Production Technology Comparison between Additive Manufacturing and Injection Moulding through Life Cycle Assessment

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Abstract: Additive Manufacturing (AM) is increasingly adopted into manufacturing context mainly due its capabilities to produce very complex components in a more cost-effective way. Today more than ever, the environmental sustainability is an aspect not to be neglected. The aim of the research was to evaluate the potentials of AM technologies in terms of environmental sustainability by exploiting the Life Cycle Assessment (LCA) methodology. This study investigates the environmental impacts of the Selective Laser Sintering (SLS) and compared them with those deriving from the injection moulding process. In this study, the LCA has been applied to a section of the product life cycle, the so-called from cradle to gate approach. The LCA is a well-established quantitative method, governed by ISO 14040's, for modelling the life cycle of a product and assessing its environmental impacts; it considers all the resources, e.g. energy and material, taken by each individual phase. The standardized steps of the LCA have been carried out using the software OPEN LCA®. A multi-scenario analysis has been conducted in order to assess the role of the production volume, the parts' geometrical complexity in determining the environmental impacts. Since AM seems to have further technology development, a future scenario has been also implemented by improving some process parameters.

Keywords: LCA, environmental sustainability, technology selection

1.Introduction

Additive Manufacturing (AM) includes all the technologies that build up the physical 3D part layer by layer starting from the CAD model. In the first years of the new century, these technologies were used for prototyping applications. Now, they represent, in some specific contexts, a valid alternative to conventional manufacturing processes, thanks to the improvement in production rate, components' quality and process control (Böckin and Tillman, 2019). Powder bed fusion (PBF) technologies are one of the AM categories; among them, Selective Laser Sintering (SLS) selectively consolidates the layers of powder-polymer material one on top of another through the thermal energy monitored by a computer-controlled laser beam (Ngo *et al.*, 2018). The AM is suitable for producing very complex components. Moreover, its advantages in terms of lead time and inventory cost reduction have been accepted by academic and practitioners (Yoon *et al.*, 2014, Rinaldi *et al.*, 2021). Nevertheless, it is worth to remember that another important aspect to be evaluated together with the operations performances in the industrial decision is the environmental impact. In fact, it becomes crucial when a new product is developed or when a new production technology is tested. Especially for AM, such assessment is very important since the energy consumption of AM processes can be up to 100 times greater than the traditional manufacturing technology (Yoon *et al.*, 2014).

In this paper SLS has been compared with injection moulding production through a Life Cycle Assessment (LCA) approach to understand and test the environmental performance of these two technologies. Although some studies already exist about this issue, very few papers carry out a comparative analysis between the two different near net shape technologies; thus, this paper tries to give a contribution of knowledge to this lack by varying the production volume and performances. The reminder of the paper is organised as follows: some studies about the problem are presented in section 2; section 3 explains the main steps of a LCA; section 4 deals with Life Cycle Inventory; section 5 presents the results of LCA. Finally, conclusions are presented in section 6.

2. Literature review

Since many years, the environmental performance of AM technologies has been explored using LCA. 3D printing has been compared to machining (Faludi *et al.*, 2015). Authors concluded AM is not a priori the greenest technology when compared to Computerized Numerical Control (CNC) machining. They demonstrated environmental impacts strictly results from usage profiles (machine utilization and idle time). Moreover, even if material wastes are less for AM, the study confirmed that machines' energy consumption could overwhelm savings. It is proved that Fused Deposition Modelling (FDM) provides better environmental performance than injection moulding (IM) and milling in producing small production volumes for parts realised in ABS P400 (Yoon *et al.*, 2014). Few studies focused on the part geometrical complexity and the light-weighting obtained by AM (Huang *et al.*, 2016 , Priarone *et al.*, 2018). In 2018 (Ingarao *et al.*, 2018), a full LCA was carried out to assess the environmental impact of SLS, machining and forming for aluminium alloy components. In such study, material losses and energy consumption during the pre-manufacturing step have been considered.

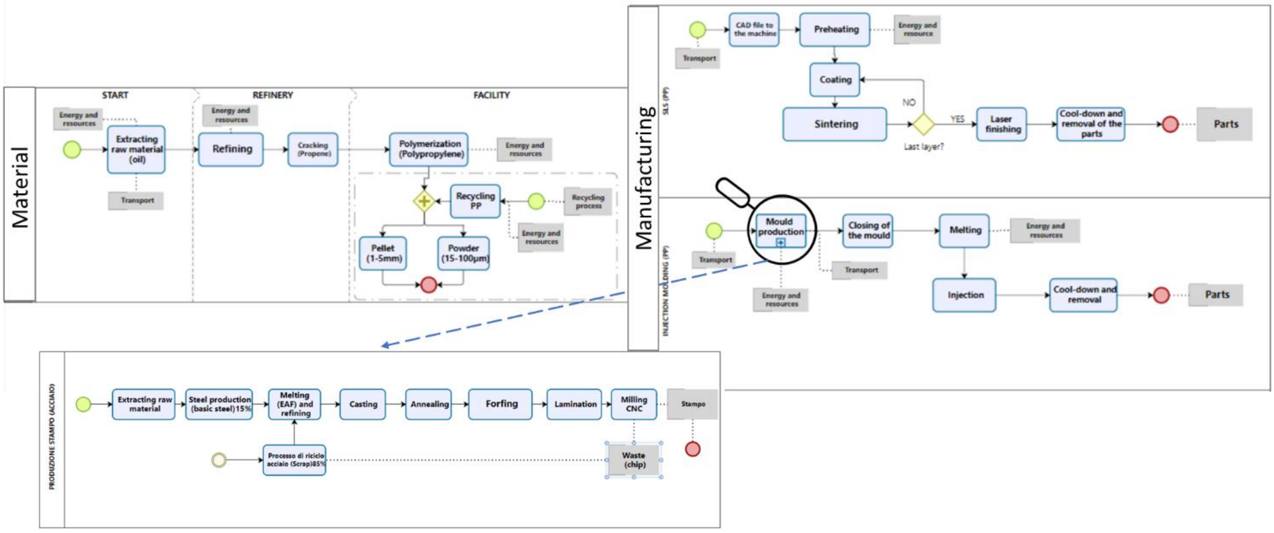

Figure 1: Cradle to gate lifespan for SLS and injection moulding

Authors used the solid-to-cavity ratio as geometrical feature to distinguish four types of products and, for each of them, the improvement of the environmental performance was highlighted. Milling process and the Electron Beam Melting (EBM) have been compared (Paris *et al.*, 2016); these technologies have been used to produce one single titanium alloy aeronautical turbine. A shape and complexity factor has been adopted to establish when a technology is more environmentally effective than another. LCA was used to find the most environmental-friendly process between Direct Energy Deposition (DED) and milling in producing gears (Liu *et al.*, 2018). Authors confirmed that environmental impacts are mostly linked to energy and material consumption. They affirmed more energy is quired in DED process due its high specific energy consumption. Injection moulding environmental performances were also compared to those of binder jetting in fabricating reactors by LCA (Raoufi *et al.*, 2020). This research showed the metal injection moulding process is less environmentally friendly than binder jetting for an annual production volume of 1000 units. Most of impacts depend on mould and solvent and decrease when production volume increase, while the most important environmental drivers for binder jetting are raw material and utilities. In general, these studies demonstrated that classical near net shape technologies have a higher environmental impact than the additive process **for** lower production volumes. The main interest of this work is to evaluate when AM is more eco-friendly than IM by considering a set of parts having different weight, volume and geometrical complexity.

3. Methodology: Life Cycle Assessment

Principles and guideline of LCA are fixed by ISO standard 14040-14044 (Finkbeiner *et al.*, 2006). According with EPA (United States Environmental Protection Agency), LCA is an analytical methodology for the "estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.)"(EPA, 2008). All LCA results are referred to a functional unit in order to compare the manufacturing approaches. The LCA must be performed following four main steps:

1. Goal definition and scoping (ISO 14040): products and processes are described, identifying the boundaries of the analysis and the environmental effects to assess.
2. Inventory analysis (ISO 14041): data about resources are collected (energy, raw material, etc. required by the system).
3. Impact assessment (ISO 14042): it evaluates the product or process impact on ecological and human health.
4. Interpretation (ISO 14043): it provides a clear and complete presentation of an LCA study.

3.1 Goal and scope

The goal is to compare the environmental performance of SLS and IM when components with different sizes and geometries are produced. The analysis in conducted by varying the batch size in order to verify the existence of break-even points (BEP). This information could be assumed as a guidelines for the sustainable manufacturing approach selection(Ingarao *et al.*, 2018).

3.2 Functional unit

The number of parts produced in a year has been chosen as the functional unit of the analysis, so all inputs and outputs are related to the total annual production of each component.

3.3 System boundaries

The boundaries determine the point from which the inventory analysis starts and the final section of the environmental analysis, that could be the factory's gate, the product end of life and disposal or recycling. A *cradle-to-gate* system boundary was adopted in this study. Such phase was performed applying the traditional principles of the Business Process Modelling (BPM) through the use of the tool Bizagi Modeler®. Thus, the system covers the components' life cycle from the raw material extraction until leave the factory. The BPM philosophy mainly puts in evidence the impacts of material and parts production, not neglecting the wastes. Hence, the process consists of two main phases: *material* and *manufacturing*. The outputs of the first phase are pellet and powder of polypropylene, which will be respectively processed by adopting IM and AM technologies. Almost all the activities require resources (electric energy, water, material, etc.). Focusing on SLS, the operating steps to obtain the end part are: (i) the preheating, (ii) the coating and (iii) the powder sintering, (iv)the laser finishing that has been chosen as finishing process. Concerning IM, it is worth to note that a sub-process was modelled for the mould production. Moreover, in such case, it is worth noting that most energy-intensive stages have been considered (e.g. closing and clamping of the mould, heat the feedstock, injection and eject part). Further details about this process cannot be within this paper due to its page number constraint. The third step of LCA could be conducted by adopting one or more methods (ReCiPe, Eco-indicator 99, cumulative energy demand, etc.). These methods distinguish themselves by the type of impact categories considered and the units of measure. This means that results may differ or give different information according with the method used.

4. Life cycle inventory

Life cycle inventory (LCI) is the core of the analysis because all relevant data about resources consumption are gathered during this phase. The LCI aims to quantify inputs material, energy, etc.) for each phase by capturing data from literature as well as using free or paid databases or consulting manufacturing practitioners. Starting from the database of an automotive company, data about components have been collected (Table 1).

Table 1: Components considered into the analysis (the blurred effect is added for copyright reasons)

Component		Volume [mm³]	Mass [g]	B.box [mm³]
	1	10972	11.52	71172
	2	430733	452.27	8335800
	3	4810	5.05	23560
	4	11429	12.00	37404
	5	10432	10.95	12243
	6	11647	12.23	400000

The components' bounding box (B.box) have been obtained by using the CAD software Rhinoceros®. The ecoinvent 3.7, that is a purchased database, has been adopted. As stated by Burham *et al.* (2020), the database *ecoinventv3.7 Apos lci* is able to provide the results for each process in a more aggregated form; for such reason, it has been adopted for the inventory analysis. Components are all made of polypropylene (PP) Polyfort 1006 (standard density 1.05 g/cm³). The 90% of the mass was recycled material, while the remaining 10% came from the primary production (Ecoinvent dataset *polypropylene, granulate, at plan, RER*). Data on the PP recycling process and PP powder production have also been found in Web (Franklin Associates, 2018) and scientific literature(Fang, Wang and Xu, 2019). Background data, i.e data about the auxiliary processes, such as recycling and transport, have been recovered as aggregated data sets from such databases. Other foreground data related to the main steps that were not found into the inventory database were found in the scientific literature(Morrow *et al.*, 2007; Kellens *et al.*, 2010; Yoon *et al.*, 2014). In this study it was assumed the production is centralised for both manufacturing processes. A mean distance of 200 km has been set between the petrochemical facility and the manufacturer where the production takes place. The distance between facilities could deeply influence the environmental impact; since this study focusses on manufacturing processes, the distance has been considered constant and is the same for both the manufacturing processes. In this way, the environmental impact depends only on the amount of transported material. Ecoinvent dataset "*transport, freight, lorry 3.5-7.5 metric ton, EURO5, RER*" has been used. Maintenance and auxiliaries (packaging, infrastructures, etc.) have not been considered since the study mainly focuses on materials and technologies. Moreover, it is really hard to find suitable data for an LCA with regard to these aspects.

4.1 SLS

Starting from the analysis of SLS, a waste of 12% of the mass has been considered (e.g., the mass of the component 2 was 513.94 g). The machine EOS P 396 has been chosen (*EOS*). It is a CO_2 laser machine, with a build chamber of 69360 cm³, and a power of 70 W. Two equations taken by literature (Luo *et al.*, 1999) were used to determine the process productivity (Pr), (Eq.1), and the energy consumption rate (ECR), (Eq.2).

$$Pr = V \times W \times T \times \rho \times 3600 \times k \quad \left[\frac{kg}{h}\right] \quad (Eq.1)$$

$$ECR = Power\ rate/Pr \quad \left[\frac{KWh}{kg}\right] \quad (Eq.2)$$

Where k is the process overhead coefficient that represent the machine efficiency and could vary from 0.6 and 0.9 (Luo *et al.*, 1999). The process parameters were set as indicated into the machine datasheet. The scanning speed (V) was set to 6000 mm/s. The road width size (W) was set to 0.4 mm. The layer thickness (T) considered for the production was 0.15 mm. By setting the process overhead coefficient (k) to 0.6, the Pr was 0.816 kg/h. To calculate the ECR, the minimum power rate of 2.1 kW was considered. Thus, the value of ECR was 2.57 kWh/kg. By multiplying this value for the material (mass) to be processed it is possible to derive the total electric energy consumption. The ecoinvent dataset "*market for electricity, low voltage – IT"* has been used to consider the Italian energy mix. Moreover, a future scenario (par.4.4) was also evaluated, where some process parameters have been improved.

4.2 Injection moulding

The PP material arrives to the manufacturer in form of pellet. In this case, the production process of the mould must be considered. Information about mould production were taken by literature (Morrow *et al.*, 2007), where the authors indicate the specific energy consumption (SEC) for the mould production in MJ/kg. The material chosen for the mould was the steel AISI H13 for its wide use. The bounding box of the part was used as a reference to obtain the needed amount of material to produce the mould. A volume 3 times greater than the part's bounding box has been considered for parts 2 and 6, while a multicavity mould (5 cavities for mould) has been consider for the smaller parts (1,3,4 and 5). Data about the SEC of IM machine have been found in literature (Thiriez and Gutowski, 2006)

5. Life cycle impact assessment

Once the inventory analysis has been completed, product systems have been created in OpenLCA ® for each process. Basically, the flow showed in Figure 1 has been translated as processes into the software. In this study, the ReCiPe Endpoint H (RIVM, 2017) has been considered for the impact assessment. First, it evaluates 18 impact categories, so called midpoint indicators, e.g. climate change human health impacts and fossil fuel depletion, and then arrange them in a set of 3 damage categories, so called endpoint indicators (Human health, Ecosystem quality end Resources). The method normalizes and weights these categories to give a single score in units of "points" that represent the annual environmental impact per person of an average European (Faludi *et al.*, 2015). The ReCiPe endpoint (H/A) and ReCiPe midpoint (H) have been used to compute and evaluate the environmental impact. ReCiPe has three different versions: *individualist*, *hierarchist* and *egalitarian* (RIVM, 2017). The *hierarchist* methodology has been chosen because it represents the default version and it is the most used in the scientific field(*ReCiPe*, 2016). In the section of contribution tree of OpenLCA®, it is possible to quantify the weight of every input in percentage. In Figure 2 the *contribution tree* to produce 10000 pieces of part 1 is shown both for SLS and IM. Energy consumption has clearly the higher weight in both cases. For SLS, this evidence would suggest the need to improve the energy efficiency of the process. The weight of energy consumption for IM is lower in percentage than those of AM. It is worth to note that the weight of the primary production of PP, although it is one-tenth of the total, is close to that of secondary production (recycling). The weight of the mould production increases when the number of produced components decrease (Figure 3). Since the lifecycle of a mould could be tens to hundreds of thousands of cycles, the mould production stage is probably the discriminant step for the selection of the most sustainable technology between AM and IM. Transport has a marginal weight in determining environmental impact in this case. Nevertheless, it could be crucial if manufacturing is not centralized and a distributed supply change is adopted.

5.1 The effect of production volume

The study aims to establish when AM is more eco-friendly than IM. For this reason, the results have been managed to make a comparison. The endpoint environmental impact was measured in points unit, that is a dimensionless measure of environmental impact (this index is as better as

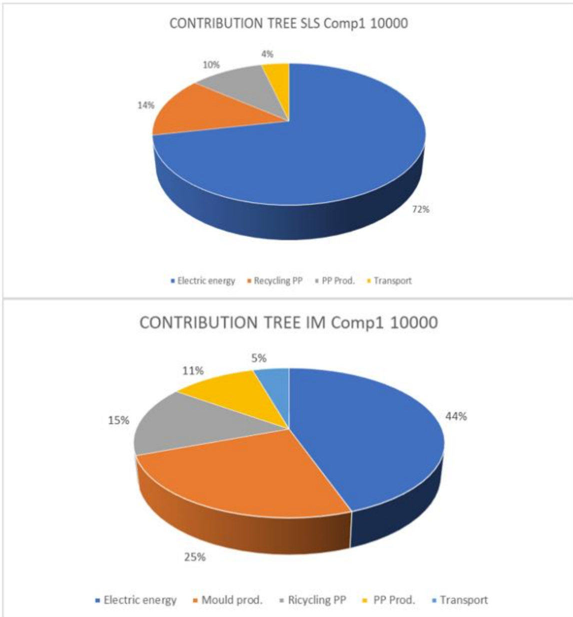

Figure 2: Contribution trees of component 1 for 10000 units produced

lower it is), and it has been calculated with different production volumes for each component. The values of impact are reported under the heading *total* in Figure 4. The results appear as shown in Figure 5 for both the analysed processes and for each scenario. Focusing on component 1 (11.52 g), SLS is no longer the most sustainable solution when the production volume is beyond 10000 units per year (Figure 6). A Break Even Point (BEP) of 11629 produced parts (50 points) was found to give the limit in term of environmental sustainability. For the part 2, that is the largest and heaviest component (452.27 g), SLS is the most sustainable solution up to a maximum of 3626. It is evident how much the volume and the mass of

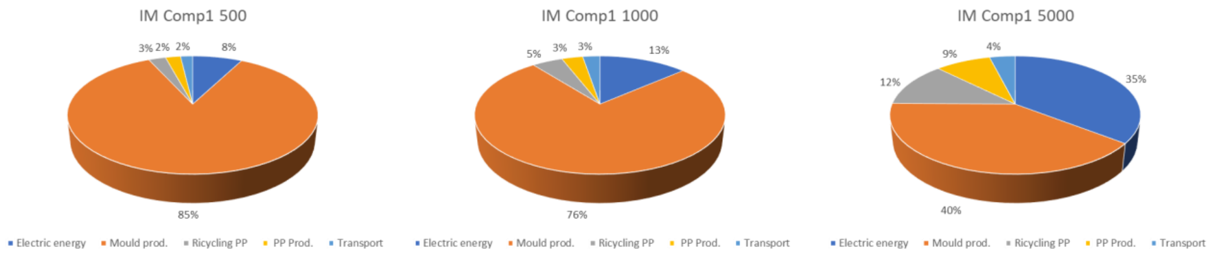

Figure 3: Contribution trees for IM of component 1 to varying the parts produced

Name	Category	Inventory res...	Impact factor	Impact result	Unit
ecosystem quality - urban land occupation				20.25689	points
ecosystem quality - natural land transformation				0.11351	points
human health - ionising radiation				0.00763	points
ecosystem quality - freshwater eutrophication				0.00563	points
resources - metal depletion				1.12493	points
human health - climate change, human health				5.68244	points
ecosystem quality - freshwater ecotoxicity				0.00203	points
human health - ozone depletion				0.00137	points
ecosystem quality - total				24.92636	points
resources - fossil depletion				10.33120	points
human health - particulate matter formation				1.26420	points
human health - photochemical oxidant formation				0.09419	points
ecosystem quality - climate change, ecosystems				3.59165	points
ecosystem quality - terrestrial ecotoxicity				0.01404	points
resources - total				11.45613	points
human health - human toxicity				0.71750	points
ecosystem quality - agricultural land occupation				0.93310	points
ecosystem quality - terrestrial acidification				0.00911	points
ecosystem quality - marine ecotoxicity				0.00041	points
human health - total				7.76733	points
total - total				44.14982	points

Figure 4: Impact result for component 1 and 10000 parts produced (openLCA)

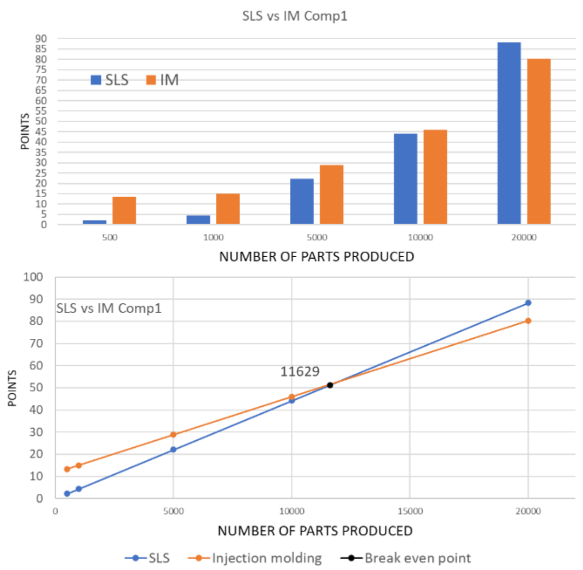

Figure 5: Comparison SLS and IM Endpoint environmental impact trend and BEP for the component 1

components influence the results. The mass of component 2 has an order of magnitude higher than component 1. This determines that the environmental impact has an order of magnitude grater too. Moreover, the BEP moves to a smaller number of components as the mass of the component increase. Figure 7 show the results for remaining components. Among all midpoint categories provide by ReCiPe midpoint, Global Warming Potential (climate change – GWP100) trend is shown in this study. GWP100 impacts are measured in kg CO2eq. In this case, the most relevant finding is that SLS always provides best results in terms of CO2eq emission compared to IM for all small components (1,3,4,5,6) in the scenario of 10000

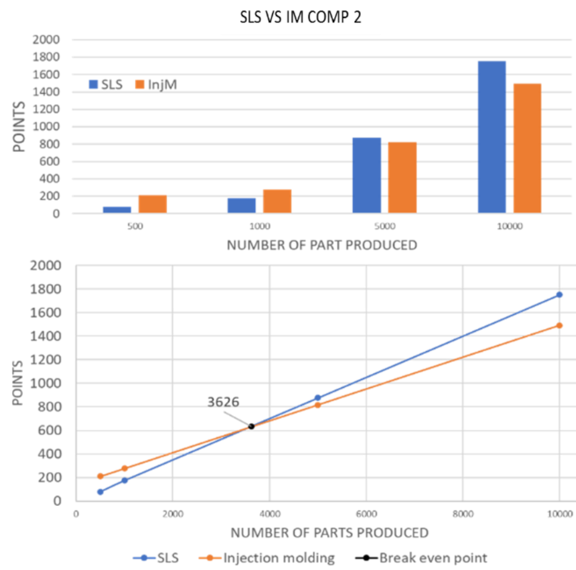

Figure 6: Comparison SLS and IM Endpoint environmental impact trend end BEP for the component 2

pieces per year (Figure 8). On the contrary, the trend changes for the component 2: in the scenario of 10000 units, SLS process involves a greater production of CO2eq than those produced by IM process.

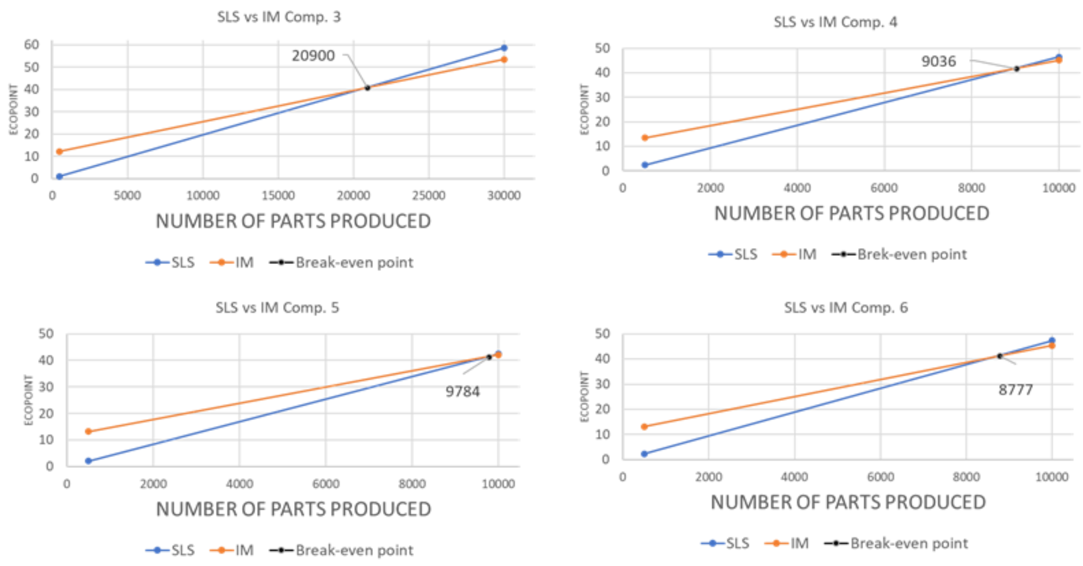

Figure 7: Endpoint environmental impact: BEP for components 3,4,5 and 6

5.2 Future scenario

After analysing the scenario with the current technologies feature, a future scenario (SLS+), characterized by improved SLS machine capabilities, has been analysed in order to assess if SLS could be environmentally favourable also for higher production volumes both from endpoint and midpoint perspectives Since the energy consumption has the highest weight in AM process, also for higher production volumes both for endpoint and midpoint perspectives process parameters that mainly influence this behaviour have been improved. Thus, an improvement of 20% has been set for the scanning speed, while the coefficient k was increased by 17%, from 0.6 to 0.7. As the scan speed increases, the process productivity increases by 40% and ECR decreases by 28.5%. The worst AM performance refers to component 2. In the future scenario these performances considerably improve. In fact, SLS+ seems to be more environmentally sustainable than IM even for 10000 units (Figure 9). Better results have been obtained also for GWP100: SLS+ involves a reduction of 25% of emission compared to SLS and of 15% as against IM. This aspect is very interesting; in fact, LCA is not just good to evaluate the environmental impact of a process, but also to identify the key steps to be improved to gain better performances.

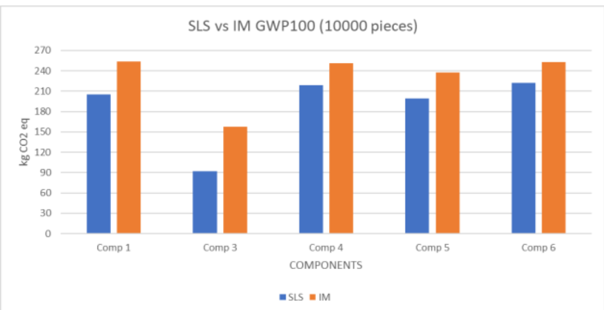

Figure 8: SLS vs IM: midpoint category GWP100

6. Conclusion

This study implements a LCA of two near net shape processes. First, the cradle to gate flow was modelled in order to identify the resource-intensive steps. Scientific literature and different databases have been used to carry out the inventory phase. The impact assessment has been evaluated by using ReCiPe method (endpoint and midpoint). It was confirmed the environmental impact proportionally rises with an increase of the processed mass; this research aims to show the possibility to identify BEPs in terms of environmental impacts.

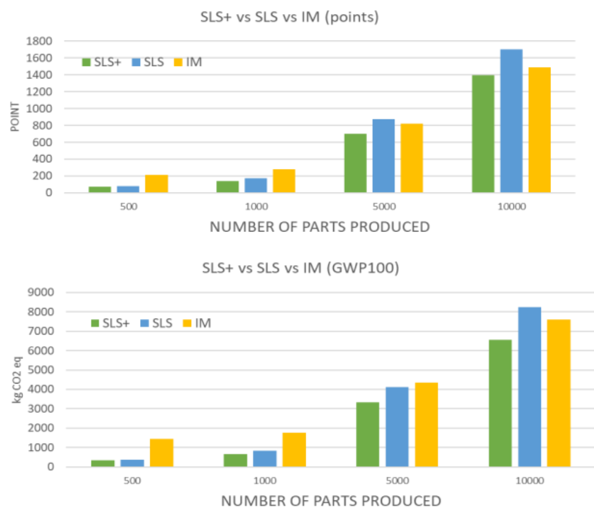

Figure 9: SLS future scenario vs SLS vs IM for the part 2

Hence, it was demonstrated that the BEP decreases when the mass of the component increases. Thus, the number of parts produced to reach the environmental break-even is lower when SLS and IM are compared in massive components productions. The midpoint analysis underlines that SLS is less impacting for the GWP100 when producing small parts. Since energy consumption was found to be the critical aspect, a future scenario has been implemented. The analysis conducted revealed that SLS could become competitive from an environmental point of view also for 5000 and 10000 units, while this is not true for the current scenario. Thus, this study demonstrated that an environmental based technology selection is possible when two alternative technologies are compared by using an LCA approach. Future research will show and discuss the environmental impacts at midpoint level for all categories considered by the ReCiPe method and, moreover, the study will deeply investigate the rule of part complexity and of the packing optimisation for AM processes.

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