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Giuseppe Ingarao[a], Paolo C. Priarone[b], Yelin Deng[c], Dimos Paraskevas[d]

[a] Department of Industrial and Digital Innovation (DIID),
University of Palermo, Viale delle Scienze, 90128 Palermo, Italy

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

[c] Department of Civil and Environmental Engineering, Soochow University, Suzhou, China

[d] Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, 3001 Heverlee, Belgium

* Corresponding Author (G. Ingarao)

University of Palermo
Dept. of Industrial and Digital Innovation (DIID)
Viale delle Scienze, 90128 Palermo, Italy
Email: giuseppe.ingarao@unipa.it

Abstract

Additive Manufacturing represents, by now, a viable alternative for metal-based components production. Therefore the designer, often, has to select among three options at process design stage: subtractive, mass conserving, and additive approaches. The selection of a given process, besides affecting the manufacturing step impact, influences significantly the impact related to the material production step. If the process enables a part weight reduction (as the Additive Manufacturing approaches do) even the use phase is affected by the manufacturing approach selection. The present research provides a comprehensive environmental manufacturing approaches comparison for components made of aluminum alloys. Additive manufacturing (Selective Laser Sintering), machining, and forming processes are analyzed and compared by means of Life Cycle Assessment techniques. The effect of weight reduction enabled by additive approach is considered. The paper aims at highlighting the strong link between manufacturing approach selection and material use. In this respect, a thorough environmental analysis of the pre-manufacturing step is developed. Moreover, the influence of eco-attributes aluminium variability on the comparative analysis results is studied. The paper, therefore, contributes to the development of a methodology for manufacturing approaches comparison, providing guidelines for green manufacturing approach selection. Results reveal that, for the analyzed case studies, the Additive Manufacturing is a sustainable solution for aluminium components only under a specific scenario: high complexity shapes, significant weight reduction, and application in transportation systems.

Nomenclature

E_B (MJ/kg)	primary energy demand for aluminum bar production ($E_B = E_V + E_E$)
E_E (MJ/kg)	primary energy demand for hot extrusion
E_{GA} (MJ/kg)	primary energy demand for gas atomization
E_{mat}^A (MJ/part)	primary energy demand for raw material production, AM approach
E_{mat}^F (MJ/part)	primary energy demand for raw material production, forming approach
E_{mat}^M (MJ/part)	primary energy demand for raw material production, machining approach
E_P (MJ/kg)	primary energy demand for aluminum powder production ($E_P = E_V + E_{GA}$)
E_R (MJ/kg)	primary energy demand for aluminum ingot secondary production (recycling)
E_V (MJ/kg)	primary energy demand for aluminum ingot primary production
m_{iA} (kg)	mass of the aluminum ingot for the AM approach
m_{iF} (kg)	mass of the aluminum ingot for the forming approach
m_{iM} (kg)	mass of the aluminum ingot for the machining approach
m_p (kg)	mass of the component
m_{sAM} (kg)	mass of the support structures
m_{sE}^f (kg)	mass of the scraps of hot extrusion process, forming approach
m_{sE}^m (kg)	mass of the scraps of hot extrusion process, machining approach
m_{sF} (kg)	mass of the machined-off material of forged components
m_{sFM} (kg)	mass of the machined-off material of AM components
m_{sGA} (kg)	mass of the scraps of gas atomization
m_{sM} (kg)	mass of the machined chips
$r_{(95\%)}$	recyclability equal to 95% (typical for bulk scraps)
$r_{(85\%)}$	recyclability equal to 85% (typical for light-gauge scraps)

Acronyms

AM = Additive Manufacturing

SLM = Selective Laser Melting

LCA = Life Cycle Assessment

EoL = End of Life

BP = Breakeven Point

PSD = Process Sustainability Diagram

SEC = Specific Energy Consumption

1. Introduction

The metal components manufacturing sector plays a significant role within the global environmental impact ascribable to the industry sector. Raw material production activities cause about 25% of global CO_2 emissions (Worrel et al., 2016). To be more specific, the top five materials alone (steel, cement, paper, aluminium, and aggregated plastics) dominate the entire world material production sector whether measured by energy used or carbon dioxide emitted. Two of the top five materials are metals: steel and aluminum are responsible for about 25% and 3% respectively of CO_2 emissions for material production (Gutowski et al., 2013).

Besides the impact of material production, the environmental impact of manufacturing has to be considered; identifying the environmental impact ascribable to metal working processes is a challenging issue as these values are often included in the material production step. Despite that, some data reporting the environmental impact of industrial sub-sectors are available for U.S. (U.S. Department of Energy, 2010) and China (National Bureau of Statistics (NBS), 2015). The analysis of these data can give a reliable idea of the responsibility of metal shaping processes within the global environmental impact. The sub-sectoral breakdown analysis of annual primary energy demand of manufacturing sector reveals that metal working processes account for about 4%. This value is much lower with respect to the impact of primary material production (Ingarao, 2017). Despite the latter statistics, scientists working in the manufacturing field play a key role also concerning the material production step. In fact, material usage and manufacturing processes are two strictly connected stages as the manufacturing process selection significantly affects the amount and the kind of used material. Moreover, the growing interest raised around additive manufacturing approaches makes the former statement more meaningful. As a matter of fact, additive-based approaches use powder instead of semi-finished bulk workpieces (such as bars, plates, etc.) and are claimed to use less material and produce process scraps.

Additive Manufacturing (AM) processes are being analyzed also under the environmental impact perspective (Ford and Despeisse, 2016). A study presenting a comprehensive and global sustainability assessment of 3D printing was developed by Gebler et al. (2014), who discussed the effect of additive manufacturing on all the three (economic, social, and environmental) pillars of sustainability. Specifically, this paper outlines cost and environmental impact potential reductions associated with different 3D printing spreading scenarios over the next ten years. A comprehensive overview has been recently published by Kellens et al. (2017 a); the authors offered a review of the published researches on the environmental analysis of AM, outlining production scenarios where AM can be beneficial form an environmental point of view. As concerns AM processes for metal based components, environmental impact analyses have already been published on: Selective Laser Melting (SLM) (Faludi et al. 2017), Direct Additive Laser Manufacturing (DALM) (Le Bourhis et al. 2013) and Electron Beam Melting (Baumers et al. 2017; Le et al. 2017). Concerning polymers, an environmental characterization of stereolithography has been recently presented by Yang and Li (2018). Material and energy efficiency of Fused Deposition Modeling (FDM) was analyzed by Song and Telenko (2017) and Griffiths et al. (2016). A Life Cycle Assessment (LCA) based analysis on Selective Laser Sintering (SLS) of polymer was developed by Kellens et al.(2014)

Despite a few studies on environmental impact quantification of AM processes have been already developed, comparative analyses are needed to understand the actual environmental performance of AM approaches with respect to traditional manufacturing routes.

Actually, as metal shaping processes are concerned, three manufacturing approaches can be followed: mass conserving (forming processes), subtractive (machining processes) and additive based approaches. The selection of one manufacturing approach over another one could result in significant material and energy savings. In consequence, when the environmental impact of a manufacturing approach is to be analyzed, the material-related flow must not be left out and has to be followed throughout the product life (Ingarao et al., 2016b). Over the last few years, researchers have started to deal with such challenges and some comparative analyses have been published. Morrow et al. (2007)

developed the first comparative analysis quantifying 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 in order to assess the influence of part complexity on the comparative analysis. The results revealed that conventional CNC milling is preferable over DMD processes for high solid-to-cavity ratios. Molds with low solid-to-cavity ratios are less environmentally burdensome when produced via DMD instead. Serres et al. (2011) compared the direct additive laser manufacturing (CLAD) approach with conventional machining. A LCA analysis on Ti-6Al-4V parts was developed, and proved that additive manufacturing leads to an environmental impact reduction as high as 70% (Ecoscore from Eco-Indicator 99 methodology), mainly because of the absence of scraps production. Paris et al. (2016) compared cumulative energy demand of conventional machining and EBM process to manufacture an airplane turbine made of titanium alloy. The material-related contributions were included and the influence of the machined-off material on the environmental impact was highlighted, showing that AM processes are 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 achievable by the weight reduction obtainable by topology optimization was included, a CO_{2eq} emissions reduction of 64 % was obtained by selecting the AM over machining. In this context, Faludi et al. (2015) applied a full LCA methodology to analyze additive and milling processes for plastic components manufacturing. Specifically, two additive manufacturing processes (Fused Deposition Model and 3D Printing) were considered and two specific parts in Acrylonitrile Butadiene Styrene (ABS), or in a similar polymer (as required by the AM machines), were selected as case studies. Several factors were taken into account: the processing electrical energy, the material used in the final parts, the material waste that was generated, the cutting fluid for CNC and the transportation and disposal costs. Results revealed that the relative sustainability of AM versus CNC machining depends primarily on the usage profiles, thus on the specific machines. Faludi and colleagues (2015) specified that it could not be categorically stated that 3D printing is more environmentally friendly than machining or vice versa. Peng et al. (2017), analyzed three different manufacturing routes to produce an impeller. Specifically, they compared an additive-based approach to both conventional- and remanufacturing-based routes by applying a LCA. The remanufacturing approach resulted the best solution in terms of environmental performance, while AM led to the highest environmental impact. Yoon et al. (2014) developed a comparative analysis with respect to the Specific Energy Consumption (SEC) for a component made out of ABS P400, considering the electrical energy consumption and the contributions related to die manufacturing. The authors compared injection molding, Fused Deposition Modelling (FDM), and milling; the influence of the production batch size on the final results was also evaluated. Resulted revealed that FDM has a great advantage over conventional manufacturing processes when the number of parts to be produced is small. The study of Yoon et al. (2014) has the merit of being one of the first examples of comprehensive analyses, as it embraced all of the three potential manufacturing approaches. However, no material-related aspects were considered. Huang et al. (2015) applied the comparative analysis to five aircraft components. In this research different additive manufacturing processes are compared to conventional manufacturing approaches. All the main factors of influence were considered: raw material production, raw material distribution, component manufacturing and component distribution to the aircraft assembly plant. The relevance of light-weighting obtainable by implementing topological optimization for additively manufactured parts was clearly evidenced.

Recently, some research efforts were aimed at developing decision support tools to identify the most environmentally friendly manufacturing approach as the production scenario changes. Ingarao et al. (201b) presented an environmental comparison between forming and turning. The influence of both part geometry and production batch size was analyzed. The authors proposed also a decision support tool named Process Sustainability Diagram (PSD), which enables the most energy efficient production approach to be identified as the main factors of influence are varied. Watson and Taminger (2016) suggested an equation-based decision support model to choose the lowest energy demanding process between AM and machining for the production of metal parts. They also remarked that many factors (such as part and material property requirements, time and material usage), in addition to energy consumption, may contribute to the selection of the optimum manufacturing method. Following the idea of Watson and Taminger (2016), some of the authors of the present paper proposed a similar tool starting from the empirical modeling of AM and machining approaches (Priarone and Ingarao, 2017). In this research the authors proposed an equation-based tool relying exclusively on processes scraps and applied the proposed procedure to both Ti-6Al-4V and stainless steel components production.

Overall, the literature review reveals that all the three possible manufacturing (additive, subtractive, and mass conserving) approaches have been never, or rarely, compared for metal component production. As a matter of fact, in most of the papers additive approaches are compared with subtractive manufacturing and the only research (Yoon et al., 2014) comparing three manufacturing routes gives partial information as it does not include the material-related impacts. Moreover, there is a lack of guidelines for the most green process selection. Also, the importance of geometrical complexity is highlighted, however detailed guidelines are still missing. The importance of light-weighting obtainable by additive manufacturing and the repercussions on the environmental impact throughout entire the life cycle were included only in few papers (Huang et al., 2016; Tang et al., 2016; Priarone and Ingarao, 2017).

Several factors affect the environmental performance of parts manufacturing (such as ecological properties of the processed material, part complexity, batch size, produced scraps). The development of reliable decision support tools enabling environmentally-friendly solution selection at the process planning stage appears to be a pressing need. Differences in material usage play a central role as material production is often the most burdensome step. The life cycle inventory of the material flow should be better analyzed including energy use and material yield during the pre-manufacturing step. Such step includes processes aimed at turning ingots into usable semi-finished products (bars, powder, plates, etc.). It is essential, therefore, using reliable data concerning the ecological performance of producing a given material. Unfortunately, data concerning material production are often affected by lack of precision. As far as aluminium is concerned, Ashby (2012) provides an average value for the embodied energy for primary production of 204 MJ/kg, with a standard deviation equal to 51 MJ/kg (that is the 25% of the average value). Such a high variability comes from several factors: the differences in process routes, the difference in energy-mix in electrical power production across countries, the difficulties in setting the system boundary, and the procedural problems when assessing the eco-attributes. Liu and Müller (2012) analyzed the variability of GHG (Greenhouse Gases) emissions intensity for primary aluminium ingot production. They state that minimum specific (for producing one kg of aluminum) $CO_{2\text{-eq}}$ emissions value is equal to 5.92 (kg $CO_{2\text{-eq}}$/kg) while the maximum one increase up to 41.1(kg $CO_{2\text{-eq}}$/kg) while the average range is expected to be around 9.7-18.35 (kg $CO_{2\text{-eq}}$/kg).

Overall, the present research provides a comprehensive manufacturing approaches comparison for aluminium based components. Additive Manufacturing (Selective Laser Sintering, SLM), conventional machining and forming processes are analyzed and compared. A full LCA approach is proposed to assess the environmental impact of different processes when manufacturing components made of aluminum alloys. The comparison among processes was developed on four different case studies to take into due account the influence of the solid-to-cavity ratio. Moreover, the effect of light-weighting enabled by the additive approach is considered, including also the benefits occurring in the use phase. As material production has a significant role, two important aspects are deepened in the present paper. The first one concerns the thorough analysis of the materiel losses and energy consumption in the pre-manufacturing step. In other words, the environmental impact caused by turning aluminium ingots into bars or powder is included in the analysis. The second one concerns the analysis of the influence of eco-attributes aluminium variability on the comparative analysis results. The developed analyses allowed some guidelines for green manufacturing approach selection to be provided in case of aluminum based components. Section 2 contains the explanation on how the aluminum primary production has been modeled. Details about the case studies are reported in Section 3. Section 4 includes the description of the used LCA framework. Results about the environmental comparison about the selected manufacturing approaches are discussed in Sections 5.

2. Geographically-dependent variability of aluminium production

Aluminium is one of the most energy intensive metals to produce from ore, mainly due to the high electricity demands (or density) of the final electrolysis step. On the other hand, aluminium production by scrap recycling (secondary production) has much lower energy requirements, and around 5% of the primary aluminium impact is needed. However, quality and dilution losses due to impurity accumulation and alloy mixing may occur (Paraskevas et al., 2013; Paraskevas et al., 2015). Due to the high energy intensity of primary aluminium production, its environmental impact per produced mass is highly geographically dependent as shown by Paraskevas et al. (2016a). More specifically, main geographically-dependent variables can be identified: the energy mixes (for electricity and heat energy production) as well as the installed technology mix for alumina refining and aluminium smelting (translated into different energy efficiencies). For example, the refining energy densities are high in China due to low domestic bauxite ore grades. Moreover, despite being equipped with state-of-the-art smelting technology (as the facilities in China are generally newer in comparison to the European ones), its coal-based electricity production increases the environmental impact compared with other countries-producers (Paraskevas et al., 2016b).

The model that was used in this study to assess the environmental impact of primary aluminium production per country-producer consists of several process layers. Figure 1 represents a simplified process structure with the energy and material flows. A total selection of 29 different countries was withheld, some active on all three levels (bauxite mining, alumina refining, and aluminium smelting) and some on one or two levels only. In total, the selected countries represent 87% of total global bauxite ore production, 98% of alumina refining, and 92% of primary aluminium smelting (Paraskevas et al., 2016a). Bauxite mining is considered as fixed for all the studied cases as its overall impact contribution is negligible when compared to the other two process steps. Important conversion ratios that were used are related to the mass of bauxite required for the production of 1kg of alumina and the mass of alumina required for 1kg of primary aluminium which are also fixed for every case to 1.53 kg/kg and 1.935 kg/kg respectively (according to the EcoInvent v3.0 database). On the alumina production level, the process is divided into two sub-processes: the production of aluminium hydroxide and the production of alumina. The required energy for alumina refining is provided by heat generation (referred to as the heat mix), of which a part can be electricity (at medium voltage) required for the auxiliary processes of the refining plant.

Information regarding the alumina refining and aluminium smelting energy densities, as well as the heat mix were taken by the International Aluminium Institute (IAI) statistics (IAI, 2017) at regional level (for Europe in this study). The electricity mixes at country level is based on the average national electricity production, and was retrieved from the International Energy Agency's energy statistics (IEA, 2017). Electricity produced by the primary aluminium smelters is thus not taken into account in this study, and a 100% grid dependency is assumed. Another important assumption is that electricity trade among countries was not considered. A study conducted by Koch and Harnish (2002) shows that important differences in CO_2 emissions related to primary aluminium smelting can occur based on the definition of the electricity mix boundary. National networks, e.g. in Europe, are highly integrated with neighboring countries, making the tracking of the exact energy mix very hard and complex. However, in order to remain within the scope of this study, 100% national grid dependency was opted for. Regarding electricity, medium voltage electricity can be obtained by transforming high voltage electricity. Transformation losses have been set equal for each country or region throughout this analysis (based on the global average value provided by EcoInvent v3.0, which is 1.02%) as they are small and practically the same everywhere. The effect of transformation losses is taken into account by the consumption of medium voltage electricity during the transformation. In turn, electricity at high voltage is produced from a mix of different sources and is country specific, and is thus a geographically-dependent variable. A selection of minimum (MIN), maximum (MAX) and average (AVG) values of environmental impact per kg of produced primary aluminium at the European context (Paraskevas et al., 2016a) is presented in Table 1. Ecopoint is selected as single point indicator for environmental impact quantification. Life Cycle Inventory (LCI) data are associated to 17 environmental damage categories through the ReCiPe H/A characterisation method (midpoints). Midpoints are then linked to damage to three areas of protection: human health, ecosystem diversity, and resource availability; and further aggregated to a single point indicator

(Ecopoint). Ecopoint as single unit, is considered as more suitable indicator for impact quantification of the several comparisons presented in this study. In addition to Ecopoints, $CO_{2\text{-eq}}$ was also selected as a single midpoint indicator for Global Warming Potential. As presented at Figures 4 and 5, the results for both indicators are in a very good agreement.

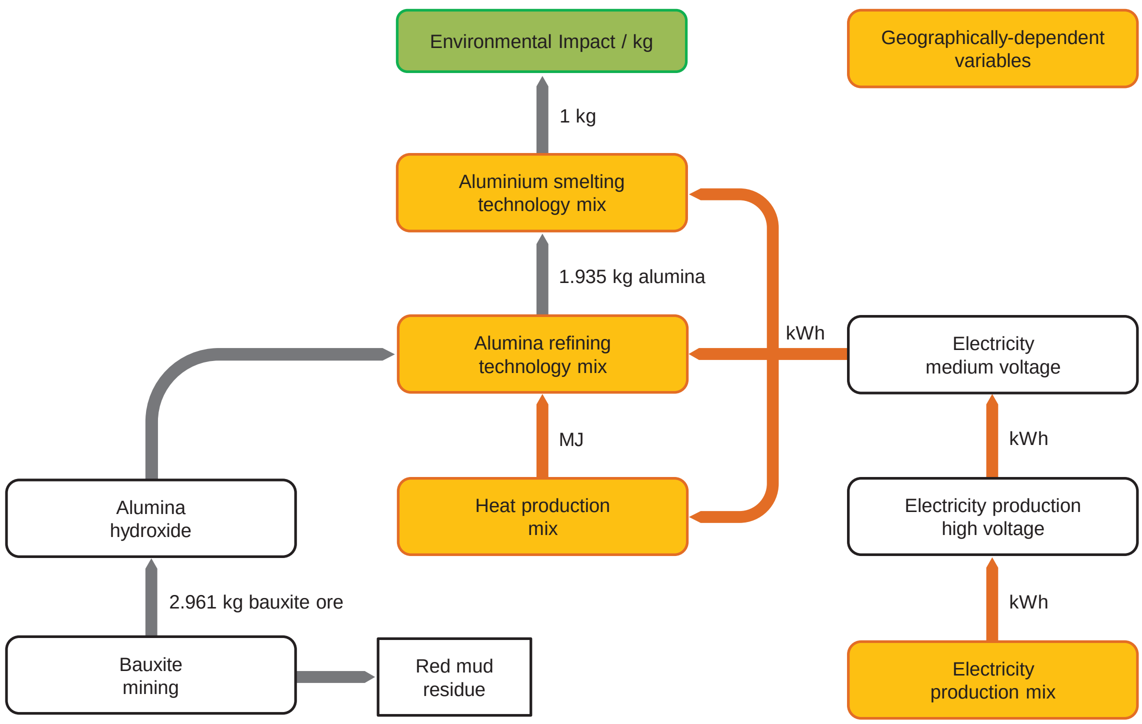

Figure 1. Process network used to calculate the environmental impact of primary aluminium production. The county-dependent variables are highlighted by the orange boxes

Table 1. Selected scenarios for aluminium primary production.

Scenario	Bauxite mining (Ecopoints/kg)	Alumina refining (Ecopoints/kg)	Aluminium smelting (Ecopoints/kg)	Total (Ecopoints/kg)
MIN	0.005	0.150	0.356	0.511
MAX	0.005	0.219	1.876	2.100
AVG	0.005	0.185	1.116	1.306

3. Analyzed case studies

Four different axy-symmetric product geometries have been considered. The components are made of a high-strength AA-7075 T6 aluminium alloy. It is worth pointing out that, for Additive Manufacturing, the AlSi10Mg is the most popular alloy for aluminium parts (Ding et al., 2016; Sistiaga et al., 2016). Therefore, the only available data for inventory compilation are for such alloy, and these have been used for the AM approach. Sketches of the four (ID1,ID2, ID3 and ID4) different parts to be manufactured are shown in Figure 2. The selected geometries are characterized by different solid-to-cavity ratios. The solid-to-cavity ratio 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. Since the material plays a crucial role in the environmental performance of a manufacturing process (Ingarao et al., 2016 b), the selected geometries enable the manufacturing approaches comparison under different material usage scenarios. Specifically, when moving from geometry ID1 to ID4, the solid-to-cavity ratio of the part decreases and the amount of material to be machined-off (in the case of the subtractive approach) increases. The involved masses, the solid-to-cavity ratios, and the amounts of machined-off material for each case study are listed in Table 2. The three processes were all modeled and analyzed for the ID1, ID2 and ID3 case studies. The ID 4 part was considered to compare additive and subtractive approaches, as it is characterized by a low solid-to-cavity ratio (equal to 0.15), and forming process would results unfeasible or requiring a large number of forming steps.

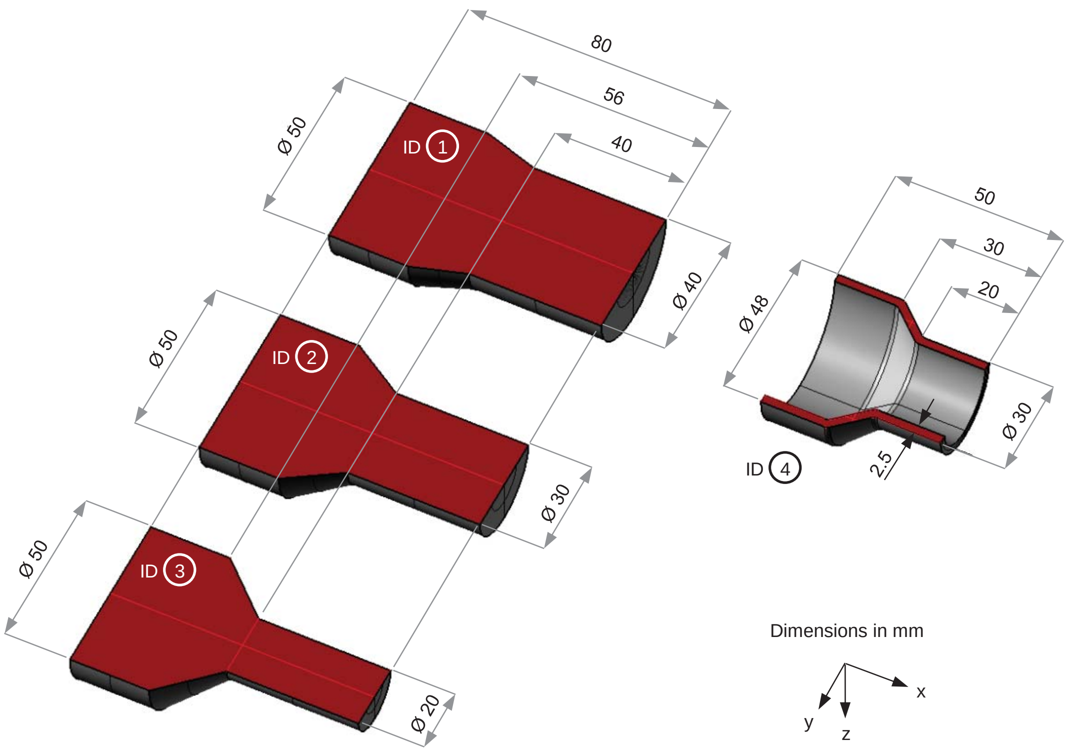

Figure 2. Sketches of the four different case studies.

Table 2. Geometrical features of the analyzed case studies and details for the Life Cycle Inventory.

Geometry ID	ID1	ID2	ID3	ID4
Analyzed manufacturing approach	Forming vs. Turning vs. SLM			Turning vs. SLM
Mass of the part (kg)	0.35	0.27	0.21	0.04
Solid-to-cavity ratio	0.80	0.61	0.48	0.15
Material (AISI H13 alloy) involved in die manufacturing for forming (kg)	7.23	6.20	5.88	n.a.
Amount of machined-off material when machining (kg)	0.09	0.17	0.23	0.22

4. LCA framework

The LCA methodology followed in this study is described in this section, which includes the definition of the goal and scope, functional unit, systems boundaries, the life cycle inventory analysis for material production and material processing stages. The interpretation and discussion of the LCA results is presented in section 5.

4.1. Goal and scope

The aim of the LCA is to characterize the environmental performance of typical aluminum-based components manufacturing processes. The LCA results can be used to compare the environmental impacts of forming, machining, and additive approaches under different production scenarios, and thus used to identify the optimal manufacturing strategy in the perspective of the life cycle environmental impacts. Thus, the LCA study can provide guidelines for the sustainable manufacturing approach selection.

4.1.1. Functional unit

The life cycle of a single aluminium-based component was analyzed from resource extraction to part disposal. The overall environmental impact per single part production (within a defined batch size) was used as a basis for the manufacturing approaches comparison. Particularly, the environmental performance of the forming approach is heavily affected by the size of the production batch, in fact the contributions related to tooling (e.g., the punches and the dies) have to be amortized over the number of parts to be manufactured.

4.1.2. System boundaries

A cradle-to-grave system boundary was adopted, and recycling was selected to be the scenario at the End-of-Life (EoL). The impact of material production, product manufacturing, and recycling were evaluated. The common parts (use and transportation phases) were neglected as the research was carried out assuming that the components manufactured by all the processes comply with the same product specifications. Concerning the materials involved in the analysis, the credit from recycling (end-of-life stage) was considered by implementing the substitution method (as proposed by Hammond and Jones, 2010). It is worth remarking that the system boundary includes the impact related to the pre-manufacturing stage (i.e., the processes required to turn ingots into usable input materials, either bars or metal powder). As regards the manufacturing step, all the energy flows were considered: energy for processing (pressing, machining, energy for melting the powder layers by SLM processes), tooling (materials and manufacturing energy) as well as heating (for the forming approach only). The authors have already proved that the differences in material transportation, even if affecting the logistic network, can be neglected in comparative approaches for medium-to-low travelled distances (Priarone et al., 2017). Therefore, in the present work, the impact of transportation has been left out. In order to take into account the light-weighing enabled by additive manufacturing, a further assessment which includes the differences in the use phase performance was also introduced, and it is detailed in Section 5.2.1. Moreover, different scenarios are constructed within this comparative LCA through changing the parameters of the batch size and part geometry when it comes to manufacturing strategy selection. Also, the scope of the study includes the analysis of the effect of aluminum eco-properties variability on the overall impact. Specifically, the influence of such variability on the decision support tool set up by the authors and named '*Process Sustainability Diagram*' (PSD) (Ingarao et al., 2016 b) will be discussed.

4.2. Life Cycle Inventory analysis

In this section, the main material/energy inputs under different scenarios are defined for each life cycle stage. Since recycling is considered as the EoL strategy, the material production and the EoL phases are discussed together in the sub-section 4.2.1 for the sake of clarification.

4.2.1. Material production

Different manufacturing approaches result in different amounts and kinds of involved materials. Normally, available databases provide the ecological properties of materials by considering the production route until the ingot production (in case of metals). When a suitable input workpiece has to be obtained, the pre-manufacturing processes have to be also evaluated. In particular, extrusion steps and gas atomization processes have to be encompassed for bar and powder production, respectively. In the present paper, such an upstream level was included and both extra energy and process scraps were accounted for. The material and energy flows for the three different manufacturing approaches applied to turn the aluminum ingot into the final part are schematized in Figure 3. All the material scraps occurring during these manufacturing phases are considered and recycling is selected as end-of-life strategy.

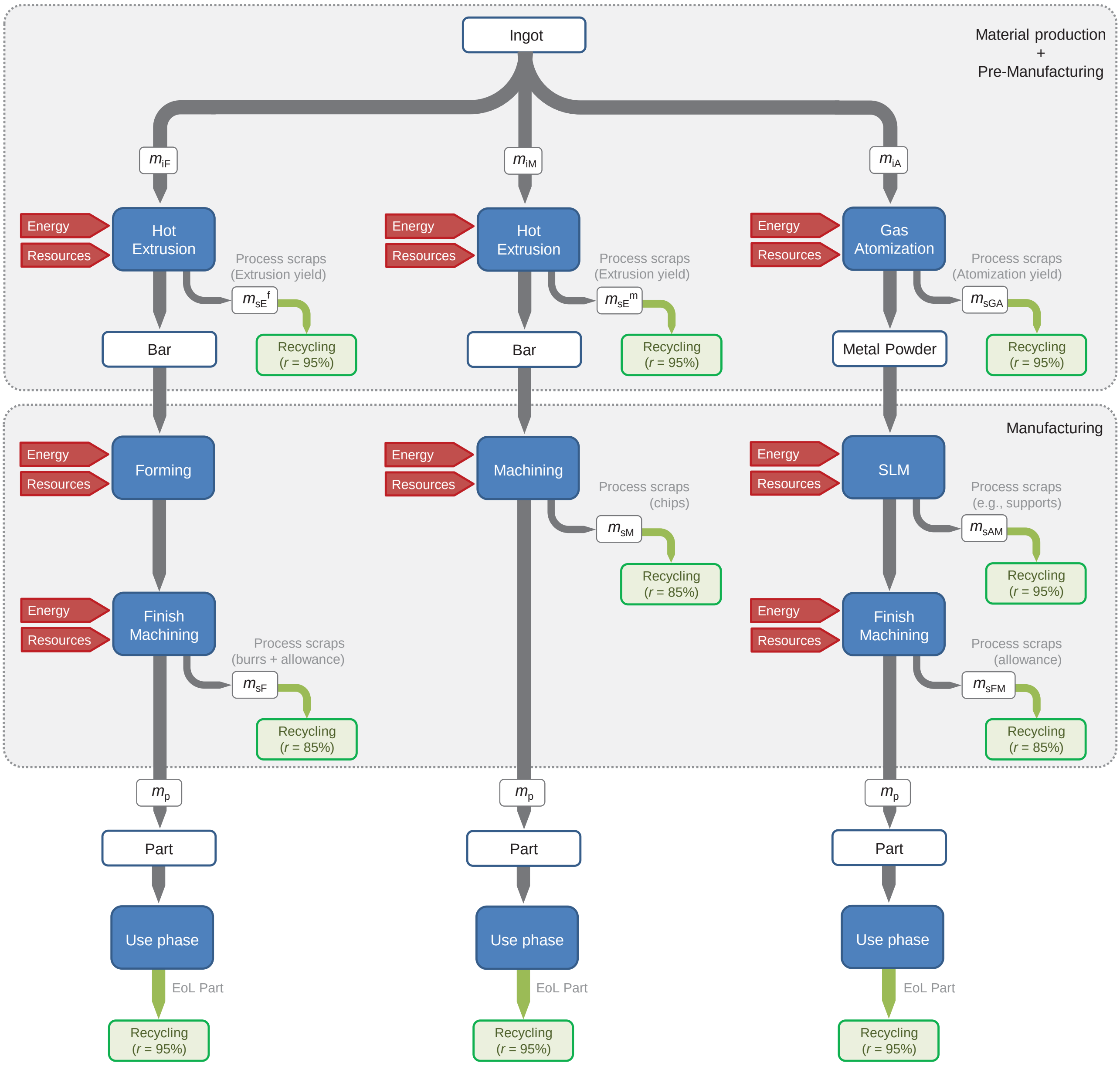

Figure 3. Energy and resources flows characterizing the three approaches during the pre-manufacturing and the manufacturing steps.

The substitution method, which considers the impacts on the present climate of the production and supply of the material (cradle-to-gate), and gives a recycling credit for future recyclability (end-of-life), has been applied according to Hammond and Jones (2010). For all the materials that do not suffer from losses in their inherent properties, such as metals, the embodied energy (E_E, in MJ/kg) is obtained by means of Equation 1, in which the recyclability (r) and the embodied impact arising from the recycled material input (E_R, in MJ/kg) are included. E_V is the embodied energy for the primary production of the material, while the embodied energy savings (E_V - E_R, in MJ/kg) are directly proportional to the material recyclability. As for the others environmental indicators, such as the Ecopoints, the impact of material can be computed accordingly.

$$E_E = E_V - r \cdot (E_V - E_R) \qquad \left(\frac{MJ}{kg}\right) \tag{1}$$

It is worth highlighting that the conventional remelting-based recycling process was assumed in the present analysis due to its wide applicability at the industrial level (EAA, 2013). Nevertheless, recycling of aluminum scraps by secondary aluminum production (by means of aluminum remelters) is considered in all the cases with different recycling efficiencies. As a matter of facts, chips created as a by-product of the machining operations are scraps challenging to recycle. In fact, light gauge scraps characterized by high surface-to-volume ratios tend to float on the melting bath, causing oxidation losses up to 20% (Xiao and Reuter, 2002; Duflou et al., 2015). To take this phenomenon into due account, 5% (i.e., r = 95%) of material losses for the bulk aluminium part were estimated, while 15% (i.e., r = 85%) of material losses during the recycling of chips were considered. The energy contribution due to the material usage can be re-written, with respect to the flows of Figure 3, as in Equations 2, 3, and 4 for mass conserving, subtractive, and additive manufacturing approaches respectively. For the sake of clarity, these equations refer to the primary energy demand; however, they can be applied accordingly in order to get all the other environmental metrics (e.g., Ecopoints, Midpoints). The assumed values for computing Equations 2-4 have been identified in different scientific and technical sources. These values along with the main references are listed in Table 3 .

$$E_{mat}{}^{F} = \left(m_p + m_{sE}{}^{f}\right) \cdot \left[E_B - r_{(95\%)} \cdot \left(E_V - E_R\right)\right] + m_{sF} \cdot \left[E_B - r_{(85\%)} \cdot \left(E_V - E_R\right)\right] \qquad \left(\frac{MJ}{part}\right) \tag{2}$$

$$E_{mat}{}^{M} = \left(m_p + m_{sE}{}^{m}\right) \cdot \left[E_B - r_{(95\%)} \cdot \left(E_V - E_R\right)\right] + m_{sM} \cdot \left[E_B - r_{(85\%)} \cdot \left(E_V - E_R\right)\right] \qquad \left(\frac{MJ}{part}\right) \tag{3}$$

$$E_{mat}{}^{AM} = \left(m_p + m_{sAM} + m_{sGA}\right) \cdot \left[E_P - r_{(95\%)} \cdot \left(E_V - E_R\right)\right] + m_{sFM} \cdot \left[E_P - r_{(85\%)} \cdot \left(E_V - E_R\right)\right] \qquad \left(\frac{MJ}{part}\right) \tag{4}$$

Where:

$$E_P = E_V + E_{GA} \qquad \left(\frac{MJ}{kg}\right) \tag{5}$$

$$E_B = E_V + E_E \qquad \left(\frac{MJ}{kg}\right) \tag{6}$$

Table 3. Assumed values for quantifying energy demand and material scraps.

Factor	Assumption	Reference
$m_{sE}{}^{m}$	$0.25 \cdot m_{iM}$	EAA (2013)
$m_{sE}{}^{F}$	$0.25 \cdot m_{iF}$	EAA (2013)
E_E	4.77 MJ/kg (billet heating + pressing electrical energy)	EAA (2013)
E_{GA}	8.10 MJ/kg (natural gas burned into a furnace)	Faludi et al. (2017); Kellens et al. (2017)
m_{sAM}	$0.20 \cdot (m_p + m_{sFM})$	Faludi et al. (2017)

m_{sFM}	Quantified by considering a constant allowance of 1 mm	Priarone et al. (2017)
m_{sF}	$0.02 \cdot m_p$	Ingarao et al. (2016a)
m_{sGA}	$0.05 \cdot m_{iA}$	Lavery et al. (2013)
E_R	6.85 MJ/kg	(Modelled on EcoInvent v3.0)

4.2.2. Processing

As regards the inventory of the manufacturing step, all the significant factors of influence have been taken into due account. Specifically, besides material scraps (as discussed in sub-section 4.2.1), the processing electrical energy as well as the impact due to tooling (material involved plus energy for tool manufacturing) have been both considered. As far as the mass conserving approach is considered, a detailed description of the life cycle inventory for ID1, ID2 and ID3 has been provided in Ingarao et al. (2016 b). The same values formerly identified by the authors are considered also in the present research. As far as the conventional machining approach is concerned, two subsequent material removal operations of roughing and finishing (by means of carbide tools) were assumed. The finishing operation was limited to an allowance of 0.5 mm. The unit process energy consumption has been computed by using the model proposed by Kara and Li (2011), that correlates, when dry cutting, the relationship between the Specific (electric) Energy Consumption (SEC) and the Material Removal Rate (MRR) for a Mori Seiki NL2000MC/500 machine tool. As a result, the SEC has been computed as a function of process parameters, as detailed in Table 4. Such assumed values are slightly different than those experimentally achieved by means of a Cortini F500/M1 lathe, and proposed by the authors in Ingarao et al. (2015). It is worth remarking that, according to Behrendt and colleagues (2012), the specific energy demand for machining has proved to be dependent mainly on the machine tool architecture, equipment, and size. The environmental impact of cutting inserts has been allocated to each produced part on the basis of the specific tool consumption, as shown in Priarone et al. (2017). Further details on cutting tool impact modelling can be found in Ingarao et al. (2016b).

Table 4. Process parameters for the roughing and finishing cutting operations.

Process parameter	Roughing	Finishing
Cutting speed, v_c (m/min)	200	250
Depth of cut, a_p (mm)	1.5	0.25
Feed, f (mm/rev)	0.3	0.15
Material Removal Rate, MRR (cm^3/min)	90.0	9.4
Specific Energy Consumption, SEC (kJ/cm^3)	5.2	19.2
Specific Energy Consumption, SEC (MJ/kg)	1.9	6.8

The Selective Laser Melting (SLM) process was selected for the Additive Manufacturing (AM) approach. The electric energy consumed by the equipment has to be monitored and, subsequently, ascribed to the functional unit. A detailed electrical energy demand characterization for AlSi10Mg part produced by means of SLM processes was developed by Faludi and colleagues (2017). A Specific Energy Consumption (SEC) can be calculated by the published data and is as high as 471 MJ/kg, which includes the electric energy consumption due to both productive and non-productive modes. However, it is worth mentioning that the utilization of the build volume affects the process energy, and therefore the SEC value itself (Baumers et al., 2011). In the present research, the electric energy consumption for SLM has been assumed as operating at full machine capacity. The selected value is consistent with the SEC values reported by Kellens et al. (2017 b) for the SLM of aluminium alloys. The energy for the post-process finish machining operations was computed by applying the finishing cutting conditions for turning already defined in Table 4. The machining allowance for additively manufactured parts was fixed to 1 mm.

4.3. Impact assessment method

The Ecopoint (single measure including all the midpoints) has been selected as environmental impact metric. The impact categories were calculated by applying the ReCiPe method H/A. The ReCiPe method is selected because it is an update of the Eco-indicator 99 and CML 2002 methods, and both of them are widely applied impact assessment methods. In addition, the ReCiPe method integrates both the midpoint and endpoint impacts into a single framework, which best fits the goal of this study. Table 5 reports the calculated conversion factors used to turn the data obtained in the Life Cycle Inventory into Ecopoints.

Table 5. Conversion factors for calculating Ecopoints.

Variable	Ecopoints
Tungsten carbide, primary production	0.286 Ecopoints/kg
Steel, primary production	0.614 Ecopoints/kg (ingot)
Steel, secondary production	0.119 Ecopoints/kg
Aluminium, secondary production	0.095 Ecopoints/kg
Electrical energy production	0.011 Ecopoints/MJ
Heat generation	0.009 Ecopoints/required MJ

5 Results and Discussion

The LCA results for different manufacturing processes are presented and compared In this section. First, the influence of part geometries (from ID1 to ID3) on optimal process identification among SLM, turning and forming is discussed. Afterwards, the pros and cons of the SLM and turning processes are evaluated by considering the ID4 geometry. The analysis provide a comprehensive interpretation of the LCA results and can be used to draw guidelines for sustainable manufacturing process selection.

5.1 SLM vs. turning vs. forming results for ID1, ID2 and ID3 geometries

In this section the results of the comprehensive comparative analysis are presented and discussed. To be more specific, the Ecopoints and CO_{2_eq} (kg) and for each manufacturing approach for ID1, ID2 and ID3 are reported. The analyses were developed for the three scenarios defined in Section 2 (namely: MAX, MIN, and AVG). The results for forming and machining approaches are detailed in Figures 4a and 4b. The Ecopoints and CO_{2_eq} (kg) for a single part manufacturing are compared while the scenario changes. According to the assumptions made in sub-section 4.4.2, only the results concerning the forming approach are batch-size dependent. In fact, the tool manufacturing has to be amortized over the number of manufactured parts (Ingarao et al., 2016b). For the sake of clarity, only the results for a batch size equal to 100 parts are plotted. Overall, it is possible to state that the results obtained with the two metrics are proportional. The same trends can be identified as well as the same conclusions can be drawn by comparing the graphs in Figure 4a and Figure 4b. Also, it is possible to notice that the impact due to material production is always the dominant factor regardless of (1) the manufacturing approach, (2) the ID geometry, as well as (3) the impact ascribed to the material production step. As a consequence, when moving from the MIN to the MAX scenario, the global environmental impact of both machining and forming noticeably increases.

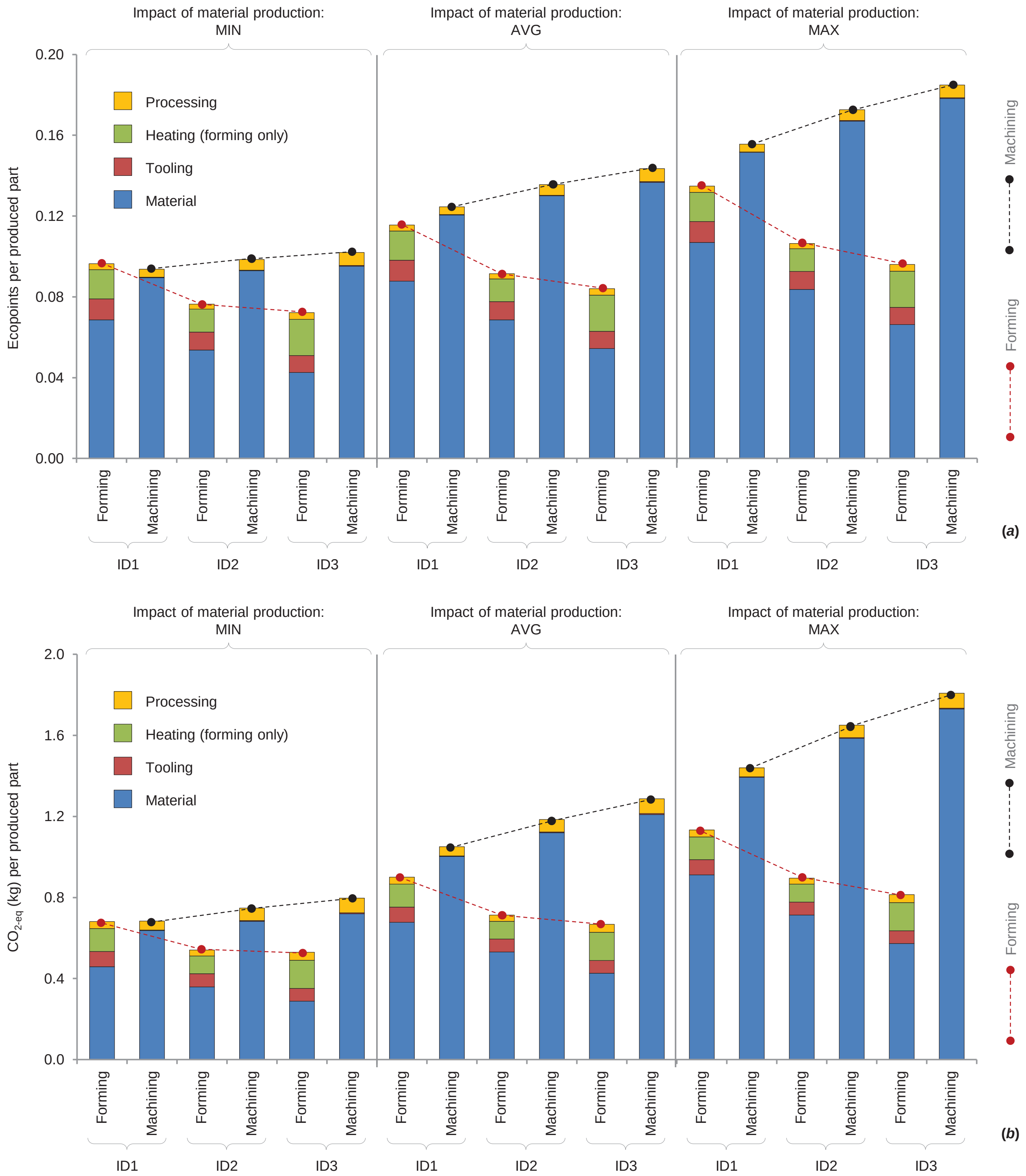

Figure 4. Ecopoints (*a*) and $CO_{2\text{-eq}}$ emissions (*b*) per manufactured part for forming versus machining approaches and for a 100 parts batch size.

The change in environmental impact ascribed to the material also affects the comparative results. In particular, for the ID1, when the MIN scenario is considered, machining is the option to be selected, while forming appears to be the most environmentally-friendly manufacturing approach for the AVG and MAX scenarios. As a matter of fact, the environmental performance of the machining approach improves as the impact of the material decreases, leading to a change in the overall comparative results for the ID1 case study. For ID2 and ID3 geometries (and for a batch size of 100 parts) the impacts of forming are always lower than that of machining. An increase in environmental impact difference between the two considered approaches (when moving form scenario MIN to scenario MAX) is clearly visible though. In fact, if ID3 is considered, the processes differ by 29% for MIN scenario, and such a difference increases up to 48% if the MAX scenario is taken into account. The results concerning the environmental impact of the additive manufacturing approach are reported in Figure 5a (Ecopoints) and Figure 5b (CO_{2_eq} (kg)). Results for the manufacturing via SLM of a single part is reported for each ID geometry with varying the environmental burden ascribed to material production (i.e., MAX, AVG, MIN scenarios). Again, the results obtained with the two metrics are proportional. Also, the authors observed the same trends also using the primary energy as metric. In consequence, for the sake of the results discussion clarity, from now on only the Ecopoints will be reported for analyzing the obtained results.

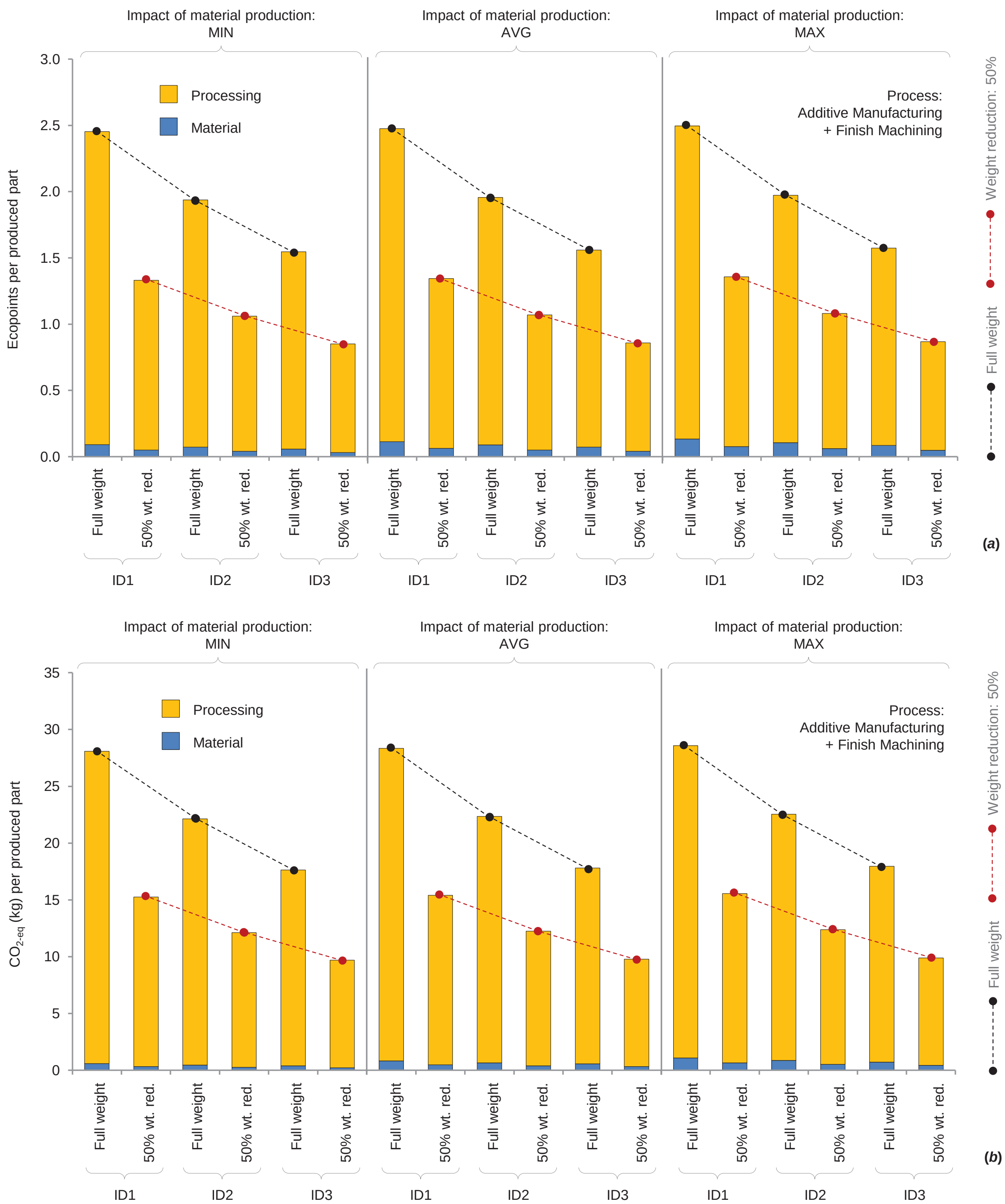

Figure 5. Ecopoints (*a*) and $CO_{2\text{-eq}}$ emissions (*b*) per manufactured part for the additive manufacturing approach.

Furthermore, for each specific condition, a possible weight reduction enabled by topological/topographical optimization during the re-design for AM is also considered. Actually, when metal based components are produced by additive manufacturing, significant weight reductions can be obtained (Huang et al., 2016). In the present research, a weight reduction up to 50% is considered. Such a weight reduction affects both the material as well as the processing step (as the amount of material to be deposited decreases). Ecopoints for the 50%-lighter components (labeled as '50% wt. red') are reported in Figure 5 besides the full-weight components to facilitate a direct comparison. Overall, in contrast to conventional manufacturing approaches, where the material phase represents the major impact, the processing (i.e., the laser-based building) is by far the dominant factor for SLM. Since material production has a minor share towards the overall impact, the Ecopoint score variation while changing the scenario is away less significant with respect to that of conventional manufacturing. When comparing the environmental performance of additive and conventional manufacturing approaches, it is possible to state that the SLM process is by far the worst approach for the analyzed case studies. As a matter of fact, in case of full-weight part manufacturing, SLM has an environmental impact higher by more than one order of magnitude. Even though the 50% light-weighting of the component is suitable to obtain a strong environmental impact reduction for the additive approach, such strategy is not enough the get the SLM process to be preferred. In fact, results for additive manufacturing are still, at least, one order of magnitude higher than that of machining, and SLM can be preferred over the forming approach exclusively for one part production for the ID3 geometry. A part from the latter specific scenario, also forming is by far a better solution with respect to SLM.

The poor performance of the SLM approach is caused by the high power needed by the laser to process aluminium. This high power is due to both the high reflectivity as well as the high thermal conductivity of aluminium, according to literature (Louvis et al., 2011; Sistiaga et al., 2016). For the analyzed case studies, the additive approach does not represent a viable solution, while the influence of the eco-properties of aluminium on the forming versus machining results deserves to be deepened. The environmental impact of machining has been modelled to be independent of the batch size, since the impact of cutting tools is basically negligible (as already shown in Ingarao et al., 2016 b). The forming approach is batch-size dependent as the tooling is to be amortized over the number of manufactured parts instead. For a given ID, there has to be a batch size (i.e., a Break-Even Point, BP) for which the two approaches are characterized by the same environmental impact. The forming approach is the less burdensome approach for batch sizes higher than the BP value, vice versa machining is to be preferred. The BP values changes as the solid-to-cavity ratio changes (Ingarao et al, 2016 b). Figure 6 depicts the differences in BP values as the environmental impact ascribed to the material production changes (for the ID1 case study).

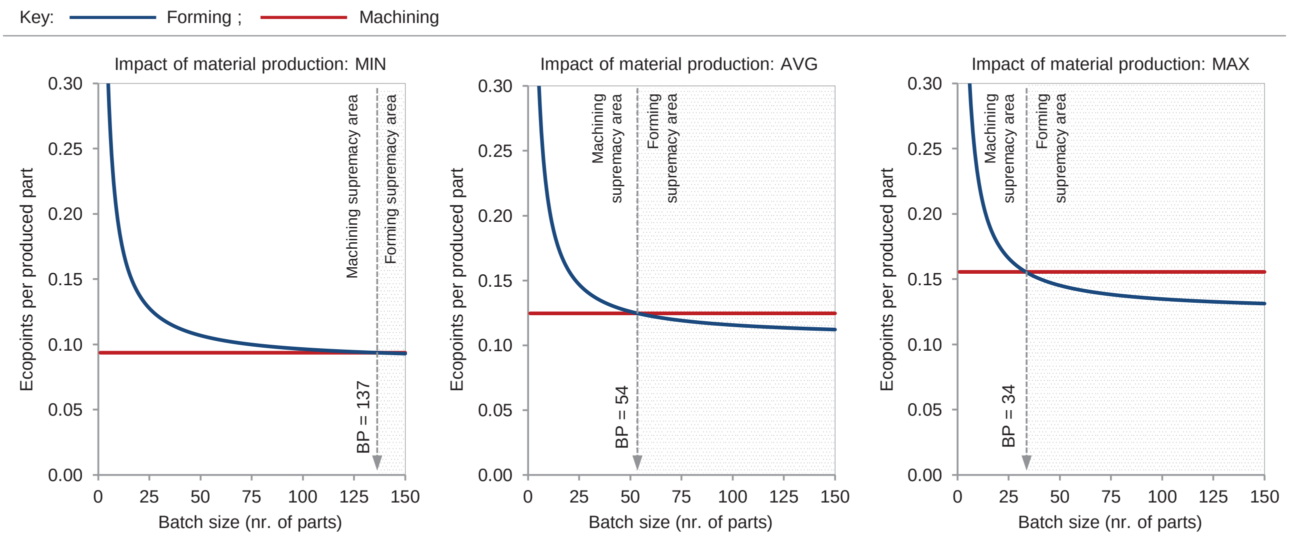

Figure 6. Changes of BP value for ID1 as the environmental impact ascribed to the material production changes.

As the ecological properties are set at their best values (i.e., for the 'MIN' scenario), the BP shifts towards right. Therefore, for the considered case study, the adoption of a subtractive approach is preferable up to a batch size as high as 137. For batch sizes larger than the BP value the forming approach is preferable. The shifting towards right of the BP value is due to the lower impact associated with chip production when the MIN scenario is selected. By identifying the BP for different solid-to-cavity ratios and plotting the obtained results in a graph, it is possible to obtain a decision support tool named Process Sustainability Diagram (PSD), as already proposed by the authors in Ingarao et al., 2016b. Such a graph enables the most energy-efficient production approach to be identified as the solid-to-cavity ratio and the batch size change. The area underneath the curve contains all the variable configurations for which the machining approach is the most environmentally-friendly process. Looking at Figure 7 the change of PSD diagram with material ecological properties changing can be noticed. Significant changes of the curves both in position and in shape is visible. With reducing the impact ascribed to the material the PSD shifts upward, this phenomenon is due to machining performance improving with improving the aluminium ecological properties. The difference among the three different scenarios is particularly noticeable when considering the ID1. In fact, the BP values rockets from 34 to 137 parts; actually, the differences between the scenarios increases as the amount of the material to be removed decreases. Such results confirm the importance of considering reliable material input data.

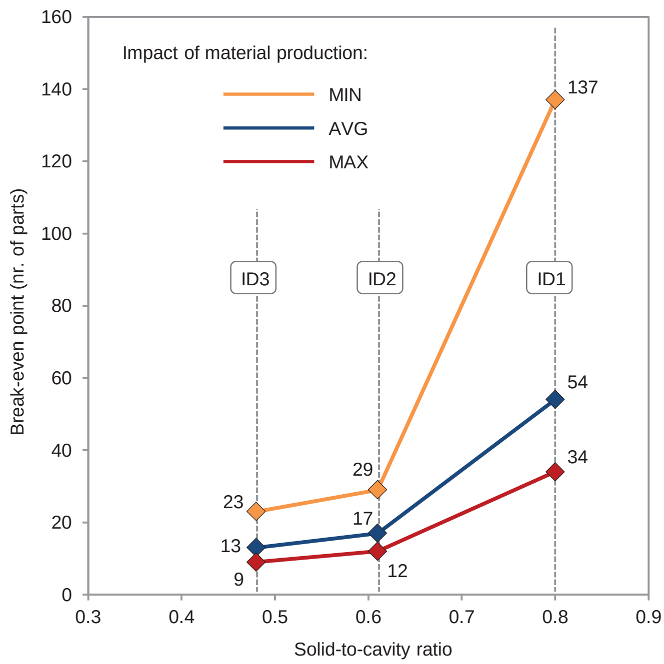

Figure 7. Influence of the material primary production impact variation on the PSD.

5.2. SLM vs. turning results for ID4 geometry

As already proved by some researchers (Morrow et al., 2017 and Priarone et al., 2017), the environmental performance of additive manufacturing approaches improve as the solid-to-cavity ratio decreases. The geometries considered so far (ID1, ID2, and ID3) are not additive-oriented, as they are quite simple bulk parts. In order to extend the domain of the present comparative analyses, the ID4 geometry has been considered. The main geometrical features are given in Table 1. Such a geometry is characterized by a very small solid-to-cavity ratio value, and it results in a high amount of material to be removed by means of machining. The environmental comparison between turning and SLM is developed in this section, the benefits of light-weighting during the use phase have been also including. As above mentioned, the forming approach is left out for the ID4 component manufacturing.

5.2.1. Scenario 1: use phase benefits neglected

The results for machining and additive manufacturing (with a 50% reduction of part weight) of ID4 geometry are reported in Figure 8. The difference between the two approaches decreases as the ecological properties of aluminium production worsen. Actually, the difference decreases from 81% (for the 'MIN' scenario) to 65% (for the 'MAX' scenario). Such a reduction is due to the higher influence of the material production stage in subtractive approaches. Even though the difference between the two manufacturing approaches is significantly reduced with respect to the results obtained for the ID1, ID2 and ID3 geometries, the machining approach outperforms the SLM in all the considered scenarios.

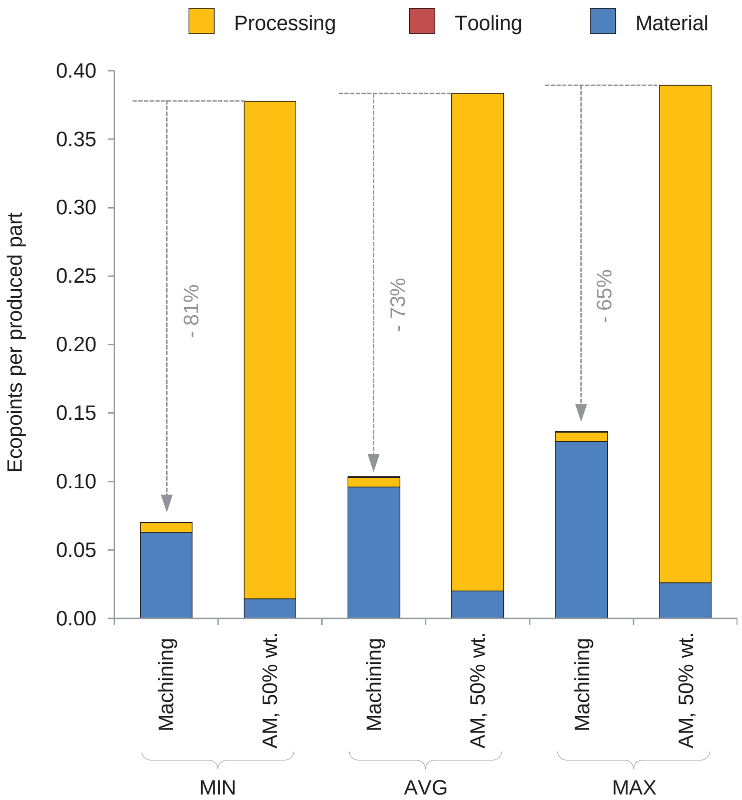

Figure 8. Ecopoints (per manufactured part) for additive manufacturing versus machining (Geometry: ID4).

5.2.1. Scenario 2: use phase benefits included

In order to explore the full potential of additively manufactured aluminum-based components, the environmental impact reduction in the use phase is to be accounted for. Therefore, an analysis considering an expanded system boundary was developed. As a matter of fact, weight reduction can lead to a strong environmental impact reduction when the manufactured component has to be assembled in a transportation system (Duflou et al., 2012). In literature, several applications of LCA-based analyses focusing on material replacing can be found (Ingarao et al., 2016a). The light-weighting is obtained in most of the studies by replacing conventional steels with light-weight materials (CFRP, aluminium alloys, magnesium alloys, and titanium alloys). These studies prove that, even though light-weight materials have a higher environmental impact during the material production step, the saving obtained in the use phase can counterbalance such extra impact. Actually, a breakeven point (e.g., driven distance in case of cars) for which the compared alternatives have the same life cycle impact is expected. For a distance higher than the identified breakeven point the lighter solution is the most environmentally-friendly choice, otherwise the standard solution is to be preferred. A similar approach was developed in the present paper: the break-even points in terms of driven distance/utilization time span were identified by applying the environmental impact saving coefficient reported by Helms and Lambrecht (2006). Results for a gasoline car and short/long-distance aircrafts are reported in Table 6. For gasoline car the breakeven point comes at about 2 million of kilometers, such results make the additive manufacturing of the aluminium component a not advisable solution for the automotive sector. On the contrary when aircraft are considered, where the use phase has a even higher impact towards the whole life cycle impact, the break-even points come quite early. Specifically, for long distance aircraft a little more than one month is enough to make the additively manufactured component the best choice.

Table 6. Break-even points for AM vs. machining accounting for the use phase of transportation system.

Scenario	MIN	AVG	MAX
Gasoline car (km)	2.4×10^6	2.2×10^6	1.9×10^6
Short-distance aircraft (years)	1.1	1.0	0.9
Long-distance aircraft (years)	0.13	0.12	0.11

6. Conclusions

The present paper provides a complete manufacturing approaches comparison for aluminum based components. Specifically, turning, forming and Selective Laser Melting performances are compared from environmental point of view. First, a methodology for taking into due account the material related impact is presented. Specifically, as each manufacturing approach is characterized by different amount and kind of involved material, the paper presents an in-depth analysis to take into due account such an aspect. A thorough model is developed to include material scraps and energy demand in the pre-manufacturing step in the LCA analysis. Also, since material production is characterized by a high variability, the influence of eco-attributes aluminum variability on the comparative analysis results is analyzed. A geographically-based variability was considered to model the aluminum primary production variability. Results revealed that such variability significantly affects the comparison among the processes. This statement was proved by analyzing the changes of the proposed Process Sustainability Diagram while varying the material input values.

As far as the environmental performance of additive manufacturing is concerned, results for two different scenarios are reported. The first one does not include the potential savings that can be achieved in the use phase due to the light-weighting of re-designed and additively manufactured components. In such a case, and for the components here considered, additive manufacturing could not be identified as an environmentally friendly solution. In fact, even considering a weight reduction as high as 50% for ID1, ID2 and ID3 geometries, conventional manufacturing approaches are preferable regardless of the considered scenario. Subsequently, the comparison was also extended by assuming a more AM-oriented (ID4) geometry. Also in this case, even though the difference between conventional and additive approach is significantly reduced, conventional machining outperforms the additive approach in all the considered scenarios. These unsatisfactory performance of AM are caused by the high energy intensity of processing for SLM. The high power, demanded by the laser while melting aluminium powder layers, is due to both the high reflectivity as well as high thermal conductivity of aluminium. The second scenario includes the savings due to the weight reduction when the manufactured component is assembled in a transportation system. Specifically, the saving due to the weight reduction enabled by additive manufacturing based approaches are included. The analyses were developed on the ID4 case study and, again, a weight reduction as high as 50% is considered. Results revealed that for car case study AM still does not result the more green choice, in fact the break-even point comes at an unfeasible driven distance (about 2 millions of km). Benefits due to light-weighting are instead well recognizable when the component is a part, or carried by, an aircraft. Actually, the break-even points come quite early. For a long distance aircraft, approximately one month is enough to compensate the high energy intensity of the AM production.

In conclusion, according to the obtained results, some guidelines for manufacturing approach selection of aluminium based components can be provided:

- When weigh reduction is not enabled: the SLM approach does not appear to be a green solution, the designer can select between subtractive and forming approach using the PSD diagram.
- When weight reduction as high as 50% is considered but the use phase benefits are not included, conventional manufacturing are still the best option. Additive can be better than forming exclusively for a very specific scenario (one single part production for ID3 case study).
- When weight reduction as high as 50% and use phase benefits are included, additive manufacturing is preferable over conventional manufacturing if the designed component has to be assembled on an aircraft

Machine builder should make an effort to reduce the energy demand for SLM, otherwise such processes can represent only part of the solution concerning the environmental impact reduction of manufacturing.

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