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Framework to combine technical, economic and environmental points of view of additive manufacturing processes

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Abstract

Additive manufacturing is an innovative way to produce complex parts. Nowadays, knowledge about mechanical properties and production costs are well known. Many studies found in the literature present comparisons between different additive manufacturing technologies based on technical or economical criterions. However, the environmental analysis of the phenomena that occur during the manufacturing step is still limited. To ensure the development of these processes it seems important to get predictive models of the environmental impacts, allowing to evaluate the product from a technical, economic and environmental point of view. This paper presents a new methodology for the environmental impact evaluation, combined with a technical and economical assessment. This methodology is applied on multiple additive manufacturing processes and will help manufacturers like a decision-making tool to make a choice of manufacturing process based on multiple criterion.

Keywords: Additive manufacturing; Environmental impact; Mechanical properties; Production cost

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1. Introduction

Additive manufacturing (AM) technologies evolved significantly over the last few decades. This technology has drawn more and more attention from the industry world, which has led to a very large progression of these processes from a technical point of view. AM processes has been applied in industrial field for a long time and plenty of researches have been conducted on the aspect of process control and product quality. The same goes for the cost of these processes, which are well known today. However, there is still very limited research on the sustainability aspect of AM processes. It is difficult to conduct an exact Life-Cycle Assessment or sustainability analysis for AM technologies, because of the lack inventory data. Those processes are often described as “clean” processes because they only use the exact amount of material to build functional parts limiting wastes. This paper presents a new methodology for the environmental impact evaluation, combined with a technical and economical assessment.

2. State of the art

Nowadays, AM techniques have been applied in various domains such as biomedical, aerospace and automotive industry [1]. There are many works in the literature on the influence of process parameters on the mechanical properties of the part [2,3]. Thus, guidelines are proposed in order to reduce the build time and material consumption [4]. Some authors are improving these processes by proposing algorithms build time estimation more precise than those proposed by the existing software [5] or by improving the surface roughness [6]. There are also linkages between the technical and cost

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aspects [7,8] and between cost and environmental aspects [9]. All this work on the improvement of these processes is a sign of maturity of these processes from a technical and economic point of view. However, the environmental aspects of these processes are less documented.

For a long time, the authors were mainly interested in the consumption of electrical energy of these processes with a focus only on the manufacturing stage [10,11]. Comparisons of electrical energy consumption between AM and conventional processes (machining, injection moulding) have also been made [12,13]. The analysis of these studies shows that for one part, AM processes are more profitable. On the other hand, for a series of several parts, the conventional processes are to be privileged. A lot of articles focus mainly on the energy consumption during the manufacturing step. Some data such as resource consumption, emissions, waste flows or recycling are still lacking.

For some years, the authors have tended to a more global vision of environmental impact. Le Bourhis et al. made a predictive model for the environmental assessment of a laser cladding process [14]. Besides the electric consumption, they took into account the atomization of the raw material, fluid and material consumption and the recycling of lost powder. Kellens et al. used the UPLCI methodology to study the environmental impact of two powder bed fusion processes [15]. This methodology allows an accurate environmental assessment for manufacturing processes[16].

It is thus important to take into account all the flows (electric energy, but also materials and fluids) through the process in order to assess the environmental performance of a machine precisely. This paper has two main objectives. The first one is to propose a generic method allowing acquisition and characterization of all the input and output flows during the manufacturing stage but also during the pre-process and post-process stages. The second one is to combine these environmental aspects with technical and cost issues.

3. Methodology

3.1. Study's limits

Firstly, the boundaries of the study must be clearly defined. In order to have a complete study, it is important to take into account all the necessary material used in the part fabrication process. Before the beginning of the part build in the machine, the CAD file must be prepared in order to select all the fabrication parameters (pre-process phase). Once the manufacturing phase is finished, the part may need support removal. Thus, this last operation can be done manually by the manufacturer or automatically by a dissolution device for support material (post-process phase). It is also important to consider all the consumptions and wastes during the manufacturing of parts. Concerning AM processes, the consumption and the wastes of the different flows are split into three categories as it shown in the Fig.1:

- Electrical energy
- Material consumption and wastes
- Compressed air and water consumption and wastes

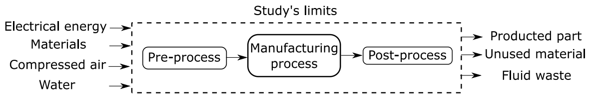

Fig.1. Study's limits with input and output flows

3.2. Methodology to combine technical, economic and environmental points of view

The goal of this methodology (Fig.2) is to give to the designer or the manufacturer a decision making tool to make a choice of a manufacturing process based on multiple criterion.

In this paper, simple models for the fluids and materials consumption are proposed. Regarding the electric consumption, more accurate models, leverage on experimental measurements, are presented. Empirical formula is used for costs models and equations for the technical model are extracted from the literature. This methodology can be decomposed into three major steps:

- First step: Method for obtaining the models
- Second step: Models writing
- Third step: Results displaying

In this first major step of the methodology, all the necessary data for the models creation are collected. The definition of the limits of the study made it possible to know precisely the input and output flows. However, it is necessary to have an accurate view of how these flows occur in the manufacturing cycle of the part. To do this, the manufacturing process is decomposed into different manufacturing stages, as follows:

- CAD file preparation (pre-process)
- Idle
- Warm-up/preparation mode
- Forming
- Post-process

3.2.1. Experimental protocol

The acquisition takes place for a given series of parts:

- Block 30x30x10 mm
- Cylinder R15 mm, H 4 mm
- Block 30x10x10 mm
- Block 10x10x30 mm.

The geometry of these parts used to create the models has been selected in such a way that the two axes X and Y are used during the manufacture of the part.

These parts are made several times under the same initial conditions in order to have reliable data. After the production of a part, a waiting time is respected in order to reach the initial temperature of the parts of the machine that are heated. The ambient temperature of the room is also the same throughout the manufacturing process.

3.2.2. Method for obtaining the electrical model

The identification of the various stages of the process makes it possible to have a generic formula for the total consumption of electrical energy during the manufacture of a part (Equation 1).

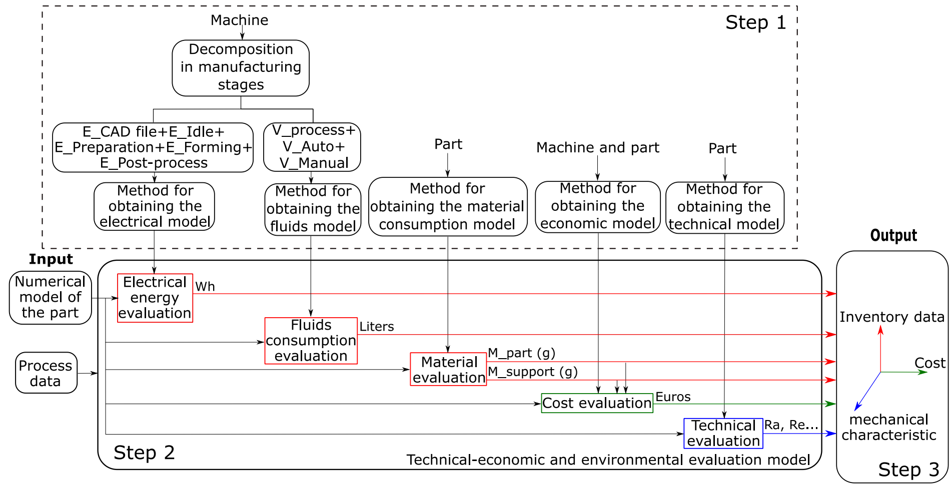

Fig.2. Methodology proposed

The total electrical energy consumption is equal to the sum of the electrical energy of each stage.

$$E_{Total}=E_{(CAD\ file\ preparation)}+E_{Idle}+E_{Preparation}+E_{Forming}+E_{(Post\text{-}process)} \tag{1}$$

The next step is to associate an average power and a duration to each stage, in order to have the energy of each stage. Then energies are summed according to (Equation 1). The acquisition for each manufacturing stage is carried out as many times as the number of manufactured part.

3.2.3. Method for obtaining the fluid model

In many manufacturing processes, fluid consumption is due to two sources, inert gas and fluid consumption. This consumption can occur during the forming stage and the post-process stage depending on the manufacturing process used. Thus, a total consumption is associated to the fluid volume during the manufacturing of a part, according to Equation 2:

$$\left(\begin{array}{l} V_{Total}=V_{Process}+V_{Auto}+V_{Manual} \\ V_{Process}=d_{Gas}\ x\ t_{Gas}+d_{Water}\ x\ t_{Water} \\ V_{Auto}=V_{(Water\ automatic\ post\text{-}process)}(V_{Part}) \\ V_{Manual}=V_{(Water\ manual\ post\text{-}process)}(d_{pump},t_{handling}) \end{array}\right) \tag{2}$$

Where d_{Gaz} and d_{Water} are respectively the gas flow rate (kg/s) and the water flow rate (l/s), t_{Gaz} and t_{Water} are respectively the duration where the gas and the water are on. Fluid consumption during the post-process stage is measured in 2 different ways. If the post-process is automatic, then the fluid volume is function of the part volume (V_{Part}). If this stage is manually, then the fluid volume is function of the pump flow rate (d_{pump}) and an associate handling time ($t_{handling}$) for the operation.

3.2.4. Method for obtaining the material consumption model

An empirical equation (Equation 3) is used to predict the total amount of material used during the process.

$$M_{Total}=\rho_{Part}\ x\ V_{Part}+\rho_{Support}\ x\ V_{Support} \tag{3}$$

Where ρ_{Part} and $\rho_{Support}$ are respectively the material density of the part and support material. V_{Part} and $V_{Support}$ the volume associated to the part and the support.

3.2.5. Method for obtaining the economic model

The estimate of the total cost is done using Equation 4.

$$Cost_{Total}=Cost_{Equipment}+Cost_{Material}+Cost_{Staff} \tag{4}$$

The cost of equipment takes into account the cost of the machine, depreciation per year and the number of hours the machine is used per year. Using all these data, an hourly cost is calculated. Then, the hourly cost is multiplied by the manufacturing time of the part. The cost of materials used during manufacture takes into account the mass of material used for the part and the support and the price per kg for both types of materials. Finally, the cost of the staff takes into account the hourly cost for an operator and the duration that the operator works during the pre-process and post-process stages. In this study, the operator cost is 53.25 Euros per hour.

3.2.6. Method for obtaining the technical model

In this study, the authors decided to focus their attention first on the surface condition of the parts produced by an additive manufacturing process. The formula that was retained comes from work done by Boschetto et Al. [17]. Equation 5 shows the formula for predicting Ra.

$$Ra=\frac{L.\csc(\alpha)}{9.\sqrt{3}} \tag{5}$$

Where L is the layer height and α is the deposit angle. Other means of characterizing the FDM process from a technical point of view will be added in future studies. Equations will also be added for other AM processes depending on what exists in the literature.

3.3. Models writing

These models are then exploited during the second stage of the methodology. All the data acquired are gathered in a single computer tool. Thus, a computer demonstrator is created so that any user can use the model with ease by only inputting data provided by the slicing software or the CAD software. The user has to enter the total manufacturing time estimated by the slicing software. But also the layer height, the different manufacturing angles, the pre-process duration, the post-process duration, the volume of the part and the density of the material used. Thus, the model allows to predict a consumption according to the different criteria studied for any shape to be produced.

3.4. Results displaying

Finally, the results of the consumption of the different criteria are displayed at the same time on a single graph. The computer demonstrator also makes it possible to display the results of several machines on a single graph, thus enabling the user to make a choice according to the criteria he wishes to highlight.

4. Results and discussion

4.1. Machines studied

As of today, the methodology has been applied on seven AM machines, described in Table 1. For all machines, there is no fluid consumption during manufacturing stage.

Table 1. Machines studied

Code	Machine	Process	Year
FDM1	Makerbot replicator 2X	Fused deposition modeling	2014
FDM2	Rapman 3.2	Fused deposition modeling	2011
FDM3	Stratasys Mojo	Fused deposition modeling	2012
FDM4	HP designjet 3D	Fused deposition modeling	2010
FDM5	Dimension Elite	Fused deposition modeling	2009
JET1	Stratasys Objet 30 pro	Material jetting	2012
JET2	Objet260 Connex	Material jetting	2011

4.2. Part studied

Fig.3 shows the studied part of 100 x 100 x 28 mm made in ABS. This part represents a prototype of femtocell. The manufacturing angle for the area A is 74.6° and for the area B 55.3°.

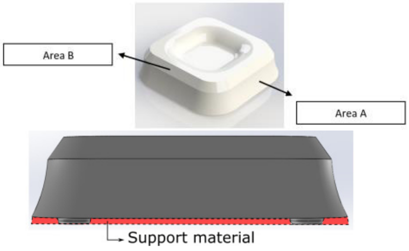

Fig.3. Part studied

4.3. Results by machines

This section shows the numerical values of the various machines for the part studied. Table 2 shows the fluids consumption during the part fabrication and the post-process stage. Table 3 shows the electrical energy consumption for each stage as well as the estimated total and real consumptions. Table 4 shows estimated and real values for part and support materials. Table 5 shows the estimated and the real cost for this specific part. Finally, Table 6**Erreur ! Source du renvoi introuvable.** shows values of the surface roughness of the part for the two different area.

4.4. Discussion

The acquisition of the energy consumption of the process stage by stage over several cycle of repetitions has made it possible to have refined models related to the electrical energy. The maximum deviation between the model and the real values is 6.22% for the JET 2 machine. These small overall deviations are explained by the fact that the variation of the electric current during each stage of the process is relatively low. This generates quite constant average powers for each phase.

The current formula for calculating the total volume of fluid consumed during manufacture only provides the real value of fluid consumed. Existing methods to estimate a volume of water or gas consumed during the manufacturing stage is based on the use of the G-code to obtain accurate information on the exact time of use of a fluid during the manufacturing of the part [18]. However, in this methodology, the authors have freed themselves from the G-code. Trails will be proposed in future works to get predicted values of fluid consumption.

Table 4 shows smaller variations for the part relative to the support. This is due to the use of the CAD file to know the total volume of the part while the slicing software estimates the total volume of the support.

Since the total manufacturing time only occurs in $\text{Cost}_{\text{equipment}}$, only this value is changed. Which leads to a small variation between the real value and the model. The costs related to the maintenance of the machines do not appear at the moment in the cost model. They will be integrated into future work.

Equation 5 used to determine the surface roughness provides acceptable results for the FDM process. However, since this formula has been demonstrated only on the FDM process, this estimation of surface roughness only works for this process. Future work will integrate surface roughness prediction for the material jetting first and then for other processes.

Fig.4 shows the combination of the estimated results for the five FDM machines and Fig.5 for the two material jetting machines. This new way of presenting the results enables a user to make a choice of machine or process according to the criteria he wishes to highlight. For example, Fig.5 makes it possible to make a choice of material jetting machine for the studied part. If the user wants a nice visual appearance of the part, it will be preferable to manufacture the part on the JET1 machine. On the other hand, if the user is more sensitive to the environmental footprint released by the part, it will be preferable to pass on the JET2 machine. It is also possible to select the best manufacturing strategy for the part. Indeed, by changing the position of the part on the virtual platform of the slicing software, a new total manufacturing time is estimated. Thus, the calculations are done again in order to have a new estimation of the consumption.

5. Conclusion

The authors propose a new methodology in order to evaluate, with accuracy, a part produced by an AM process from a technical, economic and environmental point of view. In this methodology, the study of the environmental phenomena involved in the production of a part does not stop at the manufacturing stage but is extended to the pre-process and the post-process stage. The work concerning the inventory data is not only focused on electrical consumption but also on fluids and material consumption which also contribute to the environmental impact. These environmental aspects are then coupled with technical and cost properties in order to have a multicriteria evaluation allowing a user to have a global view of the consumption of a part according to its geometry. The methodology developed is based on both analytic models (validated by experiments) and experimental models. Furthermore, this methodology will be extended to other manufacturing processes, and the inventory data will be treated for life-cycle impact assessment.

Acknowledgments

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Table 2. Fluids consumption

	V_Process	V_Auto	V_Manual	V_total (l)
FDM 1	0	0	0	**0**
FDM 2	0	0	0	**0**
FDM 3	0	0.5	0	**0.5**
FDM 4	0	0.5	0	**0.5**
FDM 5	0	0.5	0	**0.5**
JET 1	0	0	10.9	**10.9**
JET 2	0	0	15	**15**

Table 3. Electrical energy estimation

	Estimated (Wh)							**Real (Wh)**	**Deviation**
	Total manufacturing time	E_CAD	E_Idle	E_Preparation	E_Forming	E_Post-process	**E_total**	**E_total**	**%**
FDM 1	4h31	2.63	19.9	21.7	526	0	**571**	**585**	**2.51**
FDM 2	10h11	2.63	33.3	3.02	482	0	**521**	**533**	**2.22**
FDM 3	5h20	2.63	96.6	71	652	1033	**1856**	**1910**	**2.93**
FDM 4	3h20	2.63	1370	6.92	266	4800	**6445**	**6340**	**1.63**
FDM 5	4h22	2.63	2028	4.7	331	5400	**7666**	**7460**	**2.7**
JET 1	12h46	2.63	1092	47.3	4478	18.5	**5638**	**5711**	**1.31**
JET 2	3h51	2.63	539	48.8	2106	97.6	**2794**	**2620**	**6.22**

Table 4. Material estimation

	Estimated	**Real**	**Deviation**	**Estimated**	**Real**	**Deviation**
	M_Part	M_Part	%	M_Support	M_Support	%
FDM 1	81.5	78.8	**3.31**	11.4	10.1	**11.4**
FDM 2	92.3	90.1	**2.38**	13	11.2	**13.9**
FDM 3	65.3	62.8	**3.83**	12.4	11.1	**10.5**
FDM 4	65.5	63.3	**3.36**	14.8	13.7	**7.43**
FDM 5	52.9	50.4	**4.73**	18.9	16.5	**12.7**
JET 1	224	210	**6.25**	78.7	72.9	**7.37**
JET 2	224	209	**6.70**	53	46.3	**12.6**

Table 5. Cost estimation

	Estimated				**Real**	**Deviation**
	C_Equipment	C_Material	C_Staff	**C_Total (€)**	**C_Total (€)**	%
FDM 1	6.02	4.35	4.26	**14.6**	**14.8**	**1.37**
FDM 2	5.46	4.35	4.26	**14.1**	**14.2**	**0.71**
FDM 3	17.6	34	8.52	**60.1**	**60.4**	**0.50**
FDM 4	10.4	22.8	8.52	**41.7**	**42.5**	**1.92**
FDM 5	90.2	28.1	8.52	**126.8**	**125.3**	**1.14**
JET 1	51.1	106	5.86	**163.1**	**164.4**	**0.76**
JET 2	78	51.1	5.96	**135.1**	**133.1**	**1.48**

Table 6. Surface roughness estimation

	Ra_Area-A (µm)		**Deviation**	**Ra_Area-B (µm)**		**Deviation**
	Estimated	Real	%	Estimated	Real	%
FDM 1	13.3	14.5	**9.02**	15.5	16.6	**7.10**
FDM 2	16.6	18.8	**13.3**	19.5	22.6	**15.9**
FDM 3	11.8	13.3	**12.7**	13.8	15.2	**10.1**
FDM 4	16.6	18.8	**13.3**	19.5	22.6	**15.9**
FDM 5	16.6	18.8	**13.3**	19.5	22.6	**15.9**
JET 1	-	3.5	**-**	-	4.7	**-**
JET 2	-	7.4	**-**	-	9.2	**-**

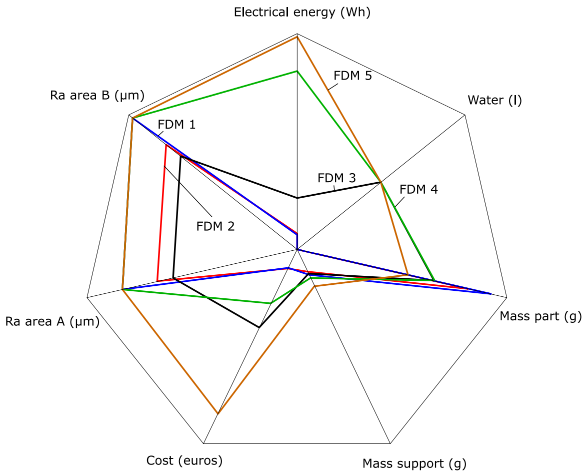

Fig.4. All FDM machines

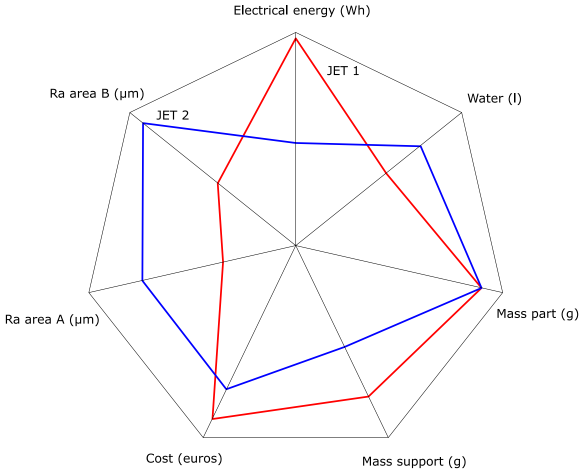

Fig.5. All material jetting machines

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