based approaches) are presented for different scenarios. The aim of the present paper is to contribute to the debate concerning the environmental impact characterization of AM processes.

Keywords: Additive Manufacturing, Process comparison, Energy saving, Decision-support tools

1 Introduction

Additive Manufacturing (AM) processes are under the spotlight at present, since their suitability for end-use component manufacturing is well recognized. This process category is characterized by some features which, in theory, would make this manufacturing approach an environmentally-friendly one. In fact, (*i*) no special tooling is required for part fabrication, (*ii*) AM enables complex components to be produced in a single step (therefore avoiding multiple manufacturing and assembling steps), (*iii*) material waste is generally reduced, (*iv*) very complex geometries can be manufactured, enabling weight reduction, and (*v*) the supply chain is drastically compressed (Rejeski et al., 2018). In spite of these positive aspects, AM processes have some drawbacks when assessing the environmental dimension. As far as the metal components fabrication is concerned, (*i*) the machine usually demands a higher specific energy in comparison to conventional subtractive or mass conserving processes (Ingarao et al., 2018), (*ii*) the input material (e.g., the metal powder) can be characterized by a high embodied energy, as the atomization process has to be included, (*iii*) process scraps actually occur since support structures have to be additively manufactured and removed at the end of the process (Priarone and Ingarao, 2017). Thus, environmental beneficial effects of AM over conventional manufacturing depend on several factors: batch size, eco-properties of the processed materials, possible weight reduction enabled by AM, and extent of component use phase. One of the most effective ways to figure out the environmental performance of AM approaches is to compare them with conventionally applied processes, such as machining. A few comparative analyses have been already developed. The authors of the present paper carried out an environmental comparison between Electron Beam Melting

(EBM) and turning of Ti-6Al-4V parts (Priarone et al., 2017): three different geometries were considered, and the results suggested that the additive manufacturing approach could be the best strategy when increasing the geometrical complexity of the part. Recently, the authors have also provided a comprehensive approach comparison for the (additive, subtractive and mass conserving) manufacturing of parts made of aluminium alloys (Ingarao et al., 2018), underlining the impact of the geographically-related variability of the material eco-attributes on the achievable results. Another study on titanium components manufacturing was presented by Paris et al. (2016), who compared the cumulative energy demand of machining and EBM to produce an airplane turbine. The influence of the amount of the material to be machined-off on the environmental impact was highlighted, and again AM processes proved to be preferable when the shape complexity increases. Tang et al. (2016) proposed a comparison between a binder jetting process and conventional CNC machining. The environmental impact saving enabled by the weight reduction obtainable by means of topology optimization was included, and a reduction in CO_{2eq} emissions as high as 64% when AM is selected over machining was quantified. Peng et al. (2017) analyzed, by applying a Life Cycle Assessment (LCA), an additive-based approach as well as conventional- and remanufacturing-based routes to produce an impeller. A few studies compared powder-based Direct Energy Deposition (DED) processes with machining. Morrow et al. (2007) quantified the energy consumption and CO_2 emissions associated with the production of molds and dies via laser-based Direct Metal Deposition (DMD) and CNC milling. Two case studies were presented and results with varying the amount of material to be machined-off were discussed. Serres et al. (2011) compared the direct additive laser manufacturing (CLAD) approach with conventional machining. An LCA analysis on Ti-6Al-4V components was developed, and the absence of scraps, characterizing the additive manufacturing approach, led to an environmental impact reduction as high as 70%. Bekker and Verlinden (2018) recently presented a comparative LCA analysis between Wire and Arc Additive Manufacturing (WAAM), green sand casting and milling for the production of steel parts, showing that WAAM yields potential in decreasing material consumption due to its high material efficiency.

Despite the research effort already established, the way to have a full understanding of environmental performance of AM processes is still long. There is the pressing need to identify proper decision support tools and guidelines for identifying the most sustainable approach (either subtractive or additive-based) while varying the factors of influence. Recently, a review paper aimed at characterizing the environmental dimension of AM has been presented by Kellens et al. (2017): potential benefits of AM processes as a function of the batch size and of the applications were discussed, nevertheless the authors stated that '*the environmental benefits of most application domains remain a rather open question'*. In the present research work, comparative analyses between an additive/ subtractive integrated approach and pure subtractive processes are carried out with respect to their primary energy requirements and accounting for the most significant material and energy flows. Three different material (namely: titanium alloy, aluminium alloy and stainless steel) are considered. This choice was driven by the will to characterize the environmental performance of the AM-based approach with varying the material eco-properties. A set of decision support tools for the manufacturing approach selection is proposed by applying the modeling approach the authors developed in a previous paper (Priarone and Ingarao, 2017). The most significant factors of influence are varied (such as eco-properties of the processes material, shape complexity and grade of light-weighting enabled by re-design) and the decision support tools are designed for three different scenarios: (1) the components manufactured by additive and subtractive approaches comply with the same specifications in terms of mass and geometry; (2) the components manufactured by AM are characterized by a weight reduction with negligible benefits in the use phase; (3) the components manufactured by AM allow use-phase benefits related to weight reduction. The main aim of the paper is to contribute to the debate concerning the environmental impact characterization of AM processes, trying to outline the domains where such technologies are actually environmentally friendly.

2 Modelling of energy requirements

Before starting a life cycle-based analysis, the functional unit has to be identified. The cumulated (primary) energy demand of a single component was chosen as a basis for the comparison. A cradle-to-grave system boundary was adopted, and recycling was selected to be the scenario at the End-of-Life (EoL). The main unit processes (concerning material production, manufacturing, use and disposal) are schematized in Figure 1 together with their material and energy flows, for both the manufacturing approaches. It is worth remarking that the system boundary includes the impacts related to the pre-manufacturing stage (i.e., the unit processes required to turn ingots into usable input materials). The here considered additive and subtractive approaches imply different amounts and kinds of feedstock materials. To be more specific, the powder-bed technologies (such as EBM or SLM) require metal powders, while the subtractive approach needs a bulk workpiece (i.e., a bar). Therefore, the gas atomization process and the extrusion step have to be encompassed for a reliable primary energy quantification.

The energy demand across the life cycle for components produced by the subtractive (CM) approach and the additive-subtractive (AM+FM) approach, to be planned as in Figure 1, could be modelled according to Equations 1 and 2, respectively (according to Priarone and Ingarao, 2017).

$$\begin{aligned} E^{CM} &= \overbrace{(m_P + m_C)\cdot\varepsilon\cdot(E_E + E_F)}^{\text{Workpiece production}} + \overbrace{m_C\cdot {U_E}^{CM}}^{\text{Manufacturing}} + \overbrace{{E_{USE}}^{CM}}^{\text{Use}} + \\ &\overbrace{+E_T\cdot[(m_P + m_C)\cdot d_1 + m_P\cdot(d_2 + d_4) + m_C\cdot d_3 + (m_P + m_C)\cdot(\varepsilon - 1)\cdot d_5]}^{\text{Transportation}} \qquad \left(\frac{MJ}{part}\right) \end{aligned} \tag{1}$$

$$\begin{aligned} E^{AM+FM} &= \overbrace{(k\cdot m_P + m_A + m_S)\cdot\alpha\cdot(E_E + E_A)}^{\text{Powder production}} + \\ &+\overbrace{(k\cdot m_P + m_A + m_S)\cdot {U_E}^{AM} + m_A\cdot {U_E}^{CM}}^{\text{Manufacturing}} + \overbrace{{E_{USE}}^{AM+FM}}^{\text{Use}} + \\ &+\overbrace{E_T\cdot[(k\cdot m_P + m_A + m_S)\cdot d_1' + k\cdot m_P\cdot(d_2' + d_4')]}^{\text{Transportation}} + \\ &+\overbrace{E_T\cdot[(m_A + m_S)\cdot d_3' + (k\cdot m_P + m_A + m_S)\cdot(\alpha - 1)\cdot d_5']}^{\text{Transportation}} \qquad \left(\frac{MJ}{part}\right) \end{aligned} \tag{2}$$

where:

- 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;
- d_1, d_1’ (km): travelled distance from material supplier to manufacturing plant;
- d_2, d_2’ (km): travelled distance from manufacturing plant to point of sale;
- d_3, d_3’ (km): travelled distance from manufacturing plant to recycling plant;
- d_4, d_4’ (km): travelled distance from disposal site to recycling plant;
- d_5, d_5’ (km): travelled distance from material supplier to recycling plant;
- 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_T (MJ/kg·km): energy demand per unit weight and travelled distance for transportation;
- $E_{USE}{}^{i}$ (MJ/part): energy demand for the use phase, for i = CM or AM+FM;
- 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 of deposited material): specific energy demand for AM;
- $U_E{}^{CM}$ (MJ/kg of removed material): specific energy demand for CM.

In order to account for the credits arising from material recycling, the ‘substitution method’ (as defined by Hammond and Jones, 2010), was implemented. The embodied energy (E_E, in MJ/kg) was obtained according to Equation 3,

$$E_E = E_V - r \cdot \left(E_V - E_R\right) \tag{3}$$

where:

- E_V (MJ/kg): energy demand for the primary production of the material;
- E_R (MJ/kg): energy demand for the secondary production of the material;
- r: End-of-Life recyclability.

The embodied impacts arising from the disposal of waste material were assumed to be negligible. The main values assumed for computing the energy demand for each material/approach combination are given in Table 1, and further details concerning the life cycle inventory can be found in Priarone and Ingarao (2017), Priarone et al. (2017) and Ingarao et al. (2018).

As far as the AM approach is concerned, two different processes were considered. Selective Laser Melting (SLM) was selected for the additive manufacturing of parts made of steel and aluminium alloy, while Electron Beam Melting (EBM) was chosen to produce the component made of titanium alloy. This choice was due to the actual industrial practice and the data available in literature. To properly model the AM unit process, the electric energy consumed by the equipment has to be monitored and ascribed to the functional unit. In this paper, the Specific Energy Consumption (SEC) approach was followed, and the specific (primary) energy demand values in Table 1 were presumed from the data available in literature, according to the researches of Faludi et al. (2017), Baumers et al (2011) and Baumers et al. (2017). It is worth mentioning that the utilization of the build volume of the AM machine affects the process energy, and therefore the SEC value itself (Baumers et al., 2011). The AM processes have been here assumed as operating at the full machine capacity. For the subtractive approaches, the specific energy demands were modelled by using the CES Selector v.17.2.0 database (Granta Design, UK).

3 Geometrical description of the case study

It has been proved that, when comparing these manufacturing approaches, the efficiency in raw material usage plays a crucial role. In this respect, the Solid-to-Cavity Ratio (SCR) could be applied as input variable to characterize the geometrical features of the components to be produced. The SCR has been defined, according to Morrow and colleagues (2007), as the mass of the final part divided by the mass that would be contained within the bounding volumetric envelope of the part itself. When the geometry is characterized by a small SCR value, a large amount of material has to be removed by machining while, vice versa, a small amount of material has to be deposited by AM. By contrast, higher values of SCR result in a small amount of material to be machined-off and in a large amount of material to be deposited. As the idea of the present paper consists in providing general decision support tools, the analyses were developed while varying the SCR. To this aim the case study depicted in Figure 2 (inspired from Watson and Taminger, 2018) was adopted. In order to cover a worthy portion of solid-to-cavity ratios, the inner radius value (R_i) has been varied from 25 mm (SCR = 1) to 5 mm (SCR = 0.18). In this research, a constant and uniform machining allowance (m_A) of 1 mm was assumed. As a simplifying hypothesis the mass of the support structures (m_S) was equal to the 20% of the mass of the part (Priarone et al., 2017).

4 Decision support tools (DSTs)

A set of possible decision support tools is presented in this section. The comparison is made on three different materials: aluminium alloy, titanium alloy and stainless steel. These materials enable the role of the substantially different eco-properties (related to both material production and component manufacturing) to be highlighted. In this section the comparative analyses are presented for three different scenarios: (*i*) geometrically identical components are manufactured by means of additive-based and subtractive approaches (Section 4.1); (*ii*) the components manufactured by AM are characterized by a weight reduction with negligible benefits during the use phase (Section 4.2); (*iii*) the components manufactured by AM allow use phase benefits (i.e., energy savings) due to the weight reduction (Section 4.3).

4.1 DSTs when manufacturing identical components

When it is assumed that the components produced by means of the two different manufacturing approaches have the same final geometry and mass, the Solid-to-Cavity Ratio (SCR) is the only factor affecting the results. Overall, it is possible to state that, as the SCR decreases, the amount of material to be removed by CM increases, while the amount of material to be deposited by AM decreases. It is straightforward, therefore, that the AM approach improves its environmental performance when decreasing the SCR. The differences between the energy demand for the AM+FM approach and the one for the CM approach (i.e., ΔEnergy) with varying the SCR are plotted in Figure 3, for each of the three considered materials. Positive values of ΔEnergy identify the SCR values for which the CM-based approaches are less energy demanding than AM-based approaches. It is possible to notice that, in this scenario and for the considered case study, the AM-based approach results preferable only for components made of Ti-6Al-4V, and this occurs for SCR values smaller than 0.47. For aluminium alloys, the CM approach is by far the most energy efficient strategy. This is due to the high value of the specific energy demand (U_E^{AM}) of Selective Laser Melting process. As far as stainless steel is concerned, the curve never intersects the horizontal axis, making the CM approach to be preferred. This evidence is mainly due to the low impact of material production. Under the hypothesis of no light-weighting, the SCR is the only factor affecting the comparative analysis results. The identified break-even point value for the titanium alloy can be seen as a one-dimension decision support tool. It is a sort of transition value: for SCR smaller than 0.47 the additive approach is to be preferred, otherwise the machining approach is still the best option.

4.2 DSTs when weight reduction is enabled by AM

As far as the weight reduction obtainable by applying the re-design for additive manufacturing strategies (such as the topological optimization) is concerned (Huang et al., 2016), the results of the comparative analyses depend on both the SCR value and 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 (i.e., a m_{part}^{AM+FM} to m_{part}^{CM} ratio allowing the specific condition $E^{AM+FM} = E^{CM}$ to be verified) below which the AM+FM approach is the less energy demanding manufacturing route. The curves showing the trend of k^* as a function of SCR for the three considered materials are plotted in Figure 4. In this case, cradle-to-gate plus end-of-life boundaries have been assumed, and only the contributions to total energy demand due to material production - including recycling - and component manufacturing have been accounted for. The two-dimensional plot could be applied as a decision support tool: for a given combination of k and SCR falling below the given material curve, the AM+FM approach is to be preferred. It is worth pointing out that the larger the area underneath the curve, the better is the material suitability to be processed by AM. In this respect, suitable conditions for which the AM+FM approach demands a smaller amount of primary energy can be identified for both titanium and steel component production. The suitability of titanium alloys (and EBM) is again proved, while for stainless steel AM is to be preferred only for solid-to cavity ratios (for the CM-based approach) smaller than 0.28, coupled with significant weight reductions. Concerning aluminium alloys, for the here considered case study, machining appears to be the energy efficient solution for any SCR-k combination.

4.3 DSTs when weight reduction is enabled by AM and use phase is included

The weight reduction can lead to substantial environmental impact savings when the manufactured component has to be assembled in a transportation system. In order to include such saving in a decision support tool, the use phase has to be considered. Besides the SCR and the k values, the extent of the use phase (i.e., the amount of driven distance or the utilization time) becomes a factor of influence. Specifically, for a given combination of SCR and k, a break-even point (in terms of travelled kilometers for cars, years of use for aircrafts) exists where the two approaches demand the same energy consumption. Two-dimensional graphs reporting BE points against k values while varying the SCRs (computed with reference to the CM-based approach) are shown in Figure 5 for gasoline cars and short distance aircrafts. The energy savings 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 (2006).

The Break-Even (BE) values can vary from zero, if the AM+FM approach is the less energy demanding even neglecting the use-phase energy savings, up to extremely high values suggesting to adopt the CM approach regardless of the extent of the use phase. Therefore, the AM+FM approach is to be preferred for all the combinations of k and travelled distance/utilization time falling above the curves plotted in Figure 5. These graphs can be used as a decision support tool. Being available the information regarding the SCR of the component produced via conventional machining (CM), and the k value achievable by means of the re-design for AM, it is possible to verify if the calculated breakeven point falls below the expected life time of the specific application (such as 30 years for aircrafts or 200,000 km for the gasoline car). In such a case, the AM-based approach is to be preferred since the energy savings during the use phase compensate for the higher energy demand during material production and manufacturing. It is possible to notice that, for the aircraft case, the AM+FM approach could be suggested since the use phase has a high impact towards the whole product life cycle and, thus, even a small light-weighting provides significant environmental benefits. As regards the gasoline car, the BE points for the aluminium alloy come for unrealistic driven distances, likely making the AM+FM approach not an advisable solution for the automotive sector, at least under the actual technology readiness level.

5 Conclusions

Primary energy demand models for machining and AM-based integrated approaches were presented in this paper. The models were implemented by considering three materials (namely: aluminium alloy, stainless steel and titanium alloy). Three different scenarios were analyzed: (*i*) the production of identical components by means of both the manufacturing approaches; (*ii*) the production of lightened components by AM with negligible benefits in the use phase; (*iii*) the production of lightened components by AM allowing energy savings in the use phase. The comparative analyses were developed while varying two factors of influence: the solid-to-cavity ratio and the extent of light-weighting enabled by AM (through the k factor). A set of possible decision support tools to select an AM-based approach over a CM-based one (and vice versa) under the energy demand perspective was presented. The decision support tools led to some decision-making guidelines for the considered case study:

- for aluminium alloys, the AM+FM approach is the best option only if a weight reduction is obtained, and if the designed component has to be assembled into transportation systems characterized by a highly energy-demanding use phase (such us the aircrafts);
- for stainless steels, AM+FM could be an energy-efficient approach when weight reduction is enabled. If components characterized by SCRs below 0.28 are to be manufactured, the AM-based approach can guarantee energy savings when a substantial weight reduction is obtained during the re-design for AM. Moreover, if the component has to be assembled into a transportation system, AM can be a suitable approach even for the automotive sector;
- for titanium alloys, AM has a larger domain of applicability, even when neglecting the light-weighting enabled by topological optimization.

It is worth remarking that, even though the results are here discussed on the basis of the considered case study, some of the most influent factors (U_E^{AM}, U_E^{CM}) are proved to be independent on the shape complexity and, thus, the results can be considered as general to a considerable extent. At present, AM seems to guarantee energy savings only within some domains, and, therefore, it has probably to be considered as a part of the solution of the broader problem concerning the energy reduction in manufacturing sector. Further technological innovations aimed at reducing the specific energy consumptions for AM could enhance the domain of applicability of such manufacturing approach. Also, the reported analysis could be enhanced by improving the modelling of the post-processing operations of the AM approach. In fact, some of the AM processes often require the Electrical Discharge Machining (EDM) for part/support removal and Hot Isostatic Pressing (HIP) processes. The inclusion of the primary energy demand of these unit processes could further improve the reliability of the presented models. Finally, the same approach could be applied for cost estimations. Concurrent comparative analyses of environmental and economic impact metrics would provide a wider picture about the potential of Additive Manufacturing technologies.

References

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I. and Hague, R. (2011) ‘Energy inputs to additive manufacturing: does capacity utilization matter?’ In: *Solid Freeform Fabrication Proceedings*, 30-40. Solid Freeform Fabrication; an Additive Manufacturing Conference. University of Texas, Austin, TX, USA.

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I. and Hague, R. (2017) ‘Shape complexity and process energy consumption in Electron Beam melting a case of something for nothing in additive manufacturing?’ *Journal of Industrial Ecology* Vol. 21(S1), pp. S157-S167.

Bekker, A.C.M. and Verlinden, J.C. (2018) ‘Life cycle assessment of wire arc additive manufacturing compared to green sand casting and CNC milling in stainless steel’, *Journal of Cleaner Production* Vol. 177, pp. 438-447.

Faludi, J., Baumers, M., Maskery, I. and Hague, R. (2017) Environmental impacts of selective laser melting. Do printer, powder, or power dominate?’, *Journal of Industrial Ecology* Vol. 21(S1), pp. S144-S156.

Hammond, G. and Jones, C. (2010) ‘Inventory of Carbon and Energy (ICE), Annex B: How to Account for Recycling; a Methodology for Recycling’, The University of Bath, Bath, UK.

Helms, H. and Lambrecht, U. (2006) 'The potential contribution of light-weighting to reduce transport energy consumption', *International Journal of Life Cycle Assessment*. DOI: 10.1065/lca2006.07.258.

Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J. and Masanet, E. (2016) 'Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components', *Journal of Cleaner Production* Vol. 135, pp. 1559-1570.

Ingarao, G., Priarone, P.C., Deng, Y. and Paraskevas, D. (2018) 'Environmental modelling of aluminium based components manufacturing routes: Additive manufacturing versus machining versus forming', *Journal of Cleaner Production* Vol. 176, pp. 261-275.

Kellens, K., Baumers, M., Gutowski, T.G., Flanagan, W., Lifset, R. and Duflou JR. (2017) 'Environmental dimensions of additive manufacturing mapping application domains and their environmental implications', *Journal of Industrial Ecology* Vol. 21(S1), pp. S49-S68.

Morrow, W.R., Qi, H., Kim, I., Mazumder, J. and Skerlos, S.J. (2007) 'Environmental aspects of laser-based and conventional tool and die manufacturing', *Journal of Cleaner Production* Vol. 15, pp. 932-943.

Paris, H., Mokhtarian, H., Coatanea, E., Museau, M. and Ituarte, I.F. (2016) 'Comparative environmental impacts of additive and subtractive manufacturing technologies', *CIRP Annals - Manufacturing Technology* Vol. 65(1), pp. 29-32.

Peng, S., Li, T., Wang, X., Dong, M., Liu, Z., Shi, J. and Zhang H. (2017) 'Toward a Sustainable Impeller Production - Environmental Impact Comparison of Different Impeller Manufacturing Methods', *Journal of Industrial Ecology* Vol. 21(S1), pp. S216-S229.

Priarone, P.C. and Ingarao, G. (2017) 'Towards criteria for sustainable process selection: On the modelling of pure subtractive versus additive/subtractive integrated manufacturing approaches', *Journal of Cleaner Production* Vol. 144, pp. 57-68.

Priarone, P.C., Ingarao, G., Di Lorenzo, R. and Settineri, L. (2017) 'Influence of Material-Related Aspects of Additive and Subtractive Ti-6Al-4V Manufacturing on Energy Demand and Carbon Dioxide Emissions', *Journal of Industrial Ecology* Vol. 21(S1), pp. S191-S202.

Priarone, P.C., Ingarao, G., Lunetto, V., Di, Lorenzo R. and Settineri L. (2018) 'The role of re-design for Additive Manufacturing on the process environmental performance', *Procedia CIRP* Vol. 69, pp. 124-129.

Rejeski, D., Zhao, F. and Huang, Y. (2018) 'Research needs and recommendations on environmental implications of additive manufacturing', *Additive Manufacturing* Vol. 19, pp. 21-28.

Serres, N., Tidu, D., Sankare, S. and Hlawka, F. (2011) 'Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment', *Journal of Cleaner Production* Vol. 19, pp. 1117-1124.

Tang, Y., Mak, K. and Zhao, Y.F. (2016) 'A framework to reduce product environmental impact through design optimization for additive manufacturing', *Journal of Cleaner Production* Vol. 137, pp. 1560-1572.

Watson, J.K. and Taminger, K.M.B. (2018) 'A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption', *Journal of Cleaner Production* Vol. 176, pp. 1316-1322.

Figures:

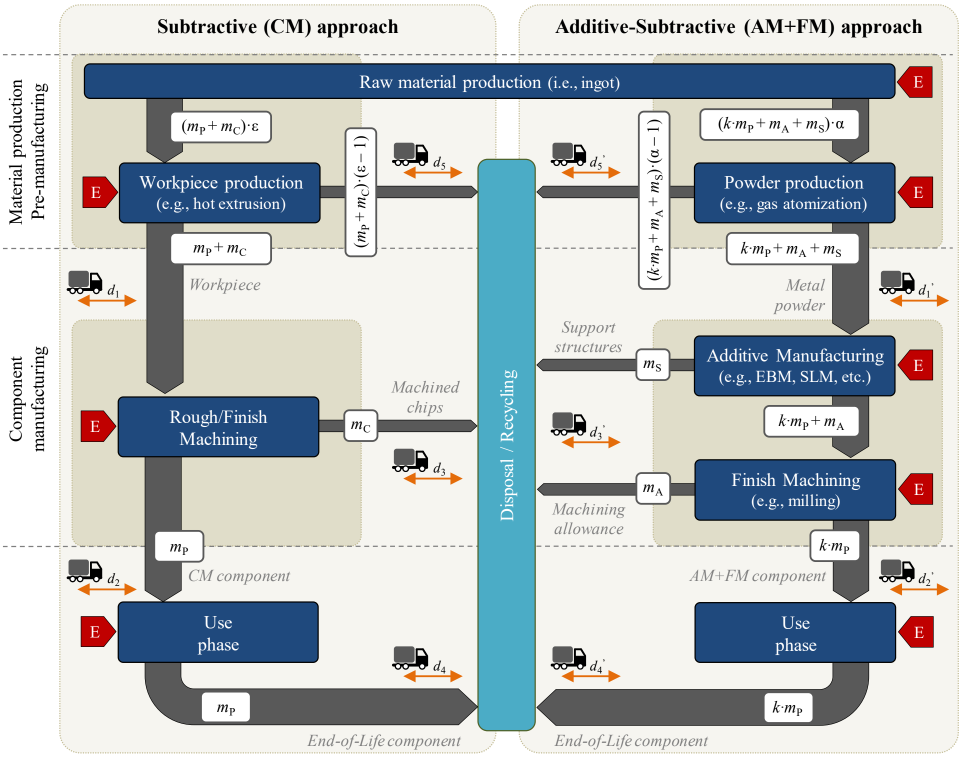

Figure 1. Material flows for a conventional machining approach (CM, *left*) and an additive-subtractive approach (AM+FM, *right*). Adapted from Priarone et al. (2018).

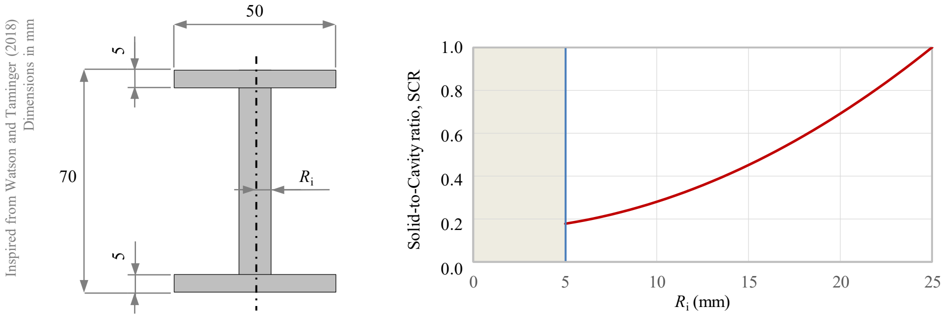

Figure 2. Geometry of the case study assumed to impose the variation of the solid-to-cavity ratio.

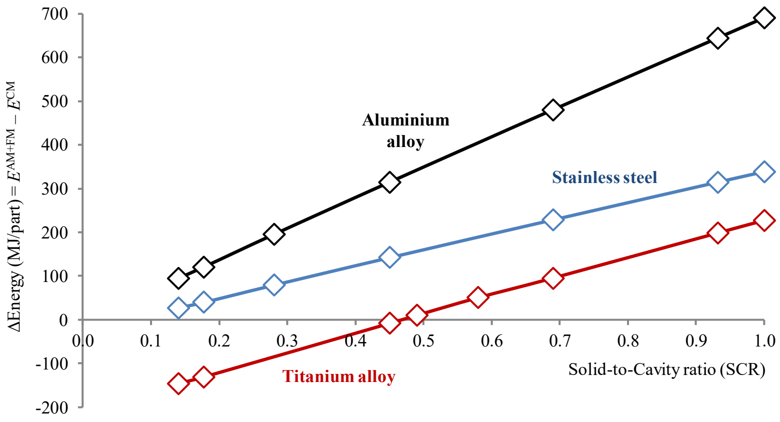

Figure 3. Approach selection tool when identical components have to be manufactured.

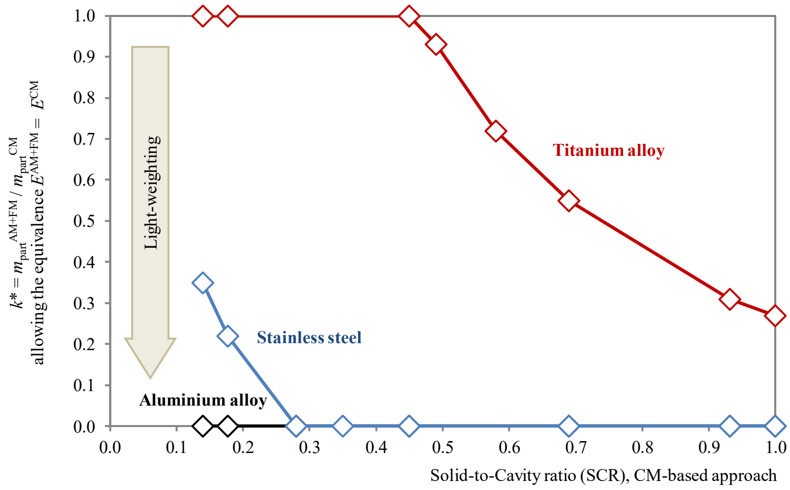

Figure 4. Process selection tool accounting for light-weighting in additively manufactured parts (use phase benefits are neglected).

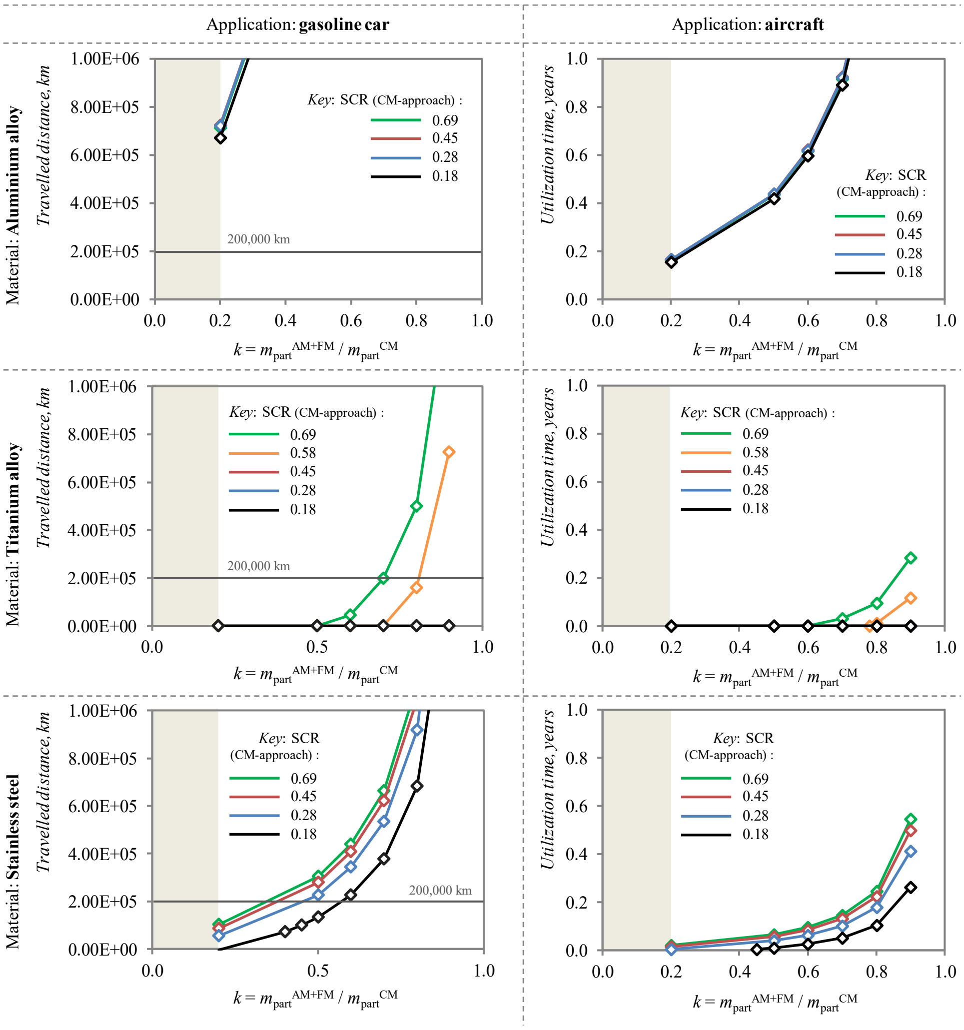

Figure 5. Process selection tool accounting for light-weighting in additively manufactured parts (use phase benefits are included).

Tables:

Table 1. Main ecological properties of the materials.

Eco-property	Ti-6Al-4V	Stainless steel	Aluminium alloy
Energy demand for the primary material production, E_V (MJ/kg)	685	85	199
Energy demand for the secondary material production (recycling), E_R (MJ/kg)	87	12	34
End-of-life recyclability, r	0.80	0.90	0.95
Embodied energy of the material (substitution method), E_E (MJ/kg)	206.6	19.3	42.2
Energy demand for forming the workpiece, E_F (MJ/kg)	14.5	8.2	5.3
Energy demand for metal powder atomization, E_A (MJ/kg)	70.0	2.9	8.1
Specific energy demand for AM, U_E^{AM} (MJ/kg of deposited material)	179.4 (EBM)	244.1 (SLM)	1385.3 (SLM)
Specific energy demand for CM, U_E^{CM} (MJ/kg of removed material)	5.7 (Machining)	1.3 (Machining)	5.1 (Machining)
Input/output material ratio for workpiece production, ε	1.25	1.25	1.25
Input/output material ratio for powder production, α	1.05	1.05	1.05