Fused deposition modelling process environmental performance through the carbon footprint evaluation

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Abstract: Additive manufacturing (AM) is a free-form build process in which an object is created adding multiple layers. AM process is characterized by on-demand freeform part manufacturing with multiple materials and not for big production batches. There are different types of additive technologies that are capable of building pieces in diverse materials. For this study, various types of materials were tested in a fused deposition modeling (FDM) process using a standard workpiece and the build process was simulated in CURA software. The aim is to show the variability of the energy and the CO2 equivalent emissions produced in FDM manufacturing technology depending on the material used, specimen orientation, and the production batches. Variability in the material choice and the orientation of the piece was found for the environmental performance.

Keywords: Fused deposition modelling, Carbon footprint, Environmental feasibility, Additive manufacturing

1. Introduction
Additive manufacturing (AM) is a build process that, from a computer-aided design, creates an object adding multiple layers from diverse types of materials including powder, molten plastic, and others.

Fused deposition modeling (FDM) uses filament form material and melts it to build an object layer by layer. The customization, design freedom, and cost of this AM technology are engaging manufacturers in the aerospace, automotive sector, and AM enthusiasts. Low-cost FDM printers and customization freedom are making this AM technology accessible for small batches [1].

There are several additive manufacturing (AM) technologies that use different forms of plastic polymers as raw materials [2]. FDM technology is capable of handle diverse types of materials such as amorphous, crystalline, and semicrystalline materials, with different performances (figure 1).

In traditional plastic manufacturing processes such as injection molding, the type of plastic influences energy performance, thus impacting the environment [4]. AM, specifically FDM, in which plastic filament is used as raw material, does not escape this reality. Other authors analyze the energy performance in AM processes through various dimensions. For example, Tao Peng [5] performed an energy model for FDM printing from a life cycle perspective. Ruoyu Song et al. [6] performed an FDM energy loss analysis due to human and machine error. Tagliaferri et al. [7] analyzes diverse AM
technologies that were compared from economic and environmental dimensions. Besides, to compare AM technologies PA12 was used to build the same pieces in the processes selected.

![Figure 1. Types of materials and performance for the FDM process, adapted from [3].](image)

Finally, Li Yi et al. [8] developed an AM eco-design framework based on an energy performance assessment. For the present study, a standard workpiece and its build process were simulated in CURA software to evaluate the energy performance and the main sources of greenhouse gases in the FDM process. The geometry selected for this work is standard [9] compared to [7,10] research. It is a type 1 tensile test specimen used to measure the tensile properties of plastics. Various scenarios were analyzed considering diverse parameters. Multiple materials were selected, diverse printing speed, and specimen orientation on the build plate were simulated for energy and environmental performance on a desktop FDM 3D printer. Primary energy was calculated based on Li Yi et al. energy performance assessment [8]. After obtaining the equivalent CO2 emissions, they were compared with the results obtained by [7]. Tagliaferri et al. [7] carried out an environmental assessment based on the eco-indicator 99 method to compare different AM technologies (FDM, SLS, and MJF). This study aims to show the variability of the emissions produced in FDM manufacturing technology depending on the build material, specimen orientation, and production batches. To reach this goal the research is structured into four sections. Firstly, an introduction related to the FDM process and the identified problem. Secondly, the methodology used to reach the data that will be analyzed. Thirdly, the results of the study are described and finally, the discussion and conclusion of the study.

2. Materials and methods
The selected FDM printer is an Ultimaker S5 3D printer. Ultimaker S5 is a popular desktop 3D printer with a low maintenance cost, two nozzles, and heated build plate. Five types of plastic materials were selected (table 1) and their printing was simulated using Cura software. Cura is an open-source slicing engine for FDM machines in which can be set up printing parameters. The printer is capable of 3D print any of the materials selected and the Cura software provides estimations for printing time and build material consumed.

The filament materials were selected due to printing difficulty, build features, and materials applications.

A single nozzle of 0.4 mm was used for the FDM printer selected. The geometry is a specimen type 1 used for the test for tensile properties of plastics according to the standard ASTM D638-14 [11]. The specimen was placed in three orientations, one with the major surface area resting on the bed called “A”, the other with the lateral surface area resting on the bed called “B”, and the last one with the smallest surface area resting on the bed called “C” (figure 2).
Table 1. Selected materials, printing characteristics, and difficulty.

| Material | Printing difficulty | Melting point (K) \(^{a}\) | Build plate temperature (K) \(^{a}\) | Latent heat (kJ/kg) | Specific heat capacity (kJ/kgK) \(^{a}\) |
|----------|---------------------|-----------------------------|-------------------------------|-------------------|---------------------------------|
| PLA      | Low                 | 433                         | 333                           | 29.1              | 1.8                             |
| PETG     | Low                 | 513                         | 333                           | 9.4               | 1.2                             |
| ABS      | Medium              | 473                         | 358                           | 207               | 1.2                             |
| TPU      | High                | 490                         | 333                           | 46.1              | 1.2                             |
| PP       | High                | 433                         | 358                           | 165               | 1.8                             |

\(^{a}\) Data from the material datasheet

Figure 2. (a) Specimen in printing orientation A. (b) Specimen in printing orientation B. (c) Specimen in printing orientation C.

In table 2 the printing speeds selected among the ranges provided by the seller specifications.

Table 2. Printing speed selected for each material.

| Material | 0.03 m/s | 0.045 m/s | 0.06 m/s | 0.09 m/s |
|----------|----------|-----------|----------|----------|
| PLA      | x        | x         |          | x        |
| PETG     |          | x         |          | x        |
| ABS      | x        | x         |          |          |
| TPU      | x        | x         |          |          |
| PP       | x        | x         |          |          |

To simulate the printing environment and for the sake of consistency, an environment temperature of 298 K was assumed, and the printed specimens were positioned in the middle of the bed. All the specimens were simulated in Cura following the material datasheet of the seller such as layer thickness, extrusion temperature, and printing speed. For a deeper analysis, various printing speed scenarios were selected based on the range provided by the seller in which the material could be extruded. No build plate adhesion was used to just consider the build material only for the specimen.

To obtain the energy consumption in FDM technology, the energy consumption formula was adapted from [12]. For the calculation of greenhouse gases, we rely on [8] and [13] which are based on the estimation of the equivalent energy from an AM process to obtain the CO\(_2\) equivalent kilograms.

For the energy consumption by an FDM printer, the equation (1) is used:
\[ E_{FDM} = E_{thermal} + E_{motion} + E_{pre-heating} + E_{cooling} \quad (1) \]

\( E_{thermal} \) is the energy necessary to melt plastic filament and heat the bed in the FDM printer. Accordingly, to the energy conservation principle, the thermal energy could be calculated in equation (2).

\[ E_{thermal} = c_{filament} m_{specimen} \Delta T + m_{specimen} x + c_{Al} m_{Al} \Delta T \quad (2) \]

In which, \( c_{filament} \) is the specific heat capacity of the filament material PLA, PETG, ABS, TPU, and PP (Table 1). The \( c_{Al} \) is the specific heat capacity for the aluminum build plate with a value of 0.9 kJ/kgK. The \( m_{specimen} \) is the mass of the specimen which depends on the material density and the specimen volume. The \( m_{Al} \) is the mass of the build plate (1.2 kg), \( x \) is the latent heat of the material (Table 1), and the \( \Delta T \) is the difference between the desired printing temperature and the environment temperature assumed in 298 K.

\( E_{motion} \) is the energy invested in the extruder and motor motion in the x, y, and z axes expressed in equation (3). The energy consumed during the standby time was also considered due to its effect in the transition between batches and impact in the energy profile according to [14–16].

\[ E_{motion} = P_{standby} t_{standby} + P_{in motion} t_{build} \frac{v}{v_{t build}} \quad (3) \]

In which, \( P_{standby} \) is the power consumed in standby mode and \( t_{standby} \) is the time in standby mode. \( P_{in motion} \) is the sum of the extruder and the x, y, and z motor motion power. Based on [17] the specific energy consumption is calculated using \( t_{build} \) for the construction time of the specimen, \( v \) for the volume of the specimen, and \( v \) for the volumetric flow of the extruded filament \( \left( \frac{m^3}{s} \right) \).

\( E_{pre-heating} \) and \( E_{cooling} \) are the energy utilized to preheat and cool down the material. The time and temperature invested in preheating compared to the printing time and temperature are minimal. In this study, the preheated energy was not considered. Although, energy used for cooling the material is considered as in [18] and is assumed that represents 15% of the total power consumed in the build process.

After obtaining the energy performance of the material and the FDM printer, an adaptation in the formulation from [8,13] to reach the kilograms of CO₂ equivalent is presented in equation (4).

\[ C_{FDM} = \beta_{material} m_{material} + \beta_{elect}(E_{FDM} + E_{finishing}) \quad (4) \]

Where \( \beta_{material} \) represents the CO₂ kilograms to produce one kilogram of raw material and the \( \beta_{elect} \) represents the CO₂ kilograms produced for every joule of electricity available for the FDM process. \( \beta_{material} \) and \( \beta_{elect} \) were obtained from [19]. The \( E_{finishing} \) is the energy invested in the post-process activities assumed in 250W based on tool mean power and time spend on post-processing activities [20].

3. Results and discussion

From the energy performance perspective, the materials selected were compared by specimen orientation on the build plate. The energy performance varies by the printing material (figure 3) the acrylonitrile butadiene styrene (ABS) and the polypropylene (PP) have the highest values. Specimens in orientation C have a comparable worst energy performance than in orientations A and B.

On one hand, the PP and ABS have the highest values in energy performance 61.7kJ and 62.7kJ respectively, compared to thermoplastic polyurethane (TPU) that has the smallest values (35.3 kJ). Figure 3b shows how the changes in printing speed and specimen orientation vary the energy performance. The worse energy consumption was performed by the ABS material, in orientation C with the slowest print speed of 0.03 m/s. Besides, the energy performance from the TPU is 59% of the ABS in the same printing orientation C and speed 0.03 m/s. The energy performance for the polylactic acid (PLA) is 62.9% of the PP in 0.03 m/s printing speed and C specimen orientation. The PLA energy performance is similar to polyethylene terephthalate glycol-modified (PETG) and is between 35 and 36kJ in 0.09 m/s printing speed (table 3).
One of the main sources of CO2 emissions in FDM is the energy consumed in the printing process. Thus, the kg of CO2 equivalent corresponds to the energy performance (figure 4). There is a representative value change in equivalent grams of CO2 between the printed specimen in C orientation and the other two orientations (figure 4).

For this study, three build orientations were considered A, B, and C. Printing time by mean was affected through the build orientation (figure 5).

Among the variables considered in this study, printing time elevates de grams of CO2 emission through the energy consumption due to the continuous operation of the FDM machine.

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**Table 3.** Calculated $E_{FDM}$ by printing speed and specimen orientation.

| Speed ($\frac{m}{s}$) | Orientation | PLA  | PETG | ABS  | TPU  | PP  |
|------------------------|-------------|------|------|------|------|-----|
| A B C                  | A B C       | A B C| A B C| A B C| A B C| A B C|
| 0.03                   | 35.7 35.9 38.8 | 59.8 60.0 62.7 | 35.7 35.8 37.0 | 60.0 60.4 61.7 |
| 0.045                  | 35.4 35.5 37.3 | 59.4 59.6 61.5 | 35.3 35.4 36.6 | 59.6 59.9 61.7 |
| 0.06                   | 35.2 36.4 36.7 | 59.2 59.2 60.9 |

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Figure 3. (a) Materials energy performance comparison. (b) Max $E_{FDM}$ by material and printing orientation.
Figure 4. (a) Grams of CO$_2$ equivalent by speed and printing orientation for ABS. (b) Grams of CO$_2$ equivalent by speed and printing orientation for PP. (c) Grams of CO$_2$ equivalent by speed and printing orientation for PLA. (d) Grams of CO$_2$ equivalent by speed and printing orientation for PETG. (e) Grams of CO$_2$ equivalent by speed and printing orientation for TPU.

Figure 5. Mean printing time between specimen orientation.
4. Conclusions

The energy performance in every process is one of the most important factors concerning the CO₂ emissions estimation. This study aimed to report the variability of the emissions produced in FDM manufacturing technology depending on the material used. Diverse scenarios were analysed to compare the effect on the CO₂ emissions produced by using different printing speed and specimen orientations.

Based on the results, it could be concluded that the energy necessary to build any workpiece really changes depending on the part orientation, printing speed, and material. The thermal energy represents at least 90% of the energy used in the FDM process, which means it is the principal source of CO₂ equivalent emissions. According to the results, in the FDM process the CO₂ equivalent emissions vary on the printing time and part orientation. For both parameters, CO₂ emissions could be reduced by increasing the printing speed to the maximum allowable according to the material specification. On the other hand, one of the main sources of energy consumption is the latent heat, necessary to change material physical state, this depends entirely to the material selection. These results go beyond other author's reports. The energy not directly associated to the printing process, such as the post-process, depends on the customer and the post-process selected, which could be assessed in further studies.

Furthermore, the comparison of the production capacity of FDM technology against those already mentioned [7] places it at a disadvantage for multiple production series. However, this is not the main advantage of the technology; FDM technology offers greater freedom in the selection of material for small to medium batches compared to powder sintering technologies.

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