

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

Original

A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case / Lunetto, Vincenzo; Priarone, Paolo C.; Kara, Sami; Settineri, Luca. - ELETTRONICO. - 98:(2021), pp. 406-411. ((Intervento presentato al convegno 28th CIRP Life Cycle Engineering (LCE) Conference tenutosi a Jaipur (India) nel 10-12 March 2021 [10.1016/j.procir.2021.01.125].

Availability:

This version is available at: 11583/2874214 since: 2021-03-12T16:10:25Z

Publisher:

Elsevier B.V.

Published

DOI:10.1016/j.procir.2021.01.125

Terms of use:

openAccess

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

28th CIRP Conference on Life Cycle Engineering

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

Vincenzo Lunetto ^{a,*}, Paolo C. Priarone ^a, Sami Kara ^b, Luca Settineri ^a

^a Politecnico di Torino, Department of Management and Production Engineering, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

^b Sustainable Manufacturing and Life Cycle Engineering Research Group, School of Mechanical and Manufacturing Engineering,
The University of New South Wales, Sydney, NSW 2052, Australia

* Corresponding author. Tel.: +39 0110905153; fax: +39 0110907299. E-mail address: vincenzo.lunetto@polito.it

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 CO₂ 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.

© 2021 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)
Peer-review under responsibility of the scientific committee of the 28th CIRP Conference on Life Cycle Engineering.

Keywords: Additive manufacturing; Machining; Cumulative energy demand; Cost; CO₂ 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].

Nomenclature

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

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 CO₂ 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 CO₂ emission metrics, as in

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 kgCO₂/kg [16]. Moreover, the upstream flow of recycled material in the current supply was assumed to be 22% [16]. The best estimation for $E_{Pre-mfg}^{CM}$ and $E_{Pre-mfg}^{EBM}$ was 14.5 MJ/kg [17] and 70.0 MJ/kg [18], respectively, with related CO₂ emissions of 1.2 kgCO₂/kg [17] and 3.8 kgCO₂/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 $SEC^{CM}(\text{kWh/kg}) = 0.19 + 2.02 / \text{MRR}(\text{kg/h})$ [7], whereas the model concerning the electric energy consumption of the EBM process during the printing phase (for an Arcam A2X system) was $SEC^{EBM}(\text{kWh/kg}) = 2.82 / \text{DR}_a(\text{kg/h})$ [8]. The secondary-to-primary energy conversion factor was 0.38 [5]. The CES of the electric grid was 0.447 kgCO₂/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 kgCO₂/kg [20, and references therein]. The contribution of the cutting fluid was also considered ($E_{lub} = 1.4$ MJ/kg, $CO_{2lub} = 0.11$ kgCO₂/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 kgCO₂/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 CO₂ 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) $\text{MRR}_{RM} = 1.90$ kg/h, (iii) $\text{MRR}_{FM} = 0.15$ kg/h, (iv) masses of allowances and support structures both equal to 10% of m_B^{EBM+FM} .

$$\frac{CED^{CM}}{CED^{EBM+FM}} = \frac{[(E_E + E_{Pre-mfg}^{CM}) \cdot y^{CM} \cdot m_{Feed}^{CM}] + \frac{3.6}{\eta} [P_{np}^{CM} \cdot t_{np}^{CM} + \sum_{i=RM,FM} (SEC_i^{CM} \cdot m_{c_i} + P_{np}^{CM} \cdot t_{tc} \cdot \frac{t_{c_i}}{T_i})] + [\sum_{i=RM,FM} (E_{tooli} \cdot \frac{t_{c_i}}{T_i}) + E_{lub} \cdot q_L \cdot t_c]}{[(E_E + E_{Pre-mfg}^{EBM}) \cdot y^{EBM} \cdot m_{Feed}^{EBM+FM}] + \frac{3.6}{\eta} [P_{np}^{EBM} \cdot t_{np}^{EBM} + (SEC^{EBM} \cdot m_{Feed}^{EBM+FM})] + E_{gas} \cdot q_G \cdot t_G + E_{Mfg}^{FM}} = 1 \quad (1)$$

$$\frac{Cost^{CM}}{Cost^{EBM+FM}} = \frac{[C_{Mat}^{CM} \cdot m_{Feed}^{CM}] + [(C_{Ind}^{CM} + \delta^{CM} \cdot C_{Op}^{CM}) \cdot t_{Mfg}^{CM}] + C_{EE} [P_{np}^{CM} \cdot t_{np}^{CM} + \sum_{i=RM,FM} (SEC_i^{CM} \cdot m_{c_i} + P_{np}^{CM} \cdot t_{tc} \cdot \frac{t_{c_i}}{T_i})] + [\sum_{i=RM,FM} (C_{tooli} \cdot \frac{t_{c_i}}{T_i}) + C_{lub} \cdot q_L \cdot t_c]}{[C_{Mat}^{EBM} \cdot m_{Feed}^{EBM+FM}] + [(C_{Ind}^{EBM} + \delta^{EBM} \cdot C_{Op}^{EBM}) \cdot t_{Mfg}^{EBM}] + C_{EE} [P_{np}^{EBM} \cdot t_{np}^{EBM} + (SEC^{EBM} \cdot m_{Feed}^{EBM+FM})] + C_{gas} \cdot q_G \cdot t_G + C_{Op}^{EBM} \cdot t_{SR} + C_{Mfg}^{FM}} = 1 \quad (2)$$

$$\frac{CO_2^{CM}}{CO_2^{EBM+FM}} = \frac{[(CO_{2E} + CO_{2Pre-mfg}^{CM}) \cdot y^{CM} \cdot m_{Feed}^{CM}] + CES \cdot [P_{np}^{CM} \cdot t_{np}^{CM} + \sum_{i=RM,FM} (SEC_i^{CM} \cdot m_{c_i} + P_{np}^{CM} \cdot t_{tc} \cdot \frac{t_{c_i}}{T_i})] + [\sum_{i=RM,FM} (CO_{2tooli} \cdot \frac{t_{c_i}}{T_i}) + CO_{2lub} \cdot q_L \cdot t_c]}{[(CO_{2E} + CO_{2Pre-mfg}^{EBM}) \cdot y^{EBM} \cdot m_{Feed}^{EBM+FM}] + CES \cdot [P_{np}^{EBM} \cdot t_{np}^{EBM} + (SEC^{EBM} \cdot m_{Feed}^{EBM+FM})] + CO_{2gas} \cdot q_G \cdot t_G + CO_{2Mfg}^{FM}} = 1 \quad (3)$$

According to each breakeven condition, the value of $m_B^{\text{EBM+FM}}$ can be obtained directly from m_B^{CM} by applying the λ^{CED} , λ^{Cost} and λ^{CO_2} values reported in Figure 2. As far as the CED and CO₂ 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 CO₂ 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 2b 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 $m_B^{\text{EBM+FM}}$, (ii) $\text{MRR}_{\text{RM}} = 1.90$ kg/h, (iii) $\text{MRR}_{\text{FM}} = 0.15$ kg/h, (iv) $m_B^{\text{CM}} = 3$ 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 $m_B^{\text{EBM+FM}}$, (ii) $\text{MRR}_{\text{RM}} = 1.60$ kg/h, (iii) $\text{MRR}_{\text{FM}} = 0.10$ kg/h, (iv) $m_B^{\text{CM}} = 5$ kg. For the worst-case, the following values were used: (i) masses of support structures and allowance = 100% of $m_B^{\text{EBM+FM}}$, (ii) $\text{MRR}_{\text{RM}} = 2.20$ kg/h, (iii) $\text{MRR}_{\text{FM}} = 0.20$ kg/h, (iv) $m_B^{\text{CM}} = 0.5$ 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 CO₂ 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 $m_B^{\text{CM}} = 5$ 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.

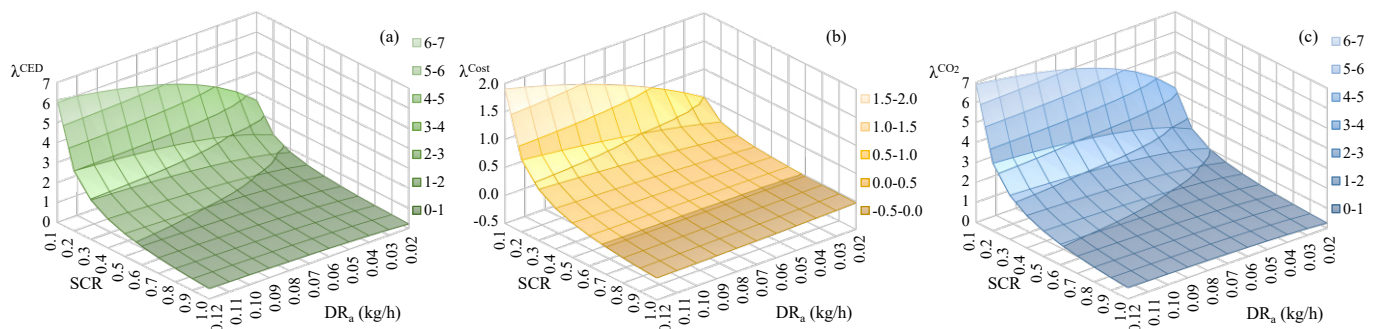


Fig. 2. Breakeven surfaces for (a) CED, (b) Cost and (c) CO₂ emissions.

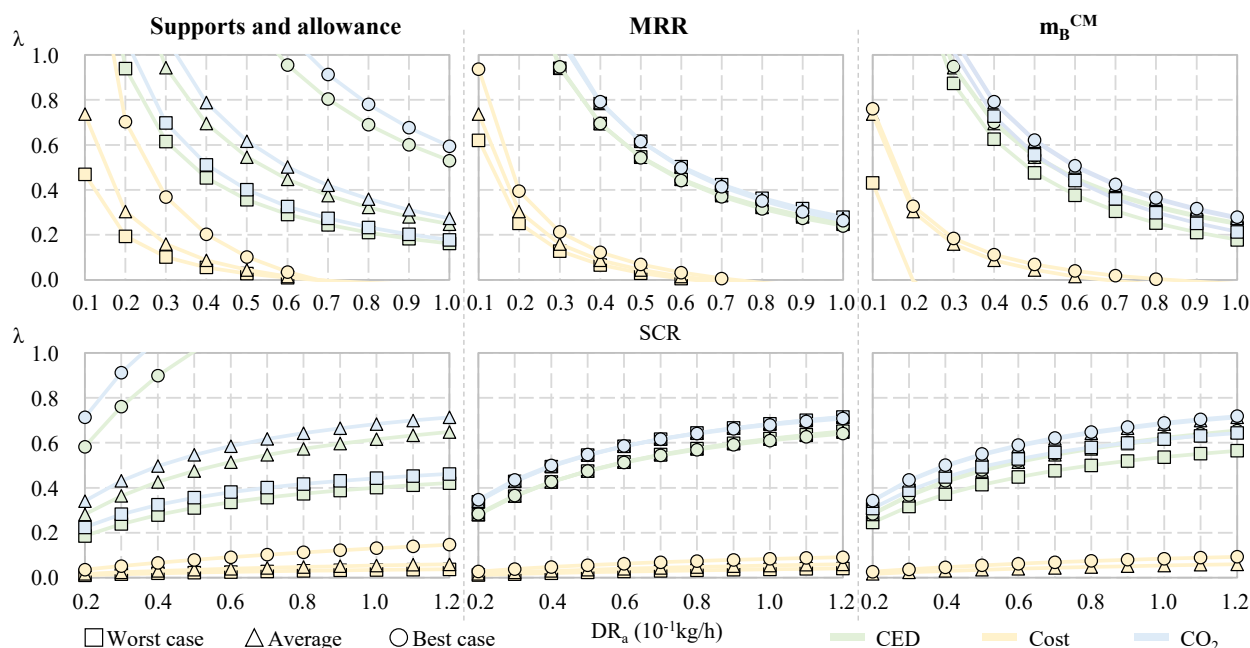


Fig. 3. Sensitivity analysis: effect of main variables.

CRedit authorship contribution statement

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

References

- Priarone PC, Ingarao G. Towards criteria for sustainable process selection: On the modelling of pure subtractive versus additive/subtractive integrated manufacturing approaches. *Journal of Cleaner Production* 2017; 144:57-68.
- Priarone PC, Campatelli G, Montecchi F, Venturini G, Settineri L. A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining. *CIRP Annals - Manufacturing Technology* 2019; 68(1):37-40.
- Ingarao G, Priarone PC. A comparative assessment of energy demand and life cycle costs for additive- and subtractive-based manufacturing approaches. *Journal of Manufacturing Processes* 2020; 56:1219-1229.
- Priarone PC, Ingarao G, Lunetto V, Di Lorenzo R, Settineri L. The role of re-design for Additive Manufacturing on the process environmental performance. *Procedia CIRP* 2018; 69:124-129.
- Priarone PC, Lunetto V, Atzeni E, Salmi A. Laser powder bed fusion (L-PBF) additive manufacturing: On the correlation between design choices and process sustainability. *Procedia CIRPe* 2018; 78:85-90.
- Kellens K, Mertens R, Paraskevas D, Dewulf W, Dufloy JR. Environmental Impact of Additive Manufacturing Processes: does AM contribute to a more sustainable way of part manufacturing? *Procedia CIRP* 2017; 61:582-587.
- Kara S, Li W. Unit process energy consumption models for material removal processes. *CIRP Annals - Manufacturing Technology* 2011; 60(1):37-40.
- Lunetto V, Galati M, Settineri L, Iuliano L. Unit process energy consumption analysis and models for Electron Beam Melting (EBM): Effects of process and part designs. *Additive Manufacturing* 2020; 33:101115.
- Lunetto V, Priarone PC, Galati M, Minetola P. On the correlation between process parameters and specific energy consumption in fused deposition modelling. *Journal of Manufacturing Processes* 2020; 56:1039-1049.
- Morrow WR, Qi H, Kim I, Mazumder J, Skerlos SJ. Environmental aspects of laser-based and conventional tool and die manufacturing. *Journal of Cleaner Production* 2007; 15:932-943.
- Hammond G, Jones C. Inventory of Carbon and Energy (ICE), Annex B: How to Account for Recycling; a Methodology for Recycling. The University of Bath, Bath, UK, 2010.
- Jeswiet J, Kara S. Carbon emissions and CESTM in manufacturing. *CIRP Annals - Manufacturing Technology* 2008; 57(1):17-20.
- Baumers M. Economic Aspects of Additive Manufacturing: Benefits, Costs and Energy Consumption. Loughborough University, Loughborough, UK, 2012.
- Baumers M, Tuck C, Wildman R, Ashcroft I, Hague R. Energy inputs to additive manufacturing: does capacity utilization matter? *Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference* 2011; 30-40. Code:104347.
- Körner C. Additive manufacturing of metallic components by selective electron beam melting - a review. *International Materials Reviews* 2016; 61(5):361-377.
- CES Selector 2017 v.17.2.0 database (Granta Design, the UK).
- Ashby, MF. *Materials and the Environment: Eco-informed Material Choice*. Second ed. Butterworth Heinemann/Elsevier, Waltham, MA, USA and Kidlington, Oxford, UK 2013. ISBN: 978-0-12-385971-6.
- Paris H, Mokhtarian H, Coatanéa E, Museau M, Ituarte IF. Comparative environmental impacts of additive and subtractive manufacturing technologies. *CIRP Annals - Manufacturing Technology* 2016; 65: 29-32.
- Priarone PC, Pagone E, Martina F, Catalano AR, Settineri L. Multi-criteria environmental and economic impact assessment of Wire Arc Additive Manufacturing. *CIRP Annals - Manufacturing Technology* 2020; 69: 37-40.
- Priarone PC, Robiglio M, Settineri L. On the concurrent optimization of environmental and economic targets for machining. *Journal of Cleaner Production* 2018; 190:630-644.
- Pusavec F, Kramar D, Krajnc P, Kopac J. Transitioning to sustainable production - part II: evaluation of sustainable machining technologies. *Journal of Cleaner Production* 2010; 18:1211-1221.
- Liemberger W, Miltner M, Harasek M. Efficient extraction of helium from natural gas by using hydrogen extraction technology. *Chemical Engineering Transactions* 2018; 70:865-870.
- Priarone PC, Robiglio M, Ingarao G, Settineri L. Assessment of cost and energy requirements of electron beam melting (EBM) and machining processes. *Smart Innovation, Systems and Technologies* 2017; 68:723-735.
- Wohlers Report 2017. Wohlers Associates.
- Glowacki BA, Nuttall WJ, Clarke RH. Beyond the helium conundrum. *IEEE Transactions on Applied Superconductivity* 2013; 23(3):6425422.