Towards a Comparative Index Assessing Mechanical Performance, Material Consumption and Energy Requirements for Additive Manufactured Parts

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Abstract. The increasing use of Additive Manufacturing technologies and systems in several industrial sectors and their numerous applications turn the attention of scientists and investigators to studying and evaluating the environmental impacts of these processes. Additive Manufacturing generally allows for a reduction of raw material consumption and waste generation. On the other hand, the need for long processing times and the necessary thermal conditioning of the manufacturing chamber to avoid product defects, lead to a considerable amount of consumed energy per produced item. Energy consumption has been a primary concern of the research on the sustainability of Additive Manufacturing indeed. More recent studies extended the analysis through more complete evaluation methods such as the Life Cycle Assessment. This approach allows a detailed description of environmental impacts but is affected by some concerns about the need for an interpretation of the final results, which can be non-univocal. This fact is particularly critical when the assessment is intended to be used for comparison between alternative solutions.

In this study, a novel index is introduced including three main aspects: material consumption, energy requirements and mechanical performance. The proposed formulation makes the index immediately usable for comparing alternative solutions. Within the scope of this study, the index has been applied to one of the most widespread Additive Manufacturing processes, namely Fused Filament Fabrication. The presented case study demonstrates the suitability of the proposed method to compare and identify the optimal choice among alternative manufacturing scenarios.

Keywords: Additive Manufacturing · Fused Filament Fabrication · Energy Consumption · Life Cycle Assessment · Performance Index

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1 Introduction

Additive Manufacturing (AM), also known as 3D printing (3DP), is becoming increasingly important in modern industry. Although prototyping is still today one of the most widespread uses of AM, several applications for the production of end-use parts can be found in the industry. The role of these processes is expected to become even more crucial to the manufacturing of the future under the impulse of the Industry 4.0 paradigm [1]. Analysts forecast an expansion of the AM market with a Compound Annual Grow Rate of 21% from 2021 to 2028 [2]. This scenario makes the research on AM sustainability especially relevant. Specifically, it is necessary to provide users with adequate tools to predict and reduce the environmental impacts of these technologies.

Most of the research focused on the electrical performances of the process. This is because 3DP is generally characterized by long processing times, which determine a higher machine utilization and energy consumption if compared to traditional technologies [3]. Conversely, AM has generated an important expectation for material saving since it allows for designing lightweight parts and reducing waste [4].

Life Cycle Assessment (LCA) has been extensively adopted to quantify the Environmental Impacts (EIs) of 3DP processes. The most common application of these studies is to compare the impacts of AM with those of traditional processes [5].

LCA methods comprise indicators describing different aspects of the impact on the environment the results of the study consist of multiple indicators which cannot be directly aggregated. This poses serious issues when LCA is used for comparison purposes. Moreover, this method does not consider the effects of manufacturing strategies on part properties. This is the main limitation since in real industrial cases it is very important to know in advance the impact that the manufacture of a new product will have on obtaining the desired mechanical properties, seeking an intelligent solution that allows the use of materials and energy to be limited.

Several indicators inspired by the triple bottom line framework and related to environmental, economic and social performance were proposed. A literary review concerning sustainable performance indicators is presented in [6]. Nearly seventy indicators were considered with the aim to identify a strategy for selecting those indicators that are principle contributors to sustainability and to validate the proposed selection through a comparison to ten of the most widely used indicator sets and guidelines. All the considered indices do not take into account the mechanical properties of materials and manufactured parts.

A novel index named Consumption Performance Sustainability Index (CPSI) is presented here for the comparison of manufacturing solutions. This index is calculated through a very simple formulation including the most relevant aspects to process sustainability, namely energy and material consumption. In addition, the mechanical properties are included to provide the designer with information on the expected resistance of the manufactured part. Two different formulations of the index accounting for different mechanical properties are presented and compared in the following sections.

The CPSI is dimensionless so that different designs, materials and production processes can be compared more easily and it is not necessary to express it in particular units such as tons of equivalent CO_2 produced.

A direct comparison with other known indicators is outside the scope of the present work.

The proposed index is presented with an application to Fused Filament Fabrication (FFF), which is the most widespread AM process on the market. There is a large body of research on this process discussing the impact of this technology and the influence of process parameters on mechanical properties [7]. A complete review of this literature is beyond the scope of this study.

Tensile specimens with different infill orientations and densities have been manufactured through an industrial-grade FFF printer. In-line measurement of energy consumption was carried out during printing. Tensile tests allowed for measuring the mechanical properties of each infill strategy. The information collected was then used to calculate the index and compare the different solutions.

2 Methods

2.1 Consumption Performance Sustainability Index

In the general formulation, the CPSI can be expressed as in Eq. 1:

$$CPSI = I_{mat} \times I_{en} \times I_{pp} \times I_{mp} \times I_{\rho} \tag{1}$$

where I_{mat} accounts for material consumption, I_{en} accounts for energy consumption, I_{an} accounts for part performance, I_{mp} accounts for material performance and I ρ accounts for part density.

The material consumption index is defined in Eq. 2:

$$I_{mat} = \frac{m_{part}}{m_{tot}} \tag{2}$$

where m_{part} and m_{tot} are the mass of the part and the total consumed material, respectively. The difference between these two quantities is determined by the auxiliary material needed for printing. For example, several AM processes require support structures to print overhang geometries [8]. The amount of these support structures is strongly affected by the design and build orientation of the part.

As it can be seen in Eq. 2, I_{mat} is dimensionless. High values of this index mean a low amount of waste during the process, i.e. an efficient use of resources.

The energy consumption index is defined in Eq. 3:

$$I_{en} = \frac{m_{tot}}{E_p} \tag{3}$$

where Ep is the energy consumed for printing. This quantity can vary significantly depending on the AM process considered. Moreover, process parameters can drastically affect energy consumption [9].

I_{en} can also be seen as the inverse of the specific energy, i.e. the energy consumption per mass unit. Therefore, for a certain amount of processed material, higher values of I_{en} correspond to lower energy consumption. If using the International System of Units

(SI), the unit of measure of this index is s^2/m^2. Although this ratio is not dimensionless, its units will be offset by those of the material performance index.

The part performance index is calculated as in Eq. 4:

$$I_{pp} = \frac{P_{part}}{P_{mat}} \tag{4}$$

where P_{mat} and P_{part} are the mechanical property of the material and the 3D printed part, respectively, along the direction of the applied load. "P" can be Young's modulus or the Ultimate Tensile Strength (UTS) depending on which of these requirements is more relevant to the design. This index is strongly affected by the printing strategy and process parameters. Particularly, build orientation and hatching strategies can determine considerable differences between the mechanical properties of the base material and those of the manufactured parts.

The formulation of the material performance index I_{mp} is shown in Eq. 5:

$$I_{mp} = \frac{P_{mat}}{\rho_{mat}} \tag{5}$$

where ρ_{mat} is the density of the feedstock material. It can be seen that substituting Young's modulus and UTS in Eq. 5 leads to, respectively, the specific modulus and specific strength of the material [10]. These properties give important information on the material resistance with reference to its weight. This is important not only to reduce the amount of waste at the end of the product's life but also for applications where lightweight parts can reduce the impacts of use[11, 12]. Both calculated based on Young's modulus or UTS, the units of the material performance index are m^2/s^2 in the SI and compensate for those of the energy consumption index as stated previously.

The part density index is defined in Eq. 6:

$$I_{\rho} = \frac{\rho_{mat}}{\rho_{part}} \tag{6}$$

where ρ_{part} is the density of the manufactured part, i.e. the ratio between the part mass m_{part} and V_{model} the volume of the virtual model. I ρ can be expressed in Eq. 7:

$$I_{\rho} = \frac{V_{model}}{m_{part}} \rho_{mat} \tag{7}$$

A difference between ρ_{mat} and ρ_{part} may be due to the non-complete filling of the part, which may be intentional, in case of hatching densities lower than 100%, or due to porosities induced by the manufacturing process [13]. This index is dimensionless.

The final formulation of the CPSI can be obtained by substituting Eqs. 2 to 7 in Eq. 1. The final formulation differs based on whether Young's modulus or UTS are considered for design; the corresponding indices $CPSI_Y$ and CPSI σ are given, respectively, in Eq. 8 and Eq. 9:

$$CPSI_Y = \frac{m_{part}}{m_{tot}} \times \frac{m_{tot}}{E_p} \times \frac{Y_{part}}{Y_{mat}} \times \frac{Y_{mat}}{\rho_{mat}} \times \frac{V_{model}}{m_{part}} \rho_{mat} = \frac{Y_{part}}{e_p} \tag{8}$$

$$CPSI_{\sigma} = \frac{m_{part}}{m_{tot}} \times \frac{m_{tot}}{E_p} \times \frac{UTS_{part}}{UTS_{mat}} \times \frac{UTS_{mat}}{\rho_{mat}} \times \frac{V_{model}}{m_{part}} \rho_{mat} = \frac{UTS_{part}}{e_p} \quad (9)$$

where $e_p = E_p/V_{model}$ is the consumed energy per unit of volume of the model.

As it can be noticed, the formulation in Eqs. 8 and 9 allows for the calculation of the CPSI with a limited amount of information. This is a key point to facilitate the adoption of the index for decision-making in real industrial cases, enhancing the sustainability of the results.

2.2 Experimental Methods

The CPSI was applied to parts manufactured by FFF for validation. Specifically, a set of tensile specimens designed as in ASTM D638–14 type I standard was used for the characterization of mechanical properties. V_{model} is then equal to 22067 mm^3. The specimens were manufactured with different combinations of infill density and orientation. Specifically, a full-factorial Design of Experiment (DOE) was carried out using three levels of infill density (namely 100%, 90% and 80%) and three directions of hatching lines, i.e. 0°, 90° and ± 45° to the load direction. Three repetitions of each specimen were tested. All the specimens were printed with a Fortus 250 by Stratasys® using ABS SR30 for parts and ABS P430 for support structures. A T14 nozzle with a 0.356 mm diameter was used for the process. The energy consumed by the printer was acquired through an ElNet Energy and Powermeter with serial and TPC/IP interface ports allowing direct interface with a PC. The specimens were tested with a universal testing machine Instron 3382 equipped with a long travel 2603–080 extensometer.

3 Results and Discussions

3.1 Experimental Results

Table 1 reports the measured data of the manufactured specimens, where t_b is the building time and the other variables are as previously defined.

In Fig. 1 UTS values versus part mass are shown. It can be seen that the highest strength is observed in specimens oriented at 0°, i.e. when the material is deposited along the load direction, being in good agreement with existing studies on the anisotropy of FFF parts. It can also be observed in Fig. 1 that the UTS of parts linearly decreases with density in the case of 0° orientation, while a drastic reduction is observed moving from 100% to 90% in the case of 90° due to that when tracks are not adjacent, the filament is not able to transmit the stress along the direction of the load. On the other hand, the printing time varies significantly with the infill strategy, as can be observed in Table 1. Specifically, the specimens oriented at 0° require less time than others due to the lower number of direction changes required by this path. Remarkably, the energy consumption is almost linearly proportional to the building time, as can be seen in Fig. 2, suggesting that the main source of energy consumption is the heating system.

In fact, during printing, the build chamber is maintained at 76 °C to ensure the quality of manufactured parts. Therefore, the energy required to maintain these temperatures appears to be the main contribution to the overall energy consumption of this technology. This result is consistent with the findings of previous studies [14].

Table 1. Measured data

Density (%)	Orientation (°)	Ep (Wh)	m_{part} (g)	tb (s)	UTSpart (MPa)	Y_{part} (MPa)
100	0	398 ± 17.8	18.4 ± 0.1	2552.7 ± 0.6	34.7 ± 0.6	743.7 ± 45.5
90	0	378.7 ± 6	16.6 ± 0.1	2396.7 ± 0.6	30.8 ± 0.4	692.1 ± 31.7
80	0	338 ± 19.1	15.3 ± 0.1	2225.7 ± 0.6	27.5 ± 0.5	673.7 ± 35.8
100	90	589 ± 21.8	18.6 ± 0	4027.3 ± 34.9	27.8 ± 1.1	728 ± 48
90	90	544.3 ± 7.2	16.9 ± 0.2	3699 ± 1	10.6 ± 1	471.3 ± 30
80	90	503 ± 11.8	15.4 ± 0	3353.3 ± 0.6	9.7 ± 0.3	287.9 ± 8.5
100	± 45	546.7 ± 9.3	18.5 ± 0.1	3697.7 ± 0.6	31 ± 0.9	638.1 ± 28.2
90	± 45	514.3 ± 2.1	16.9 ± 0.1	3391.3 ± 0.6	22.2 ± 1	538 ± 14.1
80	± 45	459.7 ± 22	15.3 ± 0.1	3101 ± 0	18 ± 0.5	381.1 ± 10.3

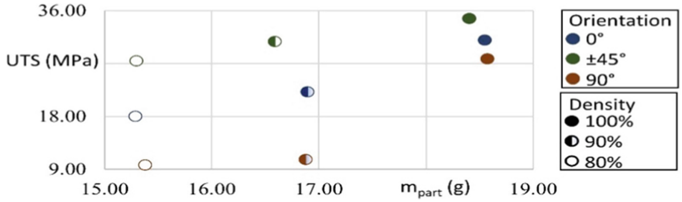

Fig. 1. Ultimate tensile strength versus part mass

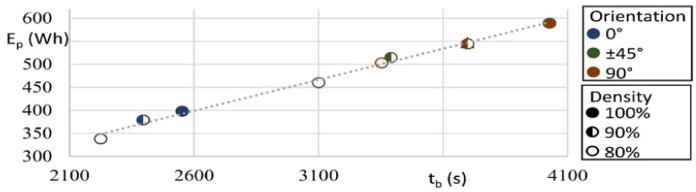

Fig. 2. Energy consumption versus printing time of parts

3.2 Consumption Performance Sustainability Index Calculation

The $CPSI_Y$ and CPSY σ indices of different specimens are plotted in Fig. 3a and Fig. 3b, respectively. Notice the difference between the CPSI values calculated using Young Modulus and UTS. Figure 3 shows that the solution with infill oriented at 0° appears to be preferable in both analyses. This is consistent with the results of Table 1, which show that this orientation allows for minimising building time and energy consumption while maximizing mechanical performance. Interestingly, the highest value of CPSI corresponds to different solutions whether Young's modulus or UTS are considered. Specifically, the solution with 80% infill density and 0° orientation is preferred in the case of Young's modulus. This finding suggests that, as far as this orientation is concerned, the improvement in stiffness achievable by maximising the infill density is less relevant than the impact on energy consumption. The solution at 100% is still slightly preferable to that at 90%. On the other hand, the maximum CPSI σ is achieved at 100% density and 0° orientation. In other words, the increase in strength justifies a higher energy consumption.

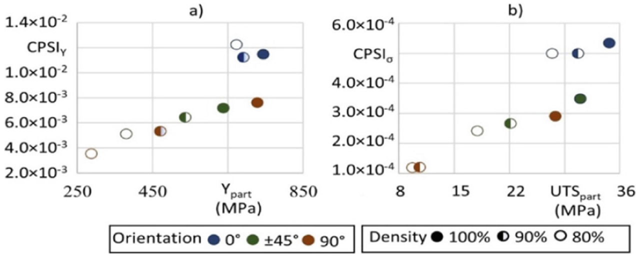

Fig. 3. Consumption performance sustainability obtained considering a) Young's modulus and b) Ultimate tensile strength

When considering other orientations, it is possible to notice that solutions at higher densities appear to be always preferable. This can be explained if considering the sharp drop in mechanical properties reported in Table 1. On the other hand, $CPSI_Y$ is higher for full specimens oriented at 90° than for those at ± 45°. This is consistent with the higher stiffness of these specimens. An opposite ranking is observed for CPSI σ. This index drops for specimens oriented at 90° with infill densities lower than 100%, which exhibit poor mechanical properties in the face of high energy consumption.

4 Conclusions

This paper presented a novel index named CPSI to compare different solutions in AM processes. This index aims at combining the environmental impacts of the process and mechanical properties of the manufactured parts. CPSI is dimensionless in order to allow for the comparison of different solutions.

The index has been obtained by multiplying coefficients accounting for different properties of the material, geometry and process. The formulation of the index allows for the simplification of numerous terms, which leads to a simplified formula. This means that the CPSI can be calculated with a limited amount of data, which eases the adoption to drive decision-making in real industrial cases.

The effectiveness of the index has been verified in a real 3D printing process. Specifically, a set of specimens for tensile tests has been printed on an industrial-grade FFF machine acquiring the energy consumption during the process. The results demonstrated that the index allows for the identification of the solution with the best compromise between mechanical performance and resource consumption. It has been shown that the preferable solution changes depending on which mechanical property is considered during design. This is due to the high influence of deposition strategies on the performance of manufactured parts in this process.

Overall, the index appears to be an easy-to-use and effective way to compare different manufacturing scenarios or part designs. Therefore, the adoption of this index is expected to foster the reduction of impacts in AM applications. In addition, we are planning further activities to extend the use of the proposed index to other manufacturing processes with particular attention to other AM processes.

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