The International Journal of Advanced Manufacturing Technology (2023) 127:2911–2920
https://doi.org/10.1007/s00170-023-11646-0

ORIGINAL ARTICLE

An empirical method for forecasting energy consumption in material extrusion

Mariangela Quarto[1]

Received: 9 January 2023 / Accepted: 22 May 2023 / Published online: 9 June 2023

Abstract
Additive manufacturing (AM) is one of the most sustainable manufacturing processes since it could build parts directly from a computer-aided design (CAD) model simplifying the production of complex geometries, and they are generally more environmentally friendly using only the exact amount of material. Despite this qualitative consideration, the quantitative convenience in terms of energy consumption has not yet been extensively investigated. In the present paper, a model is proposed to improve understanding of AM energy use by applying a novel classification system for machine components, generating, as a result, the characteristic parameters specific for each material and useful for estimating energy consumption providing a simple tool for the companies that would evaluate the technology convenience considering also the energetical component. The main outcome is represented by the characteristics parameters for the main materials used in the material extrusion process and an approach for evaluating the energy consumption a priori with a prevision error of less than 10%.

Keywords Additive manufacturing · Material extrusion · MEX · Energy efficiency · Energy consumption prediction

1 Introduction

The main part of the industrial sector is represented by manufacturing, which plays a fundamental role in the global economy by converting, through different physical mechanisms, raw materials into products, wastes, and emissions [1]. The energy required for manufacturing activities is an input of the process, and it is partly transformed into useful work and partly transformed into waste and lost heat. In particular, only a fraction of the consumed energy is actually used for value-added activities, while the greater part of it is spent for ensuring stable process conditions and supporting peripheral functions [2]. A greater part of the necessary energy is electrical, and it is mostly produced by burning fossil fuels which generates carbon footprints [3, 4] that can be linked to the CO_2 emissions through the Carbon Emission Signature (CES, Jeswiet and Kara, 2008). The manufacturing sector is historically one of the greatest energy consumers and carbon emitters in the world: it is responsible for about 33% of the primary energy use, and 38% of the CO_2 global emissions (“IEA (2021), Energy Efficiency Indicators: Overview, IEA, Paris”). Adding to these aspects, the current trend of sustainability, and the continuous increase of the price of energy, manufacturing enterprises result to be under pressure for reducing energy consumption to strongly limit both the CO_2 emissions [5] and the costs linked to production [6]. Energy savings and sustainable manufacturing are expected to be achieved by increasing both the energy efficiency of the production and the logistic processes, as the companies head forward producing “more with less” with innovative energy monitoring and management approaches [2, 7].

Several researches aim to a potential reduction in the carbon footprint of manufacturing activity through the adoption of additive manufacturing (AM) technologies; among these is the ATKINS project [8–11], collaborative research and industry partners project [12, 13]. Additive manufacturing is an important and relatively new group of manufacturing processes defined by ISO/ASTM 52900:2021 as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and or formative manufacturing methodologies.” AM processes are an evolution of a group of technologies focused on rapid prototyping; this group of technologies has

✉ Mariangela Quarto
mariangela.quarto@unibg.it

[1] Department of Management, Information and Production Engineering, University of Bergamo, Via Pasubio 7/B, 24044 Dalmine, BG, Italy

drawn increasing attention from the industrial world since it can provide a certain advantage in different areas [14, 15]. First of all, AM provides the capability of freeform fabrication: it removes traditional manufacturing restrictions and provides design freedom for innovative products [16–18]. Furthermore, AM can shorten the supply chain of fabrication and enhance the profit space for manufacturers [19, 20]. Despite all these advantages, there are also some limitations associated with the AM. Firstly, it is characterized by a low productivity rate. Secondly, the achievable dimensional accuracy and the surface quality are limited; indeed, numerous studies are underway to optimize the design of the parts and improve the repeatability of the process [21–23]. Thirdly, AM is unable to reduce production costs by applying economies of scale because the unit production cost is high for medium–high volume [24]. AM technologies provide a huge potential to reduce the environmental impact if compared to traditional manufacturing techniques [25–27]. The ability of AM to build parts directly from a computer-aided design (CAD) model with only one manufacturing step makes it an excellent alternative compared to conventional manufacturing processes [28]. These technologies can simplify the production of complex parts, and some AM processes are also able to repair and remanufacture tooling, in order to eliminate the supply chain operation of materials. Those manufacturing processes are generally more environmentally friendly because they only use the exact amount of material necessary for producing the required parts [29]. Other environmental advantages can be found in the reduction of extracting raw materials and their transportation. Despite these qualitative considerations, what is unclear so far is how to calculate the actual energy consumption occurring during the printing process; in fact, only by investigating this aspect, it is possible to understand how convenient AM processes are from an energetic point of view compared to traditional processes [30, 31]. Traditionally, energy efficiency in additive manufacturing is considered very low. Because of these promising characteristics, a lot of research has been conducted on the aspects of process control, simulation, and modelling. On the contrary, research aimed at the energy demand of AM technologies is very limited [32, 33].

The present paper proposes a novel methodology for assessing the energy consumption of material extrusion (MEX) processes. The methodology involves the measurement and analysis of the energy consumption of the MEX process using a sensor and software tools. The developed model calculates the energy consumption of AM processes, involving a novel classification system for power consumption related to the stages of the process. This approach provides a global view of the manufacturing process, while also allowing for a local analysis of different stages of production.

The methodology is divided into several steps, including identifying different stages and measuring absorbed power. The power measurement is repeated to obtain reliable data. The printing time is evaluated using open-source slicing software. The collected and calculated data are processed to define the power absorption behaviour of the process and create a predictive model of energy consumption for parts with different geometries. Finally, the model is validated through a comparison between estimated and measured data for different printed parts. The validation of the method is demonstrated through experiments conducted on a 3D printer showing that the proposed methodology can provide an accurate and reliable estimation of energy consumption during MEX processes.

Furthermore, the text discusses the validation of the proposed methodology for assessing energy consumption in MEX processes for materials other than PLA. Four additional materials, including two polymers (ABS and polycarbonate) and two metals (filaments with stainless steel 316L and 17-4PH powder), were tested to demonstrate the model robustness. The data collected during preliminary tests showed that higher temperatures of the build plate and nozzle correspond to longer heating phases but the same values of absorbed power. The analysis of the data generated a summary table that defines the characteristic parameters of each selected filament, including the absorbed power in the printing phase. The developed model and the tests carried out on different materials allow for estimating the energy necessary for printing specific products, providing a simple tool for forecasting consumption that could help in evaluating the convenience of the process.

To the best author's knowledge, there is no previous paper developing a model able to define characteristic parameters. For example, in [26], the energy consumption of different additive manufacturing processes was analysed by considering material extrusion, stereolithography, and selective laser sintering. The authors measured the energy consumption of each process during different stages of production founding that energy consumption varied significantly depending on the process used and the stage of production. This work concluded that the energy consumption of each process was influenced by factors such as the size of the object being printed and the layer thickness suggesting improvement related to the geometry/characteristics of the part or to the printing parameters.

For this reason, the present paper allows us to take a step forward in the definition of methodologies for predicting and increasing the sustainability of additive processes. It is characterized by two main novelty points. Firstly, a combination of a global view of the manufacturing process with a local analysis of different stages of production is considered. This means that the manufacturing process is not divided into different features, such as the nozzle or plate motor, but rather into different manufacturing stages. This simplifies the decomposition and identification of the necessary information. Secondly, the model allows estimating characteristic parameters useful for calculating the energy consumption for a printing process. This estimation can be achieved simply by knowing the used material and the geometry of the part. This model can also be easily adapted for other AM technologies. Overall, this research contributes to a better understanding of the energy consumption of AM processes and provides valuable information for improving the sustainability of these processes.

2 Methodology

The proposed methodology for assessing the energy consumption in the MEX process is divided into several steps (Fig. 1). The different stages of the MEX process must be identified, including the heating stages (build plate and nozzle), the calibration stage, the forming stage, and the cooling process (1). Simple geometry is selected for realizing preliminary tests during which the absorbed power of each identified stage must be measured by means of an acquisition system (2). Due to the natural variability of the process, the power measurement is repeated to obtain reliable data (3). One of the most common open-source slicing software (Cura®) is used for evaluating the printing time (4). The collected and calculated data are then processed to define the power absorption behaviour of the process (5); these data are used to create a predictive model of the energy consumption for each part having a different geometry (6). For supporting the model, it is important to validate it; thus, a final comparison between the estimated and measured data for the different parts is conducted. Specifically, in this stage, different geometries (representative of real components obtainable through the additive process) are selected and printed (7).

2.1 Process decomposition

The first stage of the printing process is the warm-up, which can be assimilated into a preparation mode. Indeed, before proceeding with parts fabrication, some components like the chamber and the plate firstly and then the nozzles need to be heated. Both the chamber and nozzle/s temperatures are kept constant during the whole printing process. Then, the calibration phase starts. In this phase, the machine checks that the nozzle/s and the plate are set up correctly in terms of the positions and ability of the material to be extruded from the nozzle. Afterwards, the forming stage can start deposing the material layer-by-layer following the desired path defined by the slicing software. Finally, the cooling stage begins, and then, the printed part can be removed from the build plate. As already said, in each phase, the energy consumption is related not only to the stage itself but also to keeping all the machine components at the correct temperature for the entire process. This means that during the nozzle heating, the printer absorbs power also for maintaining the correct temperature of the build plate. Similarly, during the calibration and printing stages, the machine needs to maintain a stable temperature of both the build plate and the nozzle. The several manufacturing stages and their duration throughout the whole process are reported in Fig. 2. The same phases can be identified in all additive processes with some tricks depending on the technology used. Thus, a similar methodology can be derived also for other AM processes. The power values of all these printing stages can vary because each power level stage will depend on the process and the machine used. Concerning the duration of each phase, warm-up (plate and nozzle), cooling, and calibration are not part-dependents and are well-known due to the measurements. The maintaining temperature and print phases are depending on the geometry of the manufactured part and the print speed. Thus, the duration of each of these stages can vary.

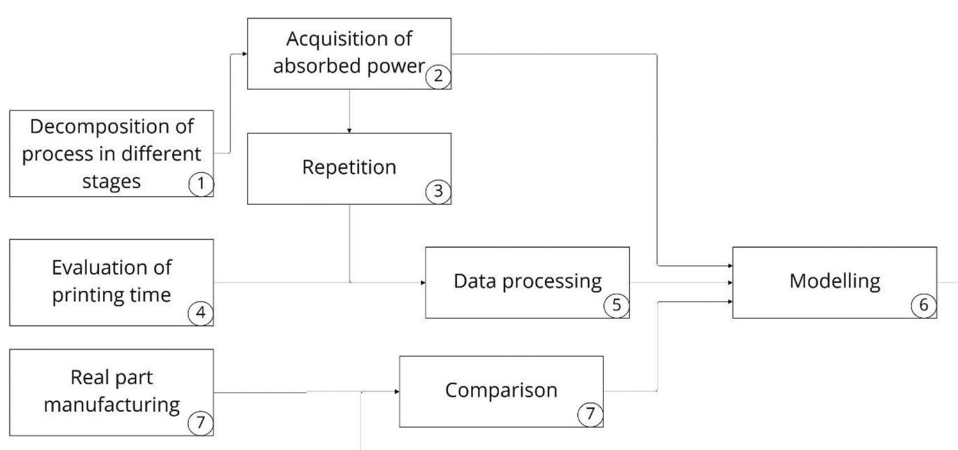


Fig. 1 Proposed methodology

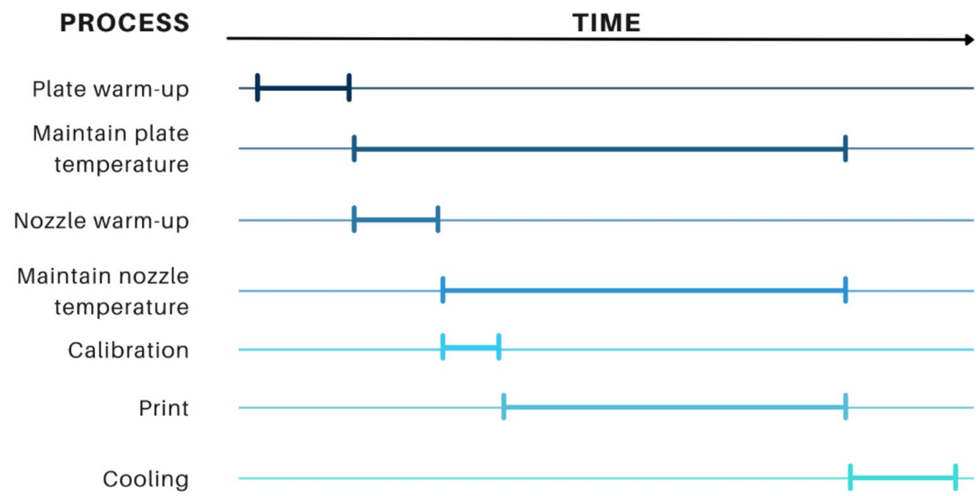


Fig. 2 Manufacturing stages and their duration along the whole process

The second step of the methodology is the acquisition of the instantaneous power consumption during the realization of some preliminary tests through an external device connected to the printing machine for recording data with a frequency of 1 Hz. A power study for all stages is realized by calculating the energy consumption of each phase of the AM process. All the printing tests were performed applying the optimal printing parameters selected on the base of material-technical datasheet and/or literature to have reliable data printing variable geometry. In the third step of the methodology, these measurements are repeated nine times.

The execution of these preliminary recording activities allows for identifying if the process is repeatable in terms of the trend and the level of the absorbed power of each process stage. Specifically, it is possible to identify if and how the power absorption changes by modifying the part geometry and to understand if the plate and nozzle temperatures affect the power absorption or simply the processing time and, consequently, the energy consumption.

2.2 Modelling

The innovative aspect of the mathematical model for the prediction of energy consumption in printing is to combine a global view of the printing process and a local analysis of different production stages. For this reason, the process is divided into stages instead of different features (nozzle, motors…). With the power and duration of each stage known, the total energy consumption (E_{TOT}) can be calculated as the sum of the energy consumed during the process stages (Eq. 1).

$$E_{TOT} = \int_{t_0}^{t_1} P(t)dt = E_{WU_{\text{plate}}} + E_{\text{keep}_{\text{plate}}} + E_{WU_{\text{nozzle}}} + E_{keep_{nozzle}} + E_{\text{cal}} + E_{\text{print}} + E_{\text{cool}} \tag{1}$$

where $E_{WU_{\text{plate}}}$ and $E_{WU_{\text{nozzle}}}$ are the energy consumption for heating the build plate and the nozzle. $E_{\text{keep}_{\text{plate}}}$ and $E_{\text{keep}_{\text{nozzle}}}$ represent the energy necessary for keeping the constant temperature of the build plate and nozzle. E_{cal} is the energy consumption for the calibration stage, E_{print} is the energy for the part forming, and E_{cool} represents the energy for the cooling stage.

Observing the duration and the overlap of the different stages (Fig. 2), it is possible to see how the machine must keep a constant plate temperature for the entire duration of nozzle heating ($t_{WU_{\text{nozzle}}}$), calibration (t_{cal}), and printing stages (t_{print}) ($t_{\text{keep}_{\text{plate}}}$—Eq. 2).

$$t_{\text{keep}_{\text{plate}}} = t_{WU_{\text{nozzle}}} + t_{\text{cal}} + t_{\text{print}} \tag{2}$$

A similar consideration can be done for the $t_{\text{keep}_{\text{nozzle}}}$, except for the nozzle warm-up stage (Eq. 3).

$$t_{\text{keep}_{\text{nozzle}}} = t_{\text{cal}} + t_{\text{print}} \tag{3}$$

Introducing these relations into Eq. 1, the total energy can be estimated as reported in Eq. 4.

$$\begin{aligned} E_{TOT} = {} & \left(\mathrm{P}_{\text{keep}_{\text{plate}}} + P_{\text{keep}_{\text{nozzle}}} + P_{\text{print}}\right) \bullet t_{\text{print}} \\ & + P_{WU_{\text{plate}}} \bullet t_{WU_{\text{plate}}} + \left(P_{WU_{\text{nozzle}}} + P_{\text{keep}_{\text{plate}}}\right) \\ & \bullet t_{WU_{\text{nozzle}}} + \left(P_{\text{keep}_{\text{plate}}} + P_{\text{keep}_{\text{nozzle}}} + P_{\text{cal}}\right) \bullet t_{\text{cal}} + P_{\text{cool}} \bullet t_{\text{cool}} \end{aligned} \tag{4}$$

where $P_{WU_{\text{plate}}}$ and $P_{WU_{\text{nozzle}}}$ are the absorbed power for heating the build plate and the nozzle. $P_{\text{keep}_{\text{plate}}}$ and $P_{\text{keep}_{\text{nozzle}}}$ represents the absorbed power for maintaining the temperature of the build plate and nozzle to the correct value. P_{cal} is the absorbed power for the calibration stage, and P_{print} and P_{cool} are the absorbed power of the printing and cooling stages respectively.

Given the assumption of the distribution of the stages as indicated in Fig. 2, it is possible to rewrite Eq. 5 by collecting all the not part-related terms, in a new variable called ψ_i, where i identified the material. Furthermore, the absorbed power during the printing stage ($P_{\text{keep}_{\text{plate}}} + P_{\text{keep}_{\text{nozzle}}} + P_{\text{print}}$)

can be called P_{work_i}. According to this consideration, Eq. 5 can be rewritten as follows:

$$E_{TOT} = t_{\text{print}_i} \bullet P_{\text{work}_i} + \psi_i \quad (5)$$

t_{print_i} indicated the time required for printing the part with the defined printing parameters related to the selected material which can be estimated by a slicing software and depends on the part geometry, too. In this way, the total energy can be estimated a priori by means of two terms characteristic of the material: (1) ψ_i describing the energy consumption of preparation and cooling stages; (2) P_{work_i} describing the average value of the absorbed power during the actual printing process including the absorbed power for keeping constant the plate and nozzle temperatures.

2.3 Validation

2.3.1 Experimental set-up

This methodology has been applied to a dual extruder 3d printer Ultimaker S5. This machine is also equipped with a movable up and down heat build plate and a heating resistor on the extruders that rise, respectively, their temperature to 60 °C and 200 °C. The parts used in this investigation are a cube of 15 × 15 × 15 mm, a cylinder of ϕ15 × 30 mm, and a parallelepiped of 20 × 20 × 5 mm made in PLA. According to MEX machine manufacturers, different machines may have different configurations from that of Ultimaker one. Therefore, the material and the equipment vary from one machine to another. Sometimes, the heat build plate is replaced by a heat chamber or, for low-cost machines, nothing. Given this, the order of different stages during the production process can change as a function of the machine brand. Table 1 lists the parameters used in this process.

Table 1 MEX machine parameters

Nozzle temperature (°C)	60
Plate temperature (°C)	200
Material	PLA
Filament diameter (mm)	2.85
Nozzle diameter (mm)	0.4
Layer height (mm)	0.2
Infill (%)	100
Print speed (mm/s)	70
Travel speed (mm/s)	150

During these tests, the instantaneous power absorbed by the printing equipment was measured by means of CLM1000, a power measurement instrument, showing that the power consumption during the non-printing stages has the same behaviour regardless of the printed part. For all tests, all measurements were realized under the same initial condition. The workshop temperature was 21 °C, and the build plate and the nozzle were expected to cool down to room temperature before starting each measurement. Three tests were performed for each geometry for evaluating the repeatability of the data collection.

Figure 3 shows a representative power measurement from the Ultimaker S5. The power measurement started with the start of the printing process. The first part of power absorption (blue area) corresponds to the rising temperature of the build plate. The second level of power (orange area) corresponds to the nozzle warm-up. During this stage, the heat plate continues to warm up to keep constant the temperature. After all the components have finished their warm-up stage, the calibration (yellow area) starts, and then, the machine is ready for the printing stage (purple area). A lot of oscillation can be observed during the last stage. These oscillations are not generated by the motors; in fact, the current and voltage values are the same all the time during the printing stage because of the nature of the motors. Oscillations are generated by the maintenance of the right temperature of the build plate and nozzle and are visible due to the high acquisition frequency.

According to Fig. 3, it is evident how the absorbed power behaviour and duration differ only in the printing stage according to the different geometries of the parts. Hence, since the heating, calibration and cooling times are not part-related, the energy consumption during these phases can be considered a fixed parameter in the calculus of the total energy. Furthermore, the preliminary tests also showed that the absorbed powers during the printing stage for the different parts have approximately the same average values (Fig. 3). Even if the several printing stages are characterized by a certain variability of the absorbed power over time as reported in Fig. 3, the instantaneous power value can be successfully substituted by its average value P_{work_i}. This can be confirmed by applying the moving mean to the sampled data: it is evident how it remains almost constant during the entire printing stage. These considerations support the assumption used for obtaining Eq. 5.

2.3.2 Data processing

Considering the data collected during the preliminary test, through a Matlab code developed by the authors, the data were elaborated for estimating the energy consumption for each not part-related calculating the duration of each of them. The same code also includes the instruction for the calculation of the P_{work_i}. These data were used for the definition of the characteristic coefficient ψ_i and $P_{\text{work}\,i}$. The consumed energy was calculated as the integral of the power vs. time curve. Thus, regarding the PLA filament printed by applying the printing parameters reported in Table 1, it results to be characterized by $\psi_{PLA} = 54.60\text{kJand}P_{\text{work}\,PLA} = 0.154\text{kW}$.

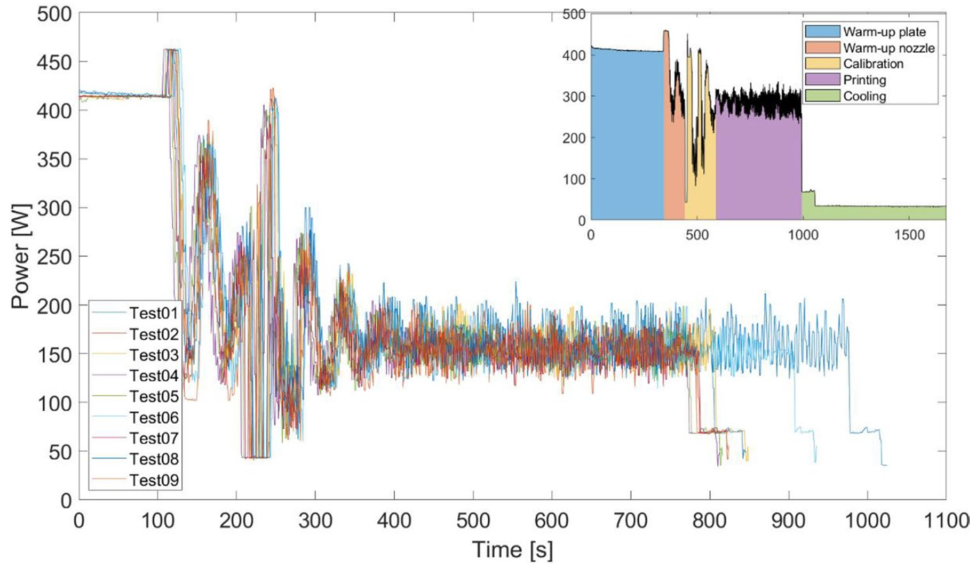


Fig. 3 Manufacturing cycle for different PLA parts

Defined these characteristics values, it was investigated if Eq. 5 works for the estimation of the energy consumption a priori. For evaluating it, three new parts were considered for testing the predictive model. The parts had different levels of complexity determined by the shape complexity coefficient (C_{FDM}) developed by Pradel et al., 2017 (Eq. 6).

$$C_{FDM} = \frac{SA_c}{V_{es}} \tag{6}$$

where SA_c is the surface area of the component and V_{es} is the volume of the envelope space between the functional surfaces. Lower C_{FDM} identifies a low level of shape complexity; on the contrary, an increase of C_{FDM} indicates parts with a higher level of complexity. The decision to consider different levels of complexity is driven by the desire to validate the model not only for elementary geometries which therefore have a more linear and, in some cases, short printing process, but to demonstrate that the approach works for components characterized by complex details and long processes. Thus, the geometries reported in the first column of Table 2 were printed considering the same conditions reported in the previous section and the instantaneous power absorbed by the printing equipment was measured. In the meantime, considering the estimated printing time and the characteristic parameters of PLA, the energy consumption was mathematically calculated (E_{TOT} model). The data collected from the experiments were elaborated by Matlab code. All results are reported in Table 2. The obtained results, regardless of the degree of complexity, show a very low deviation between the experimental value and that derived from the model demonstrating the robustness of the developed model. This underlines the good ability of the model to predict the energy needed, even if it tends to underestimate it, especially for the simpler part. The only particular aspect related to the error estimation is related to the fact that the second geometry, despite the small C_{FDM}, shows an error three times greater than the other two geometries. This result can suggest that the degree of complexity does not directly affect the reliability of the prevision model. A hypothesis that can justify this increment may be the greater height of the product, which therefore involves a greater number of layers in the production. This aspect, together with the particular geometry (considering the horizontal section), generates a greater number of changes in the nozzle direction during printing, which may have increased the actual energy consumption.

2.4 Outcome

So far, the validity of what was stated in the modelling section has been demonstrated only for PLA, the simplest material to process through MEX. In order to prove the general validity of the definition of characteristic coefficients, the methodology was tested broadening the range of materials. Specifically, the power absorbed was collected for 4 more materials: 2 polymerics (acrylonitrile butadiene styrene — ABS and polycarbonate — PC) and 2 metals (polymer filament with stainless steel 316L and 17-4PH powder respectively) filaments. Each of them is characterized by different build plate and nozzle temperatures as reported in Table 3, and, as can be seen from the details of the warm-up activities reported in Fig. 4, higher temperatures of the build plate and nozzle correspond to longer heating phase but same values of absorbed power. Then, some preliminary printing tests with the relative power absorption recording have been

Table 2 Comparison between energy estimated by the model and recorded in the experiment for geometries characterized by different shape complexity

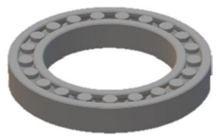
Parts	Main Dimensions	C_{FDM}	E_{TOT} Model	E_{TOT} Tests	% Error
	81x81x12 mm	0.783	2494.90	2416.02	-3.16%
	119x119x70 mm	0.331	3486.45	3144.74	-9.80%
	30x30x30 mm	0.200	912.73	884.79	-3.06%

Table 3 Characteristics energy parameters for different materials

Material	T_{plate}	T_{Nozzle}	ψ_i(kJ)	$P_{work\,i}$(kW)
PLA	60	200	54.60	0.154
ABS	85	240	211.76	0.235
PC	110	270	309.38	0.304
316L	100	240	240.61	0.284
17-4PH	100	240	275.04	0.289

conducted for observing the repeatability of this effect on printing base geometries showing the reproducibility of the power absorption trend (Fig. 5) regardless of the kind of material. The curves mainly differ in the duration of each stage and the P_{work} values.

The data collected by the preliminary test are analysed for describing the base process defining specific ψ_i and $P_{work\,i}$. The data elaboration allows to generate a summary table

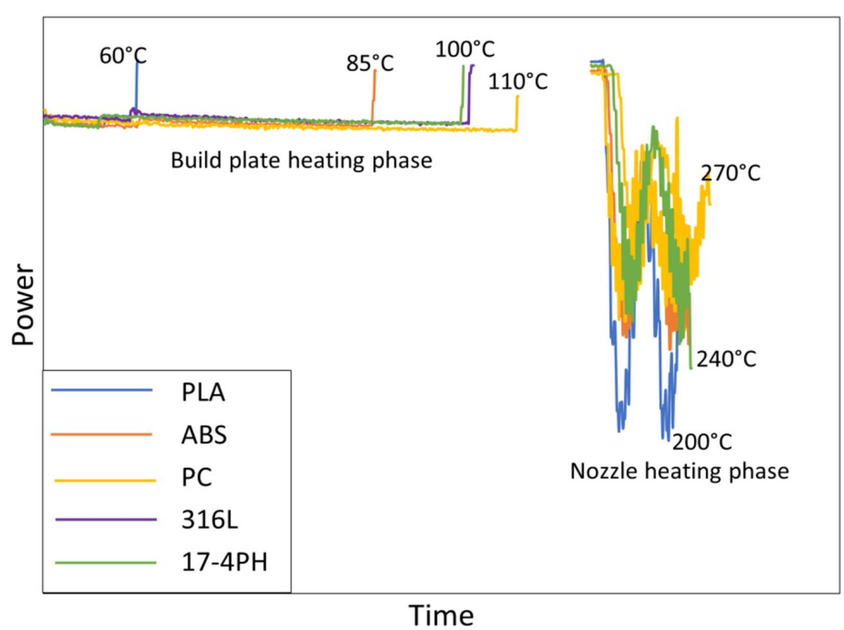


Fig. 4 Detail of duration of the build plate and nozzle heating

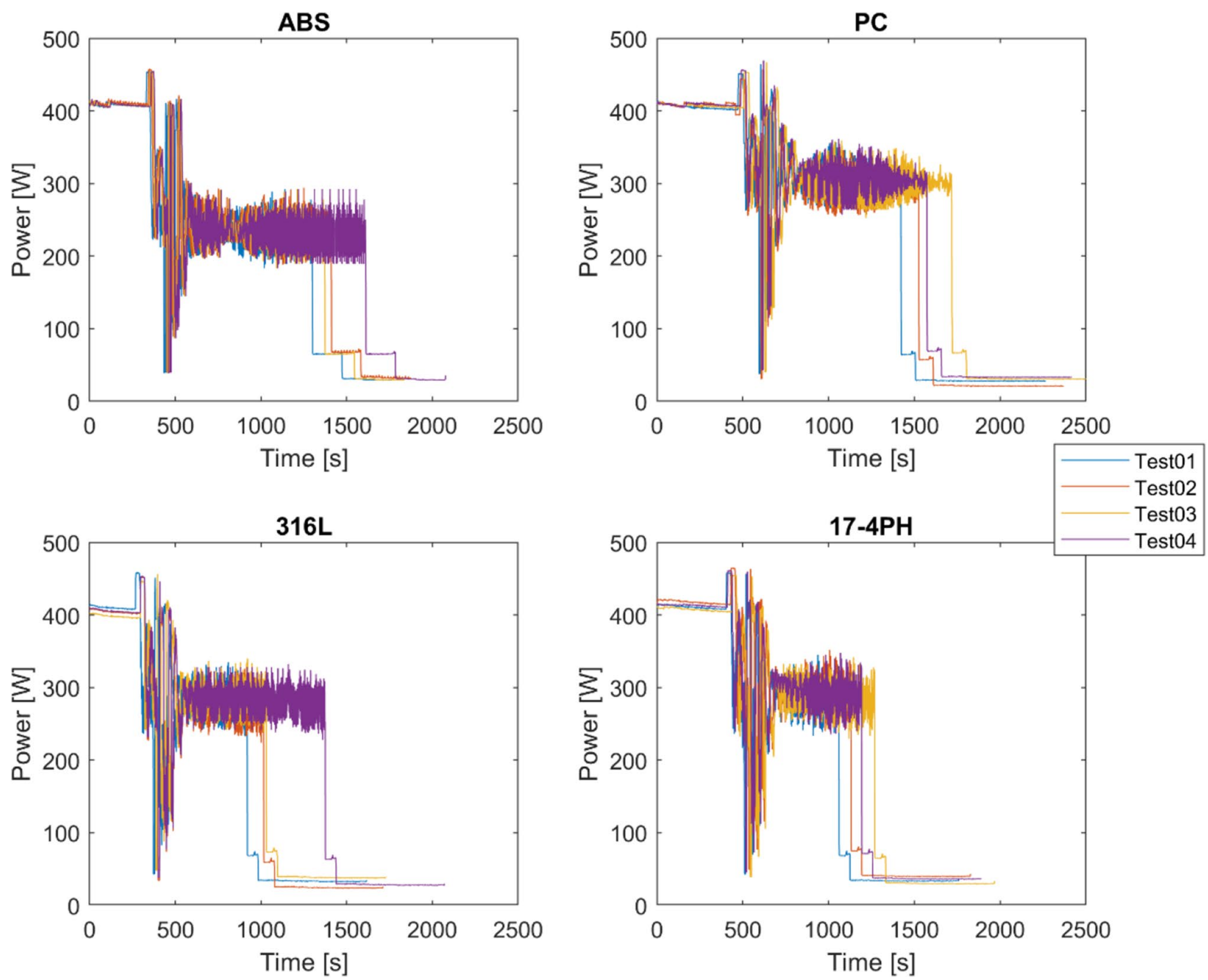


Fig. 5 Manufacturing cycle for different materials printing same pilot geometries

(Table 3). The data highlight that, for corresponding phases, the levels of absorbed power are the same, but their duration varies according to the temperatures to be reached during the heating phase.

The data processing defines an average value of the power absorbed in the printing phase, highlighting a large difference in $P_{\text{work}\,i}$ for the materials belonging to the class of polymers.

In conclusion, the developed model and the tests carried out on different types of materials allow identifying the characteristic parameters of each selected filament. Thanks to this processing, it is now possible to estimate the energy necessary for printing specific products simply by applying Eq. 6 introducing the values reported in the final table providing the industry with a very simple tool for forecasting consumption which could help in evaluating the convenience of the process.

2.5 Application

The developed mathematical relation is useful for the definition of energy convenience of the printing process compared to the other machining solution. At the same time, this relation can be integrated into a cost model for the correct and reliable estimation of production cost. In this way, the estimation of a priori parameters necessary for the economic evaluation of the production of an individual part can be completed. This means that by integrating the model developed in this work with the economic model in the previous paper [34], it is possible to estimate production costs by having a detailed estimation of energy consumption and consequently its costs. Thus, by introducing Eq. 5 into the economic model reported in [34], the general formula for the estimation of the energy cost (C_e) (reported for sake of clarity in the Eq. 7) can be simplified as indicated in Eq. 8.

$$C_e = \left(t_{su} + \sum_i t_{cc_i} N_i + t_w \gamma \right) \left(C_0|_{1h} + c_{en} P_i \right) + t_{wu} \left(C_0|_{1h} + c_{en} P_{wu} \right) + t_w \left(C_0|_{1h} + c_{en} P_w \right) \quad (7)$$

$$C_e = \frac{N_{ord}}{1-\varepsilon} \left(t_{print_i} \bullet P_{work_i} + \psi_i \right) \bullet c_{en} \quad (8)$$

where t_{su} is the setup time, t_{cc_i} is the time spent on consumable replacement activities, N_i represents how many units of a single consumable, γ is a fraction of the entire production time (t_w) dedicated to the auxiliary activities, $C_0|_{1h}$ is the hourly fixed cost, c_{en} is the unit cost of the energy, and t_{wu} is the warm-up time. Furthermore, P_i, P_{wu}, and P_w represent the power consumption of the machine during idle, warm-up, and production states, respectively. N_{ord} is the dimension of the customer order, and ε is the percentage of non-compliant parts.

The simplification of the equation allows for the reduction of variables and information necessary for the estimation of energy cost, and it is possible to predict them without actually producing the part. Correlating these two models, it is possible to estimate a priori the energy consumption and the production cost of a unit part, helping the companies within the evaluation of the technology convenience without wasting a lot of time in the collection of several data and without performing simulation which are characterized by a long computing time. The modification of the cost energy estimation modifies the general equation of the unit cost (*UC* — Eq. 9 [34]) as reported in Eq. 10.

$$UC = \frac{C_0|_{1h} \bullet t + C_e + C_m + C_c}{N_{\text{ord}}} \quad (9)$$

$$UC = \frac{C_0|_{1h} \bullet t + C_m + C_c}{N_{\text{ord}}} + \frac{\left(t_{\text{print}_i} \bullet P_{\text{work}_i} + \psi_i \right) \bullet c_{en}}{1-\varepsilon} \quad (10)$$

where t is the sum of the duration of all printing activities, C_m is the material cost, and C_c is the cost of consumables elements (e.g. nozzle).

3 Conclusions

In this work, a model for predicting energy consumption during the MEX process has been developed. It has shown a different point of view on energy evaluation, considering the different stages of the process instead of the different components of the machine. The mathematical model has been validated by applying the energy prediction model to printed parts with different levels of complexity. The validation shows a good level of accuracy in the prediction of energy consumption and its comparison with the experimentally recorded energy. The model has been validated for a PLA, and then, to evaluate the robustness of the model, some tests for the definition of the characteristic parameters are carried out also considering other printable materials and products with different levels of complexity. In total, three kinds of polymers and two metal filaments have been considered. As a conclusive result, a user-friendly tool for the prediction of the MEX energy demand has been defined and validated obtaining as the outcome a collection of "power" parameters typical for each material. In conclusion, the work demonstrates that the developed model allows for supplying a reliable prediction of energy consumption with an error that slightly underestimates the values, but still less than 10%. In the last part of the work, the characteristic parameters for different materials were estimated for supplying the necessary values for the estimation of energy consumption using different materials.

In general, this work defines a method for the definition of characteristics parameters which, once calculated, allow predicting the energy consumption of the process regardless of the geometry of the part. Furthermore, a priori knowledge of energy consumption is possible, simplifying the cost evaluation since fewer variables and information are necessary.

Data availability The data that support the findings of this study are available on request from the corresponding author, M. Q.

Declarations

Competing interests The author declares no competing interests.

References

1. Yuan C, Zhai Q, Dornfeld D (2012) A three dimensional system approach for environmentally sustainable manufacturing. CIRP Ann Manuf Technol 61(1):39–42. https://doi.org/10.1016/j.cirp.2012.03.105
2. Apostolos F, Alexios P, Georgios P, Panagiotis S, George C (2013) Energy efficiency of manufacturing processes: a critical review. In Procedia CIRP 7:628–633. https://doi.org/10.1016/j.procir.2013.06.044
3. Horn TJ, Harryson OLA (2012) Overview of current additive manufacturing technologies and selected applications. Sci Prog 95(3):255–282. https://doi.org/10.3184/003685012X13420984463047
4. Duflou JR, Sutherland JW, Dornfeld D, Herrmann, C, Jeswiet J, Kara S, Hauschild M, Kellens K (2012) Towards energy and resource efficient manufacturing: a processes and systems approach. CIRP Ann - Manuf Technol 61(2):587–609. https://doi.org/10.1016/j.cirp.2012.05.002
5. Yusuf LA, Popoola K, Musa H (2021) A review of energy consumption and minimisation strategies of machine tools in manufacturing process. Int J Sustain Eng 14(6):1826–1842. https://doi.org/10.1080/19397038.2021.1964633
6. Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR (2012) Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! initiative (cooperative effort on process emissions in

manufacturing). Part 2: Case studies. Int J Life Cycle Assess 17(2):242–251. https://doi.org/10.1007/s11367-011-0352-0
7. Stavropoulos P, Chantzis D, Doukas C, Papacharalampopoulos A, Chryssolouris G (2013) Monitoring and control of manufacturing processes: a review. In Procedia CIRP 8:421–425. https://doi.org/10.1016/j.procir.2013.06.127
8. Net Zero Technical Report (2019). https://www.theccc.org.uk/publication/net-zero-technical-report/
9. Achillas C, Tzetzis D, Raimondo MO (2017) Alternative production strategies based on the comparison of additive and traditional manufacturing technologies. Int J Prod Res 55(12):3497–3509. https://doi.org/10.1080/00207543.2017.1282645
10. Hettesheimer T, Hirzel S, Roß HB (2018) Energy savings through additive manufacturing: an analysis of selective laser sintering for automotive and aircraft components. Energ Effi 11(5):1227–1245. https://doi.org/10.1007/S12053-018-9620-1/FIGURES/8
11. Jackson MA, Van Asten A, Morrow JD, Min S, Pfefferkorn FE (2018) Energy consumption model for additive-subtractive manufacturing processes with case study. Int J Precis Eng Manuf - Green Technol 5(4):459–466. https://doi.org/10.1007/s40684-018-0049-y
12. Digital Enterprise, Siemens (2022) https://new.siemens.com/global/en/company/topic-areas/digital-enterprise.html
13. Robinson DKR, Lagnau A, Boon WPC (2019) Innovation pathways in additive manufacturing: methods for tracing emerging and branching paths from rapid prototyping to alternative applications. Technol Forecast Soc Chang 146:733–750. https://doi.org/10.1016/j.techfore.2018.07.012
14. Post BK, Lind RF, Lloyd PD, Kunc V, Linhal JM, Love LJ (2016) The economics of big area additive manufacturing. In: Solid Freeform Fabrication 2016: Proceedings of the 27th annual international solid freeform fabrication symposium - an additive manufacturing conference, SFF 2016. Austin
15. Babu SS, Goodridge R (2015) Additive manufacturing. Mater Sci Technol 31(8):881–883. https://doi.org/10.1179/0267083615Z.000000000929
16. Beaman JJ, Barlow JW, Bourell DL, Crawford RH, Marcus HL, McAlea KP (1997) Solid freeform fabrication: a new direction in manufacturing (1st ed.). Springer US. https://doi.org/10.1007/978-1-4615-6327-3
17. Ji R, Liu Y, Zhang Y, Dong X, Chen Z, Cai B (2011) Experimental research on machining characteristics of SiC ceramic with end electric discharge milling. J Mech Sci Technol 25(6):1535–1542. https://doi.org/10.1007/s12206-011-0327-x
18. Xu X, Meteyer S, Perry N, Zhao YF (2015) Energy consumption model of Binder-jetting additive manufacturing processes. Int J Prod Res 53(23):7005–7015. https://doi.org/10.1080/00207543.2014.937013
19. Huang SH, Liu P, Mokasdar A, Hou L (2013) Additive manufacturing and its societal impact: a literature review. Int J Adv Manuf Technol 67(5–8):1191–1203. https://doi.org/10.1007/s00170-012-4558-5
20. Trappey AJC, Trappey CV, Hsiao CT, Ou JJR, Chang CT (2012) System dynamics modelling of product carbon footprint life cycles for collaborative green supply chains. Int J Comput Integr Manuf 25(10):934–945. https://doi.org/10.1080/0951192X.2011.593304
21. Lavecchia F, Guerra MG, Galantucci LM (2022) Chemical vapor treatment to improve surface finish of 3D printed polylactic acid (PLA) parts realized by fused filament fabrication. Prog Addit Manuf 7(1):65–75. https://doi.org/10.1007/s40964-021-00213-2
22. Quarto M, Carminati M, D'Urso G (2021) Density and shrinkage evaluation of AISI 316L parts printed via FDM process. Mater Manuf Processes 36(13):1535–1543. https://doi.org/10.1080/10426914.2021.1905830
23. Mollah MT, Comminal R, Serdeczny MP, Pedersen DB, Spangenberg J (2021) Stability and deformations of deposited layers in material extrusion additive manufacturing. Addit Manuf 46:102193. https://doi.org/10.1016/j.addma.2021.102193
24. Baumers M, Tuck C, Bourell DL, Sreenivasan R, Hague R (2011) Sustainability of additive manufacturing: measuring the energy consumption of the laser sintering process. Proc Inst Mech Eng, Part B: J EngManuf 225(12):2228–2239. https://doi.org/10.1177/0954405411406044
25. Luo Y, Ji Z, Leu MC, Caudill R (1999) Environmental performance analysis of solid freeform fabrication processes. IEEE Int Symp Electron Environ 1–6. https://doi.org/10.1109/isee.1999.765837
26. Gutierrez-Osorio AH, Ruiz-Huerta L, Caballero-Ruiz A, Siller HR, Borja V (2019) Energy consumption analysis for additive manufacturing processes. Int J Adv Manuf Technol 105(1–4):1735–1743. https://doi.org/10.1007/s00170-019-04409-3
27. Yosofi M, Kerbrat O, Mognol P (2018) Energy and material flow modelling of additive manufacturing processes. Virtual Phys Prototyp 13(2):83–96. https://doi.org/10.1080/17452759.2017.1418900
28. Dass A, Moridi A (2019) State of the art in directed energy deposition: from additive manufacturing to materials design. MDPI, Coatings. https://doi.org/10.3390/COATINGS9070418
29. Lunetto V, Priarone PC, Galati M, Minetola P (2020) On the correlation between process parameters and specific energy consumption in fused deposition modelling. J Manuf Process 56:1039–1049. https://doi.org/10.1016/j.jmapro.2020.06.002
30. Gutowski T, Dahmus J, Thiriez A (2006) Electrical energy requirements for manufacturing processes. In: 13th CIRP international conference on life cycle engineering, Leuven, pp 623–628
31. Ramesh P, Vinodh S (2021) Analysis of factors influencing energy consumption of material extrusion-based additive manufacturing using interpretive structural modelling. Rapid Prototy J 27(7):1363–1377. https://doi.org/10.1108/RPJ-05-2020-0100
32. Majeed A, Ahmed A, Lv J, Peng T, Muzamil M (2020) A state-of-the-art review on energy consumption and quality characteristics in metal additive manufacturing processes. J Braz Soc Mech Sci Eng 42(5):1–25. https://doi.org/10.1007/s40430-020-02323-4
33. Krishana M, Sven S, Wu W (2022) The net-zero transition: what it would cost, what it could bring. McKinsey & Company
34. Quarto M, Giardini C (2022) Additive manufacturing of metal filament: when it can replace metal injection moulding. Prog Addit Manuf 8:561–570. https://doi.org/10.1007/s40964-022-00348-w
35 Jeswiet J, Kara S (2008) Carbon emissions and CES^{TM} in manufacturing. In CIRP Ann - Manuf Technol 57:17–20. https://doi.org/10.1016/j.cirp.2008.03.117. (Elsevier)
36. IEA (2021) Energy efficiency indicators: overview, IEA, Paris. March 29, 2022 from https://www.iea.org/reports/energy-efficiency-indicators-overview/highlights
37. Pradel P, Zhu Z, Bibb R, Moultrie J (2017) Complexity is not for free: the impact of component complexity on additive manufacturing build time. Loughborough University's Institutional Repository of component complexity on additive manufacturing