Environmental Impact Assessment Studies in Additive Manufacturing

Olivier Kerbrat, Florent Le Bourhis, Pascal Mognol and Jean-Yves Hascoët

Abstract This chapter focuses on the environmental studies in additive manufacturing. For a cleaner production, environmental impacts that occur during the manufacturing phase should be assessed with accuracy. First, the literature on all the studies led to the characterisation of the environmental impact of additive manufacturing processes. The studies on electric energy consumption of these processes are analysed here, and then some studies taking into account raw material and all the flows through the process are detailed. Secondly, a new methodology in order to evaluate, with accuracy, the environmental impact of a part from its CAD model is presented. In this methodology, the work is not focused only on electrical consumption but also on fluids and material consumption which also contribute to the environmental impact. In addition, the inputs of this methodology correspond to the set part process, which allows taking into account different manufacturing strategies and their influences on the global environmental impact. The methodology developed is based on both analytic models (validated by experiments) and experimental models. And finally, an industrial example shows that for some manufacturing strategies, the environmental impact due to electrical consumption is not the predominant one. In this case study, material consumption has an important impact and has to be taken into consideration for a complete environmental impact assessment.

Keywords Additive manufacturing · Environmental impacts · Product design optimization · Life-time performance · Electric energy consumption

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S.S. Muthu and M.M. Savalani (eds.), *Handbook of Sustainability in Additive Manufacturing*, Environmental Footprints and Eco-design of Products and Processes, DOI 10.1007/978-981-10-0606-7_2

1 Introduction

This chapter gives an overall view of the environmental impact assessment applied to additive manufacturing processes. As young as the additive processes are compared to more traditional ones, the literature on this topic is relatively recent, but the number of publications drastically increases. A whole methodology to assess environmental impact is presented, with a case study in laser cladding, a directed energy deposition process. It is divided into three main sections.

The first section of this chapter is a literature review. The aim of this section is to give a precise view of what has been done when assessing environmental impact in additive manufacturing. It is divided into three subsections. In a first approach, focus is put on studies dealing with electrical energy consumption. The link between manufacturing strategies, part's orientation, process parameters, and the whole electrical energy consumption is established, based on a literature review (Luo, Mognol, Bourell, Baumers, Verna, etc.). The objectives of these studies could be to help to compare additive processes between themselves and with more 'traditional' processes (machining). At the end of this subsection, a comparative table is given to classify processes and machines considering their energy consumption rate (in KWh/kg).

Secondly, focus is put on material consumption. In fact, additive manufacturing is known to produce parts without lost material. However, a certain amount of material should be removed from the machine or the part at the end of the process. In order to reduce the environmental impact due to this lost material, a few studies (Dotchev, Gornet, etc.) try to develop methodologies to reuse (with or without new raw material) or recycle this raw material.

Finally, some studies evaluate the environmental impact considering energy, material, and fluid consumption. A few methodologies, such as the CO2PE! Initiative (Kellens, Duflou, etc.), are based on a global input–output inventory and take into account energy consumption, resource consumption, and process emissions.

Based on this state of the art, the second subsection is constituted of a whole methodology for environmental impact assessment when considering an additive process. The methodology considers the part's design and machine technology. It allows us to determine the environmental impact of the set part process. The methodology is divided into three steps: raw material preparation impact, process impact, and lost material recycling impact.

The methodology is based on predictive models that are developed to evaluate the environmental impact of the whole flux consumed (electricity, material, and fluids) during all manufacturing steps. The models concern all the features of the machine that contribute to the global environmental impact. It is a local (features)–global (impact) approach, based on an accurate modelling of the process.

Then, the third section is a case study on laser cladding, a directed energy deposition process. Fluid, material, and energy consumptions are calculated, directed from the CAD model of the part, in order to establish a predictive environmental impact assessment, during all manufacturing steps (from material extraction to powder recycling). The results can help the designers to choose the best geometry for the part when taking into consideration the environmental impact of the product in its manufacturing step.

2 Literature Review

2.1 Introduction

The first environmental studies on AM processes put forward the possibilities of gain in terms of environmental impact compared with the more traditional processes such as machining [1]. Indeed, only 10 years after the development of the first industrial AM machines, studies on the environmental impact of these processes were conducted. This was due to the necessity of taking into account these aspects, with the aim of favoring the large-scale development of the AM processes. AM already offers a new freedom of design, but their industrial development will be more important if these processes have a lesser environmental impact [2].

Five years ago, Hao et al. from the University of Exeter proposed a study allowing putting forward the possibilities offered by the AM processes to minimise electric energy consumption during manufacturing [3]. They expressed five major areas for AM to generate positive environmental impacts:

- *Material utilisation*: AM can efficiently utilise raw materials and their functionality. Nonconsolidated raw materials in a powder-based process such as powder bed fusion can be reused so that the material waste can be minimised.
- *Product design optimisation*: The free-form fabrication nature of AM enables optimisation in the design of the products. The optimal design will result in the reduction of the materials, energy, fuel, or natural resources in the product manufacturing.
- *Manufacturing process*: The AM has the potential to replace processes where significant amounts of energy are wasted, such as casting or moulding. It can also save many resources spent on the fabrication of specific tooling for production.
- *Supply chain*: As a direct digital manufacturing approach, the AM machines can be distributed closer to customers and managed by a Web-based system to coordinate the demands and requirements of product stakeholders and maximise the efficiency of the supply chains. This can reduce the need of long-distance transportation, warehousing, logistics, and, for many cases, disposable packaging.
- *Life-cycle performance*: AM can be used to repair and add advanced functions to existing products and as such the life-time performance can be extended.

In this section, we focus on the studies which led to the characterisation of the environmental impact of AM processes. In the first part, the aspects of electric energy consumption of these processes is analysed, because most of the studies deal with electric energy consumption. In the second part, we are interested in the works that are specifically on the consumption of raw material, because it is one of the main advantages of these processes. In the third part, we study the few works that take into account all the flows consumed to determine an associated environmental impact. And at the end of this section, we show the possibilities offered by AM processes on the whole life cycle of a product.

2.2 Electric Energy Consumption of AM Processes

2.2.1 First Study: Luo et al.

In a first approach, in order to estimate the environmental performance of AM processes, a number of studies were interested in their electric energy consumption. This first approach allows us to compare, on a simple criterion, the AM processes between themselves and even to compare them with the more traditional ones.

The first works led on the energy aspects were conducted by Luo et al. [4, 5]. In their studies, the authors compare three SLA machines. An equation gives the scanning speed, a second one gives the process productivity, and then the energy consumption rate (ECR, kWh/cm^3) is calculated, and the environmental impact of the energy used to process one cm^3 of epoxy resin is obtained (with eco-indicator index). The results show that the machine with the highest laser power, resulting in the highest scanning speed, has the least ECR.

These first studies are interesting because they propose a first comparison of the processes between themselves. There were completed to compare different machines by Sreenivasan et al. [6]. But these studies take into account the energy consumption of the manufacturing processes by considering only the machine, and not all the sensitive parameters (shape of the part, positioning, etc.) that can modify the ECR by modifying the power rate of the machine during the process.

2.2.2 Influence of the Manufacturing Orientation

Most of the AM processes use the concept of layer-by-layer manufacturing. This concept requires the implementation of a slicing of the part to be produced. One of the first studies taking into account the set part process to determine the electric consumption of an AM machine was proposed by Mognol et al. Indeed, to evaluate the influence of the slicing orientation of the part on the energy consumption of the machine, test parts were produced considering different manufacturing orientations and the electric energy consumption during the manufacturing has been measured.

This has been done on three technologies (material extrusion, material jetting, and powder-based fusion) [7, 8].

Figure 1 illustrates the various orientations of the part taken into account in this study. This work allows us to put forward the major influence of the manufacturing orientation on the machine consumption. This most important parameter is the total manufacturing duration, which is strongly dependent on the height to be produced. Therefore, the more important the manufacturing time is, the more important the energy consumption of the machine is.

On the same criterion of optimisation of the manufacturing orientation, Verma et al. proposed a study allowing the minimisation of the electric energy consumption and the material consumption, depending on the orientation [9]. The authors developed a multistep optimisation enabling the AM process towards energy efficiency (Fig. 2). Process objectives such as material waste and electric consumption are minimised both in the part and layer domains.

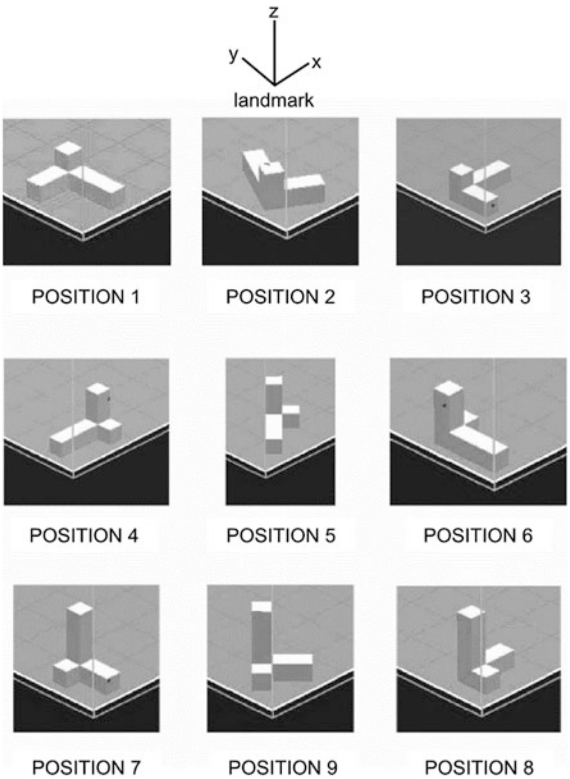


Fig. 1 The various position of the part [8]

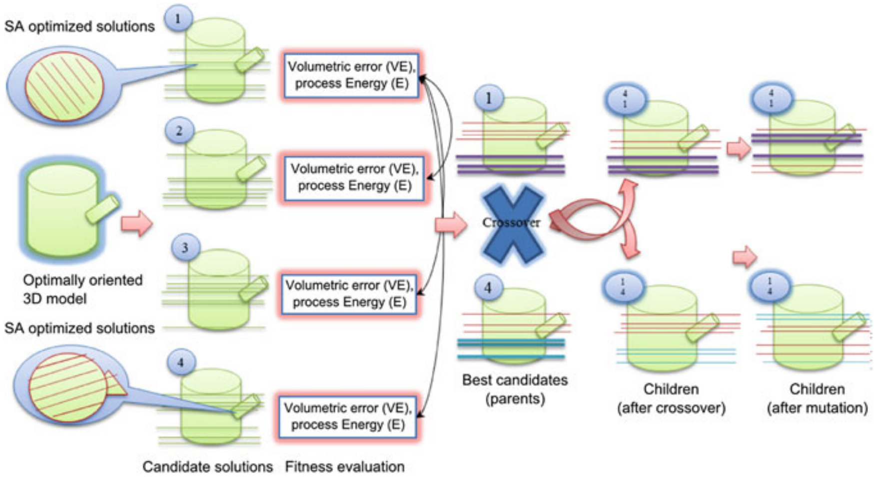


Fig. 2 Candidate solution generation and various operators on sample 3D part [9]

2.2.3 Influence of Packing Density of AM Platforms

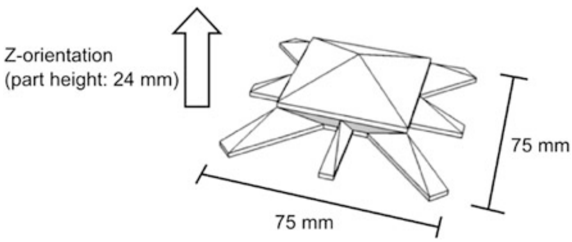
Afterward, Baumers et al. studied the influence of the geometry of the part and the packing density of the space machine on the electric energy consumption [10, 11]. In their works, they analysed the energy consumption of two machines, one SLS and one EBM.

The part used for this study is presented in Fig. 3. The part geometry was chosen to analyse the influence of the ratio section/volume and perimeter/section on the energy consumption.

Furthermore, by analysing the influence of packing density of the platform (Fig. 4) on the energy consumption, the authors show that the consumption is not linked to the number of parts realised. It confirms the other studies showing the energy consumption is strongly dependent on the height of the part.

The works realised by Mognol et al. and Baumers et al. are very interesting because they highlight the importance of the consideration of the set part process within the framework of an analysis of the electric energy consumption of the AM processes.

Fig. 3 The standardised test part [11]



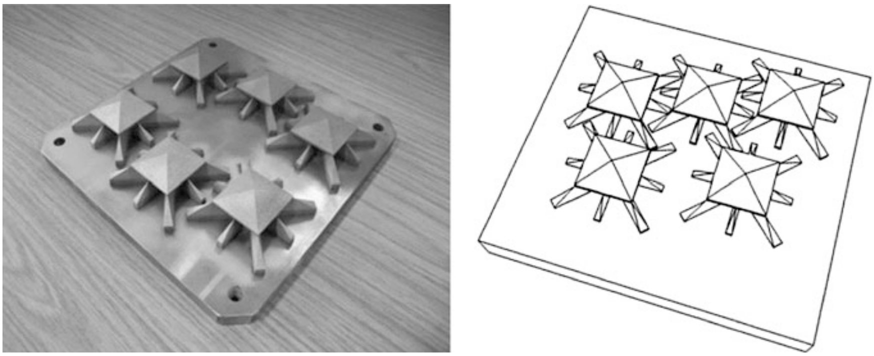


Fig. 4 Full build configuration for SLM and DMLS (*left*) and EBM (*right*) [11]

2.2.4 Comparison Between AM Processes and More Traditional Ones

At first, AM processes essentially allowed us to make plastic parts. Therefore, one of the first studies leading to the comparison of AM with other processes was interested in plastic injection [12, 13]. In these studies, Telenko et al. compared both processes from an electric energy consumption point of view. There is a large discrepancy between monetary and energy crossover volumes; this indicates that SLS may be more cost effective than energy efficient in some cases. In fact, the results of this comparative analysis of SLS and injection moulding indicate that manufacturers can save energy using SLS for parts with small production volumes.

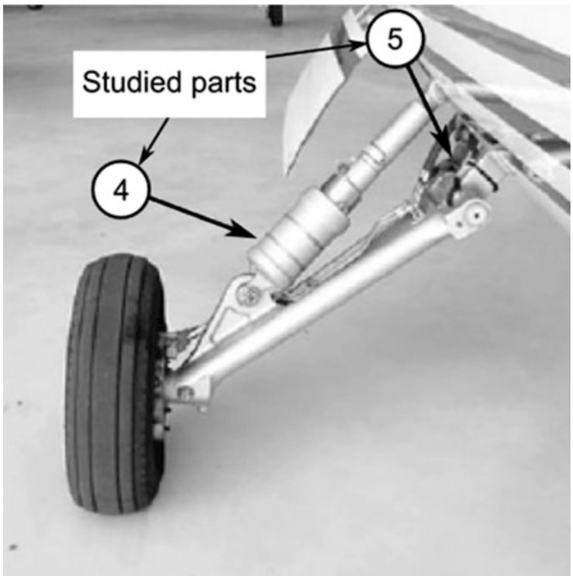


Fig. 5 Part for process comparison [14]

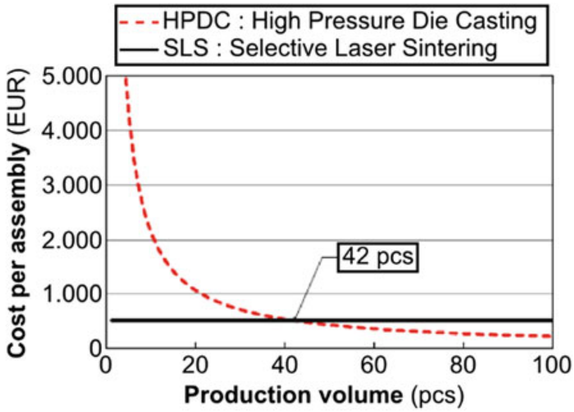


Fig. 6 Breakeven analysis comparing conventional high-pressure die-casting and selective maser sintering [14]

Energy crossover production volumes are much larger for a small part, indicating that specific crossover production volumes are sensitive to the size and geometry of the part to be produced. Nevertheless, this study does not take into account the manufacturing of the mould. This should be completed to integrate all the necessary data for an environmental analysis.

Atzeni et al. evaluated the production volume for which AM processes (selective laser sintering) are competitive with respect to conventional processes (high-pressure die-casting) [14]. In this study, they took into account the possibilities offered by AM (less material, less assembly; Fig. 5). Using an example of an aircraft part, they concluded that the breakeven point is estimated for a production of 42 components made of aluminium alloy as shown in Fig. 6.

In their study, Ruffo et al. compared, with the same criterion, injection moulding and AM processes (Fig. 7) [15]. Figure 8 shows different breakeven points between injection moulding and AM techniques for the different cost models utilised, with a comparison to the Hopkinson and Dickens model [16]. The breakeven point moved from 8000 to 14,000 parts, for plastic materials.

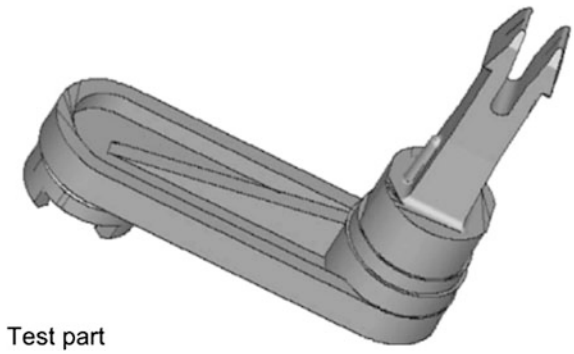


Fig. 7 Lever, object of the study [15]

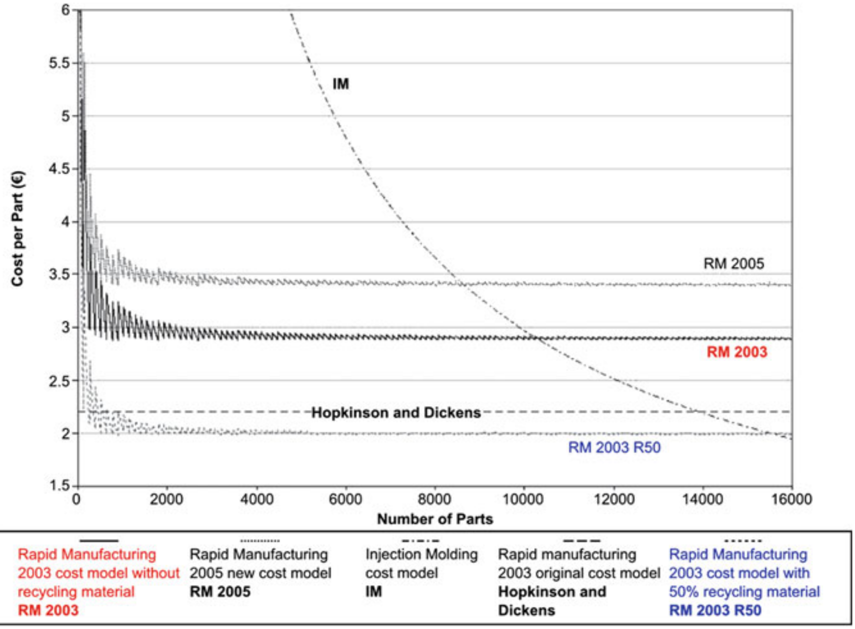


Fig. 8 Cost model comparison [15]

With the same process comparison purpose, Morrow et al. provided a study to compare AM with machining [17]. The case studies were on a mould insert and a mirror and revealed that the relative energy consumption of machining versus AM is driven by the solid-to-cavity volume ratio. At low ratios, an AM pathway minimises energy consumption and emissions, whereas at high ratios the CNC milling pathway minimises energy consumption and emissions.

More recently, Serres et al. proposed a study comparing an AM process (CLAD, a directed energy deposition process) and machining on a mechanical part manufactured out of titanium alloy (Fig. 9) [18]. This study helps to highlight that on the

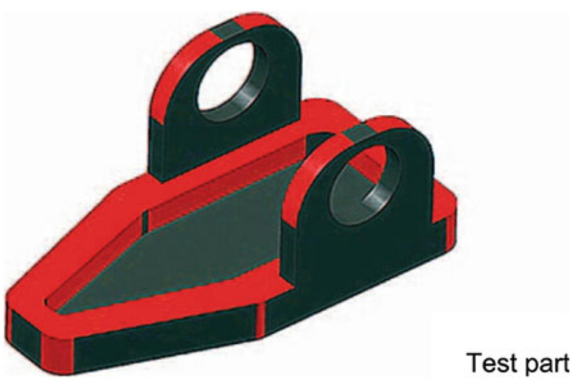


Fig. 9 Test part for the study [18]

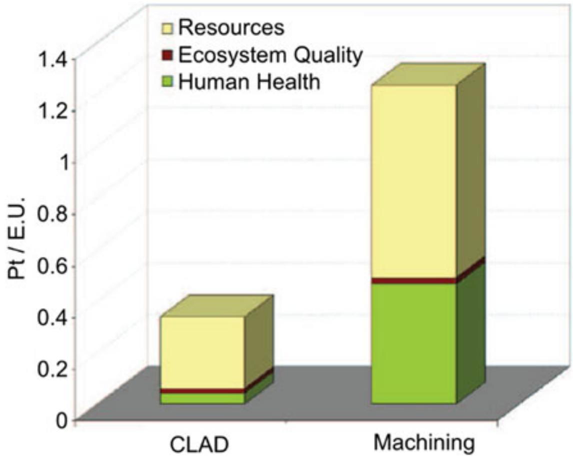


Fig. 10 Environmental impact assessment of the test part, considering two processes [18]

whole life cycle, from raw material extraction to manufacturing, AM reduces about 80 % of the environmental impacts (Fig. 10). Nevertheless, this study took into account only one part geometry for both processes, and did not consider design for manufacturing rules for optimising geometries from a manufacturing point of view.

Recently, Faludi et al. compared additive manufacturing versus traditional machining via life-cycle assessment [19] and Yoon et al. did a comparison of energy consumption in bulk forming, subtractive and additive processes [20]. They characterised the processes via their specific energy consumption (SEC), in J mm^{-3} or KWh kg^{-1}. The values of the SEC of similar additive manufacturing processes are so different, with lots of uncertainty on the method of calculation, that it is practically impossible to use SEC for an environmental performance assessment.

2.2.5 Considering Energy Consumption and Quality of the Part

Of course, a part whose geometric quality does not meet the specifications will not be accepted even if the electric energy consumption during production has been minimised.

Strano et al. have studied the correlation between the final surface roughness of the part produced and the energy consumption of the machine [21]. This study investigated a computational technology for the identification of optimal part orientations for the minimisation of surface roughness and simultaneously energy consumption in the manufacturing process. Figure 11 shows the sample geometry to be manufactured and Fig. 12 the related optimisation, represented by the Pareto set. The results show that, moving along the Pareto front, although most solutions have similar values of energy required to manufacture the part, choosing certain angles allows part quality to be increased considerably.

Fig. 11 Artefact to be manufactured [21]

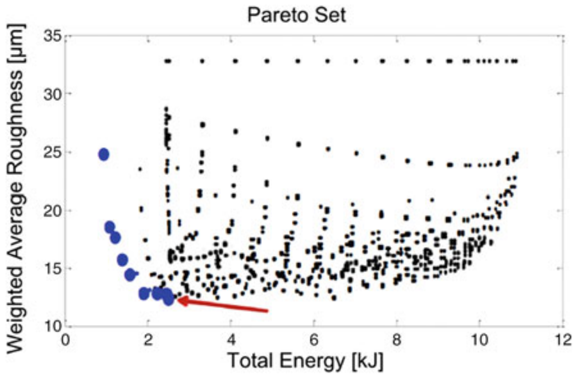


Fig. 12 Related pareto solutions [21]

This study was partially based on the modelling of the surface roughness previously proposed by Campbell et al. [22] and was recently completed in another study by Strano et al. [23].

2.2.6 Synthesis of Electric Energy Consumption Studies

This section of the literature review refers to a number of studies on electric energy consumption in additive manufacturing processes. It can be seen that it is important to consider the set part process when characterising such a process. The morphology of the part produced as well as its position and orientation in the machine space have strong influences on the final results.

Table 1 summarises all studies concerned with electric energy consumption. The specific energy consumption (SEC, in KWh/kg) is used to compare the different processes.

This table allows a first comparison between AM processes. In this table, five technologies have been studied. It is still difficult to make a machine choice, considering which one has the least environmental impact, because these machines do not allow the production of parts with identical specifications. For example, stereolithography will produce prototypes whose lifetime is limited, unlike selective laser melting or electron beam melting which will realise functional parts, whose lifetime may well be longer.

Table 1 Comparison of specific energy consumption

Technology	Machines	Materials	SEC (KWh/kg)	Parts number[a]	References
Stereolithography	SLA-250	Epoxy resin SLA 5170	33	c	[5]
	SLA-3000	Epoxy resin SLA 5170	41	c	
	SLA-5000	Epoxy resin SLA 5170	21	–	
Selective laser sintering	Sinterstation DTM 2000	Polyamide	40	c	
	Sinterstation DTM 2500	Polyamide	30	c	
	Vanguard HiQ	Polyamide	15	b	[24]
	EOSINT M250 Xtended	Metallic powder (Bronze + Ni)	710	1	[8]
	EOSINT P760	Polyamide PA2200 balance 1.0	37	63	[25]
		Polyamide PA2200 speed 1.0	40	12	
		Polyamide PA3200GF	26	11	
Fused deposition modelling	FDM 1650	ABS plastic	346	c	[5]
	FDM 2000	ABS plastic	116	c	
	FDM 3000	ABS plastic	697	1	[8]
	FDM 8000	ABS plastic	23	c	[5]
	FDM Quantum	ABS	202	c	
Selective laser melting	MTT SLM 250	Metallic powder SAE 316L	31	6	[10]
Electron beam melting	Arcam A1	Metallic powder Ti-6Al-4 V	17	5	

[a]Number of parts built in the same time during the experiments
[b]Fabrication of the entire build volume of the machine (380 × 330 × 340 mm^3)
[c]Calculation depends on the material flow

This table shows the environmental impact of the manufacturing phase, due to electric energy consumption. However, for a more complete environmental assessment, material consumption also has to be taken into account. That is the main point of the next section.

2.3 Raw Material Consumption

2.3.1 Introduction

Additive processes are seen as environmentally interesting because they seem to consume only the required material for the production of the final part. Nevertheless, whatever the technology, it cannot be considered that all the raw material consumed is found on the final part.

In 3D printing, it is necessary to consider material consumption to create the supports needed to manufacture the part. These supports will be subsequently removed either by dissolving or manually removing them. Similarly, when using selective laser melting technology, an amount of the powder present in the workspace may not be reused [26]. In powder bed or powder projection technologies, a part of the deposed material is not fused, and it is necessary to consider this raw material lost in the environmental analysis. In powder bed, all the powder present in the workspace is not merged, fused, or sintered and could require a post manufacturing treatment to be reused.

2.3.2 Powder Recycling

The use of plastic (and, of course, metallic) powders requires some attention. In fact, plastic powders are sensitive to aging which reduces their mechanical properties [27].

To avoid premature aging of plastic powders, Dotchev et al. have developed a methodology to recycle the unsintered powders [26]. In this study, they analysed the influence of the recycled powder rate mixed with fresh powder on the final part quality. The objective was to limit the 'orange peel' texture on the parts produced. Finally, they defined a methodology that could improve the powder quality control, minimise the part quality variation, and reduce the amount of fresh powder used in the laser sintering process.

Metallic powders may be sensitive to the moisture contained in the air, causing their oxidation. Usually, the nonfused powder is reused after sieving treatment, and a few studies are focused on recycling the metallic powder in AM processes.

2.4 Other Flows that Affect the Environment

The environmental performance assessment of a manufacturing process must necessarily take into account all of the flows through the process (input and output). Even if AM processes use less consumables than most conventional ones, it is therefore not possible to assess the environmental performance by considering only the electric energy consumption. The quantity of raw material used as well as waste produced during the process, all the fluids such as inert gas to prevent oxidation, and cooling fluids for the machine must also be taken into account because they contribute to the overall environmental impact.

Kellens et al. developed the UPLCI (unit process life-cycle inventory) methodology for systematic analysis of the manufacturing process [28]. They applied it to the selective laser sintering process [29–31]. This methodology took into account all the flows through the system. They analysed the electric energy consumption, compressed air consumption, and material consumption, and took into consideration the environmental impact due to powder, consumables, and emission. Figure 13 shows a schematic overview of the parametric estimation model for the SLS process.

The methodology developed by Kellens et al. allows us to comment, analyse, and improve the process knowledge, especially for manufacturing prototypes or small batch sizes. The knowledge generated by this methodology allows us to bring data on manufacturing processes to LCA databases [32]. In their work, the UPLCI methodology was applied on additive manufacturing, laser cutting, and EDM. Finally, it proposed new ways to improve these processes from an environmental

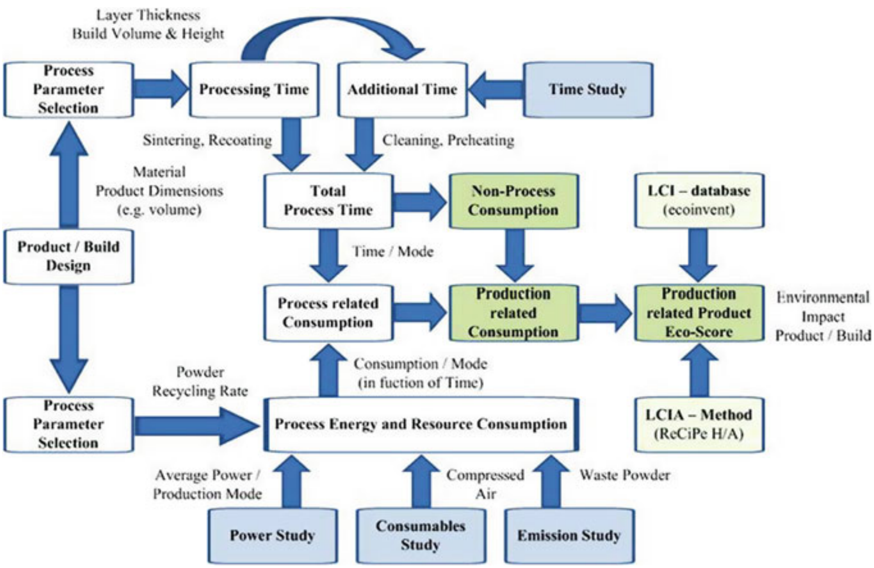


Fig. 13 Overview of the parametric impact estimation model for the SLS process [31]

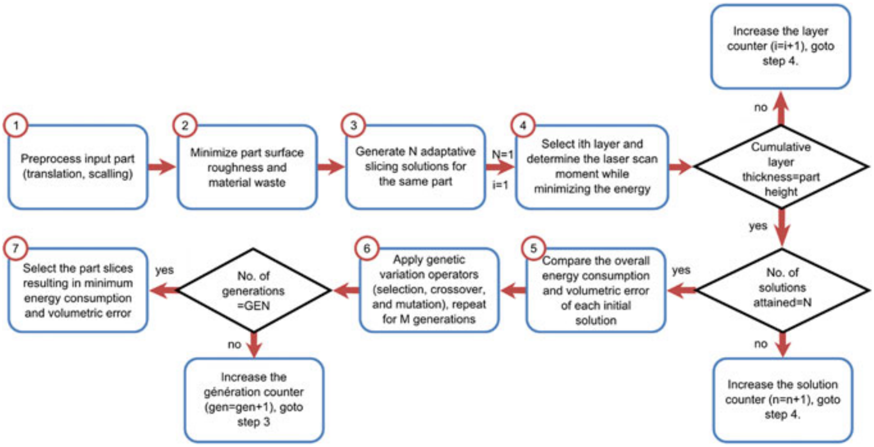


Fig. 14 The developed optimisation framework for adaptive slicing [9]

point of view, based on the electric energy consumption and on the material consumption, but also on the architecture of the machines.

Similarly, Verma et al. offered a study, also cited in Sect. 2.2.2, oriented not only on the optimisation of energy consumption but also focused on material consumption [9]. Considering these two consumption factors, they set up a multiobjective optimisation to minimise overall material consumption and power consumption. Furthermore, they imposed a certain quality of the part by coupling the aforementioned minimisation of consumption with maximising the surface quality (controlled by the surface roughness). In this study, they set up a double-loop optimisation. Initially, they optimised the overall part, minimising the amount of raw material and surface roughness. Secondly, they optimised, for every slice of the part, the electric energy consumption. Figure 14 summarises the optimisation algorithm.

This consideration of all consumption flow is an essential step for the characterisation of manufacturing processes. Studies taking into account these remarks are very recent and need to be developed with further investigations.

2.5 *Possibilities Offered by AM Processes on the Whole Life Cycle of a Product*

The studies presented in the previous sections are generally centred on the process. These studies help to compare the manufacturing processes between themselves, allowing us to make a choice on the most environmentally friendly technology in the manufacturing stage. But even if the environmental impact due to the manufacturing phase may be important, it may be negligible when considering the whole life cycle of the part. On this point, additive manufacturing may offer interesting design of parts, from an environmental point of view, on the whole life cycle. In this case, analysing the possibilities offered by the additive manufacturing process, such as topology optimisation, optimised design minimising mass, multifunction integration, and the like, could help designers to create an additive manufactured part with fewer environmental impacts than a machined one.

The collaborative project Atkins was interested in this issue [33, 34]. In this project, the authors studied all the possibilities for reducing the environmental impact of parts produced by AM processes. Apart from the already mentioned advantages in design, AM also reduces the availability time and the impacts generated by transportation (from production stage place to use stage place). Indeed, manufacturing facilities can be built close to the use stage location. The part to be produced is sent as a numerical file and will be realised close to the place of consumption. Then, this reduces the environmental impact caused by the transportation stage, which is a source of significant environmental impacts. Manufacturing companies also take advantages from additive manufacturing because they need very little time to adapt their production chain at the market; the changeover time is considerably reduced.

The Atkins project helped to highlight the possibilities of AM in order to minimise the overall environmental impact of a product. Moreover, as a result of the project, a software tool was developed as a guide in the choice of processes, with purposes to minimise the environmental impact or the economic impact. One of the major conclusions of this project was that additive manufacturing can be of great benefit in the aeronautic and transport fields, because of the mass minimisation opportunities for embedded parts.

2.6 Synthesis of the Literature Review

Efforts to characterise the environmental performance of AM processes have often focused on electric energy consumption. In this section different studies were analysed. One can realise that only a few studies were concerned with the raw material consumption or fluid consumption for these processes.

This lack of data is probably due to the youth of AM processes. However, as has already been noted in this section, it is important, in the environmental analysis context, to take into account all the flows through the process in order to assess its environmental performance precisely.

3 Environmental Impact Assessment Methodology

3.1 Introduction

In the third part of this chapter, a methodology to assess the environmental impacts of an additive manufacturing process is presented.

In the next section, as a general approach of the process leading to the production of a mechanical part, all the life-cycle stages of the part (from raw material to end of life) must be taken into consideration to correctly evaluate the environmental impacts.

In a third section, the manufacturing process is the main point. AM process modeling from an environmental point of view is done. The environmental impacts generated at this stage are mainly due to the resource consumption (material, electric, etc.) and waste production (support, etc.). An approach coupling all consumptions is presented.

Finally, the fourth section summarises the contributions of such a methodology.

3.2 General Approach

The methodology for evaluating the environmental impacts of AM processes that is presented in this chapter aims to open the scientific locks that have been outlined in the literature review.

This methodology, based on an accurate knowledge of manufacturing processes, allows the analysis of the environmental performance and takes into account two aspects. The first one is interested in the whole life-cycle stages of the part (Fig. 15). The second is focused on the process's objectives to estimate quantitatively all the resource consumption of the set part process (Fig. 16).

The production of mechanical products is generally made by the succession of stages. Indeed, parts are rarely produced directly by using only one single process. Figure 15 shows one of these sequencing stages.

It is thus necessary to take into account all the stages needed for the manufacturing of the part. Indeed, a vision being interested only in one stage can lead to a wrong analysis because the environmental impacts which could be minimised during a stage can be drastically increased in another one. For instance, when

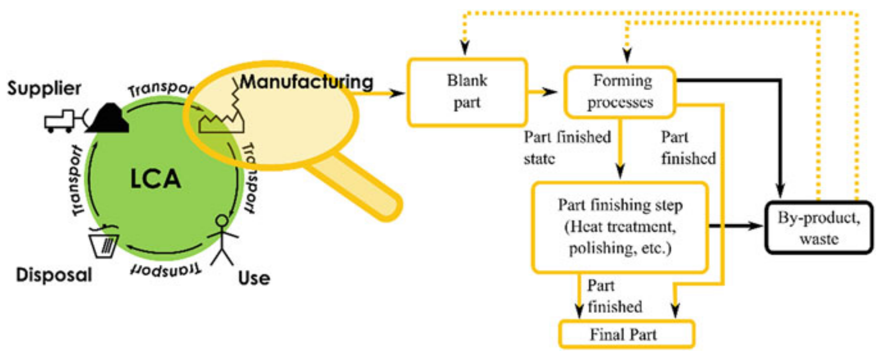


Fig. 15 Life-cycle stages and the manufacturing phase

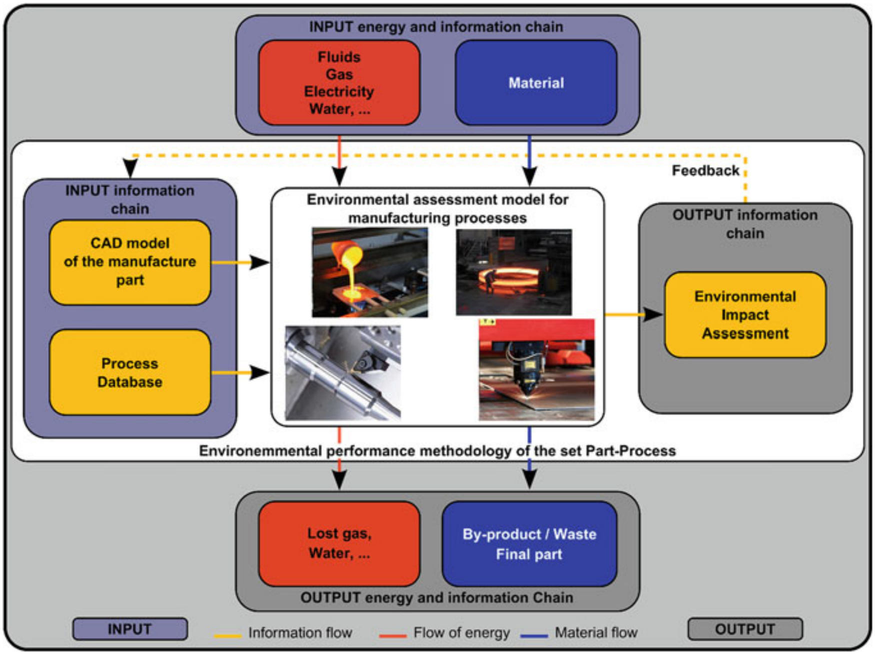


Fig. 16 Methodology for assessing environmental impact of a set part process

considering a directed energy deposition process such as projection of powders, it seems little sensible to be interested only in the manufacturing stage without being concerned in the stage of production of powder or the finishing postprocess. That is why a global approach, as proposed by life-cycle analysis, must be used to estimate the environmental performance of a manufacturing process.

Then the proposed methodology is thus interested in all the stages of manufacturing a product. In particular, the stages taken into account are listed below.

– *Raw material production.* In an AM process, raw materials are most of time plastic filament, plastic or metallic powder, or liquid resin.
– *Shaping*. This stage consists, thanks to a set of manufacturing substages, in transforming the raw material, obtained in the previous stage, into a finished or semi-finished part.
– *Postprocessing*. This last stage allows us to obtain the final dimensions and expected characteristics of the part. For example, it concerns the support removal operations; some finishing processes such as machining, polishing, or laser polishing; and so on.
– *Waste recycling*. This waste can be of various materials such as unsintered powder or support material, or fluids needed during manufacturing, among others.

The knowledge of all manufacturing stages is essential to propose a global and accurate assessment of environmental impacts. From this knowledge, it is then possible to define a modelling of each stage from an environmental point of view. This is the main topic of the next section.

3.3 Manufacturing Process Modeling

3.3.1 Framework and Limits

In life-cycle analysis, data concerning the manufacturing processes could be extracted from databases (for instance, Ecoinvent). What is found in these databases is just a macroscopic vision of the processes, with a global average value for characterising each process. Now this global vision does not allow us to take into account the influence of the manufacturing parameters (strategies, feed rate, temperature, etc.) on the final energy consumption. So these data often suffer from accuracy. Furthermore, they are only a 'picture' of a process and do not allow us to put forward the relation between manufacturing parameters, the part to be produced, and the total environmental impact. And AM processes are still not referenced in such databases.

Therefore, a modelling of the manufacturing stages, taking into account all input parameters of the machine is necessary. The objective of this model is at first to be able to predict all the consumption-generating impact during the process, and then, secondly, to set up a minimisation loop by modifying design parameters or manufacturing parameters.

Figure 16 presents the global vision of the developed methodology. The figure illustrates the necessity of taking into account all the flows of materials, energies, and information in the manufacturing stages modelling.

From the well-detailed knowledge of the manufacturing process, translated as predictive models, it is then possible to link part design and environmental impacts during manufacturing. The aim is thus to link the environmental impact due to the part production to its numerical model.

The first stage necessary is to define all the flows which will be taken into account and consequently the limits of the study. Indeed, in the developed methodology, even if it has been suggested to take all the flows, it is quite evident that certain limits must be set before completing the study.

Figure 17 shows the limits imposed on a manufacturing process, in the case of a directed energy deposition process. Similar limits may be easily constructed for other processes. In this figure, it can be noticed that the consumption of inert gas, compressed air, hydraulic fluids, and metallic powders, as well as electricity are taken into account during the environmental impact assessment. It is important to underline that the chosen limits are similar to the 'system boundaries' as defined in the standard ISO 14955-1, Machine tools—Environmental evaluation of machine tools, Part 1: Design methodology for energy-efficient machine tools [35]. Indeed,

Fig. 17 Directed energy deposition (CLAD) process

the inert gas production, hydraulic fluids production, and compressed air production are not included in the system boundaries. The manufacturing of the machine is also not within the scope of the study. It would be possible to extrapolate the study by including the production of all the inputs and the manufacturing of the machine. It would be interesting because such a study would allow us to show that an optimal choice of components (axes motor drives, for instance) as well as the architecture of the machine allows the optimisation of its energy consumption during its use phase (when manufacturing a product). These studies have already been conducted by Kroll et al. [36] and Nuyen et al. [37].

3.3.2 Input Data

In the methodology, the goal is to remain centred on the set part process. Indeed, based on the literature review in the previous section, geometry of the part as well as its positioning in the machine workspace could influence the process consumption in terms of material or energy.

The major input data of the methodology is the numerical model (CAD model) of the part. It could allow the modification of its geometry, and furthermore, it is possible to advise designers with a software tool which will indicate the areas of the part for which the environmental impact could be optimised.

The second input data are based on a well-detailed knowledge of the manufacturing process, more specially the process parameters, path trajectories, axes motor drives, cooling unit system, and the like. This knowledge is stored in a database, defining the AM process in the set part process, which will be used during the environmental impact assessment.

3.3.3 A Multistep Methodology

Figure 18 presents a global view of the developed methodology. This methodology has for its objective to link the environmental impact (output) to the numerical model (input) in a set part process approach.

Different methods can be used to classify the impacts caused on the environment. In this study, the method is Eco-Indicator 99, which is a method-oriented damage classifier and translates all the impacts into a unique point value, a nondimensional number used to compare the different sources of impacts [38]. The value of 1 point is defined by a thousandth of the environmental impact caused by a common European during a year. For comparison, the production of 1 kg of primary steel is around 100 mPts and the production of 1 kg of stainless steel is around 900 mPts. The choice of this method has been made because it was the one used in most of the studies on environmental assessment of additive processes that have been analysed in the state of the art.

This methodology is decomposed into four steps:

– Numerical programme generation
– Extraction of the command parameters

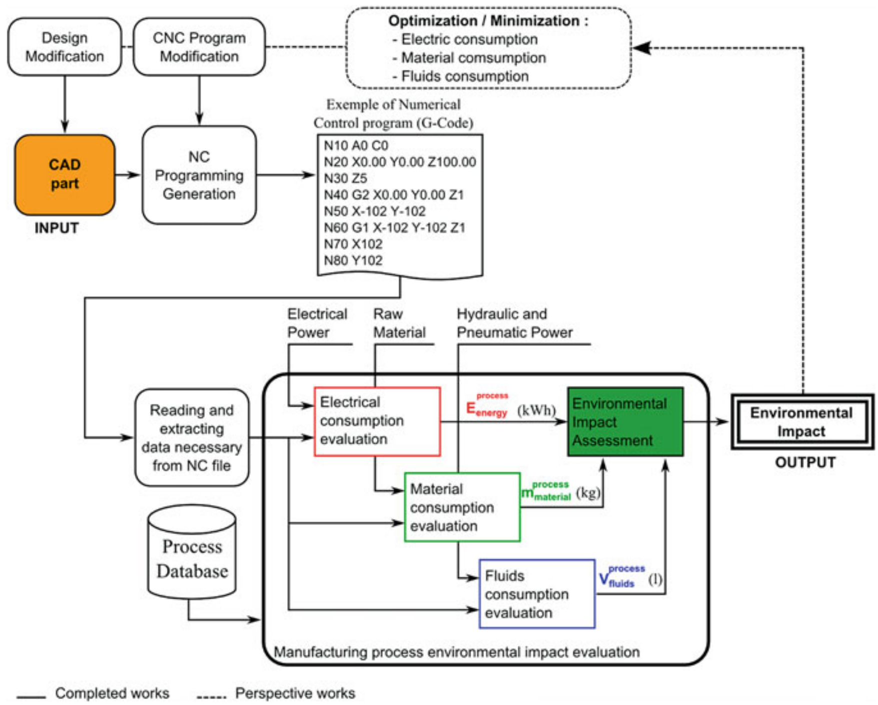


Fig. 18 Environmental performance assessment methodology of the set part process

– Construction of process database
– Environmental impact assessment

These steps are detailed in the next section, which also gives complementary information on the methodology.

4 Application to Directed Energy Deposition

4.1 Introduction to Directed Energy Deposition Process

This study is based on a directed energy deposition process, known as the CLAD process, which manufactures 3D metallic parts from a CAD model. In this process, a five-axis deposition nozzle, where metallic powders are injected into the laser beam, creates a small melt pool on the workpiece which is cooled down when the laser beam moves on. The part is built as the nozzle moves. Figure 19 shows the design of the nozzle, with laser beam, and an example of a part produced by the machine. The machine is equipped with two kinds of nozzles, which allows us to obtain a welding bed from 0.8 mm (the MesoCLAD nozzle) to 4 mm (the MacroCLAD nozzle). The machine structure is a five-axis machine tool (Huron KX8), with its conventional machining spindle (for machining operations such as finishing), in which were added the two nozzles, two powder feeders (for raw material powder), and a 4-kW fibre laser.

4.2 Atomisation of Raw Material

The first step for the process is to produce powder (metallic, ceramic, glass) which will be introduced in the machine. An atomisation process is used to obtain this powder (Fig. 20).

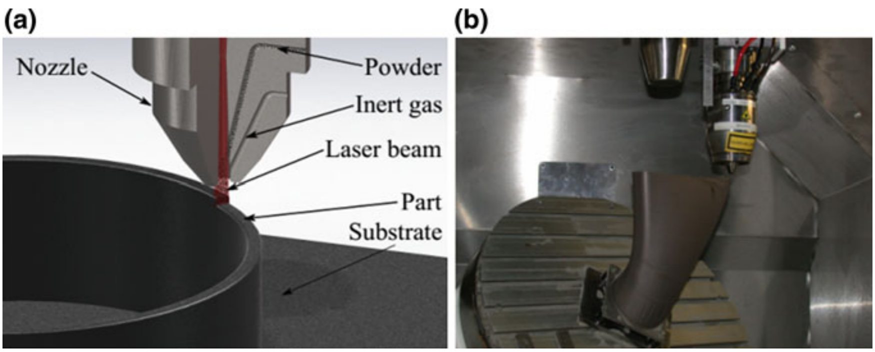


Fig. 19 **a** CLAD nozzle design; **b** example of part produced by this AM process

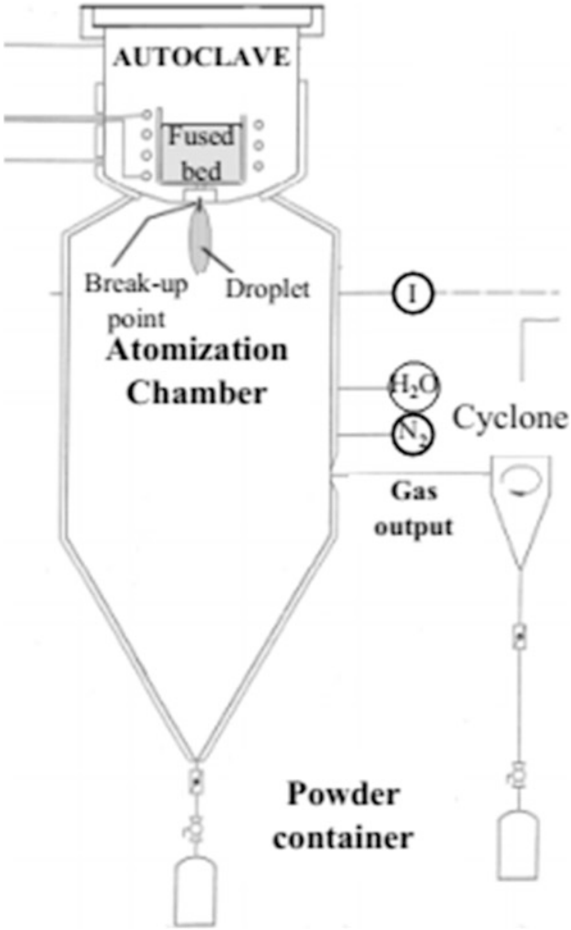


Fig. 20 Atomisation process

In this process, raw materials (from block or cylinder) are heated to melting point in a chamber and then atomised with an inert gas (in the case study: argon). This atomisation consists of compressing, under high depression, the metallic fluid which will be atomised into small droplets in reaction to depression.

In this process, many values can be saved and it is possible to establish a model for the atomisation step. The model is made with experimental values such as

- Gas consumption
- Water consumption
- Electrical consumption

Table 2 shows all the parameters that have been monitored or calculated during experiments on the atomisation process in order to build the modeling of the process.

Table 2 Nomenclature for atomisation process

Parameters	Name	Units	Saved/calculated
V_{argon}	Volume of consumed argon	Cubic metre	Calculated
d_{argon}	Argon flow rate	Cubic metre per second	Monitored
ρ	Gas density	Kilogram per litre	–
V_{water}	Volume of consumed water	Litre	Calculated
d_{water}	Water flow rate	Litre per second	Monitored
$t_{atomization}$	Time for atomisation	Second	Monitored
$E_{electrical}$	Electric energy	KWh	Calculated
$P_{inductor}$	Electrical power of the inductor	Watt	Monitored
$P_{depression}$	Electrical power of the vacuum system	Watt	Monitored
t_{vacuum}	Total time of the vacuum system ON	Second	Monitored
$P_{preheating}$	Electrical power of the preheating system	Watt	Monitored
$t_{preheating}$	Total time of the preheating system ON	Second	Monitored

4.2.1 Gas Consumption

Gas consumption is linked to the volume of the inert chamber and the atomisation step. Figure 21 shows the variation flow of argon in the chamber, during the atomisation of 1 kg of metallic glass.

From these experimental data, an empirical modelling for gas consumption is determined, according to Eq. (1):

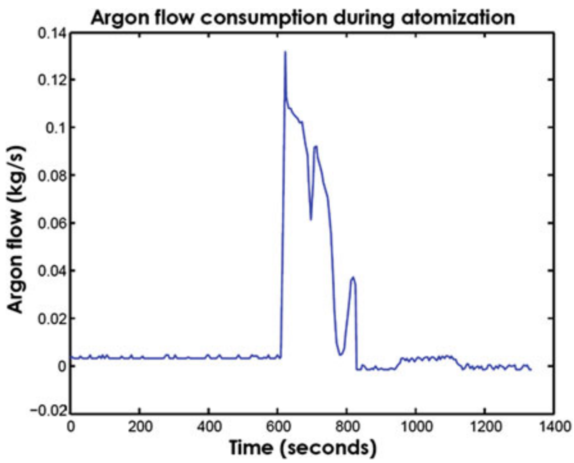


Fig. 21 Argon flow consumption

$$V_{\text{argon}} = \frac{1}{\rho} * \int_{0}^{t_{\text{atomisation}}} d_{\text{argon}} * \mathrm{d}t \qquad (1)$$

4.2.2 Water Consumption

In this system, water runs in a closed-loop system. However, an amount of used water is released into nature and a corresponding amount of fresh water is obtained because the cooling system is not efficient enough. The total volume of consumed water is calculated according to Eq. (2):

$$V_{\text{water}} = d_{\text{water}} * t_{\text{atomisation}} \qquad (2)$$

4.2.3 Electrical Consumption

Electrical consumption is due to different features of the machine (inductor, preheater, vacuum pump). Figure 22 shows a profile of the inductor electrical consumption during the atomisation process.

From this experimental monitored value, an empirical model for electrical consumption is determined according to Eq. (3).

$$E_{\text{electrical}} = P_{\text{depression}} \times (t_{\text{atomisation}} + t_{\text{vacuum}}) + P_{\text{preheating}} \times t_{\text{preheating}} + \int_{0}^{t_{\text{atomisation}}} P_{\text{inductor}} \cdot \mathrm{d}t \qquad (3)$$

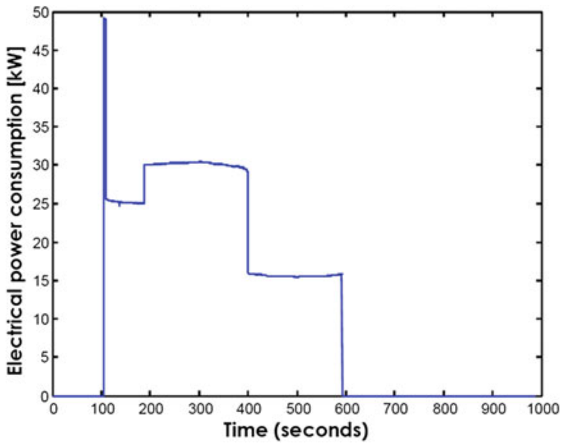


Fig. 22 Inductor electrical power consumption during atomisation

Table 3 Values of the experimental data monitored and calculated

Input consumption	Value
Gas consumption	7 m^3
Water consumption	155 l
Electrical consumption	4 kWh
Efficiency	46 %

Table 3 presents the results of the study for 1 kg of glass powder atomisation. These values will help to elaborate the complete environmental assessment.

4.3 Environmental Performance Modeling for the AM Process

According to the methodology presented in Fig. 18 the environmental impacts generated in the manufacturing stage are modeled from three inputs:

- Electrical consumption
- Material consumption
- Fluids consumption

For each input's consumption, a model based on an empiric model or analytical model has been developed. These models allow evaluation of the global environmental impact of the part from its CAD model. From the CAD model, a G-code file is created which will give the instruction for the machine. From this file, every parameter required to evaluate the environmental impact is extracted.

As well as what has been done for the atomisation process, Table 4 shows all the parameters monitored during the experiments or calculated.

For environmental impact assessment, the Eco-Indicator 99 has been used, with the following characterisation factors:

- $fc_{\mathrm{argon}} = 1.78$ mPts.kg^{-1};
- $fc_{\mathrm{material}} = 86$ mPts.kg^{-1};
- $fc_{\mathrm{elec}} = 12$ mPts.kWh, corresponding to the French electricity production characterisation factor.

4.3.1 Fluid Consumption

Fluid consumption is due to the inert gas used during the process which allows us to project and protect metal powder in the melting pool. In this study, the inert gas is argon; it is the same gas for the two functions. Its consumption varied during the manufacturing step and depends on the part morphology. An environmental impact is associated with the inert gas consumption during the manufacturing step, according to Eq. (4).

Table 4 Nomenclature for directed energy deposition process

Parameters	Name	Units	Saved/calculated/machine knowledge
EI_i	Environmental impact for substance *i*	mPts	Calculated
t_{man}	Manufacturing time	Second	Monitored
d_c	Desired carrying gas	Kilogram per second	Monitored
d_f	Desired forming gas	Kilogram per second	Monitored
k	Weight factor (lost/fused powder)	–	Machine knowledge
d_p	Powder flow rate	Kilogram per second	Monitored
e_n	Nozzle efficiency	Kwh	Machine knowledge
$g(Pl)$	Function for laser electrical power consumption	–	Monitored
t_{laser}	Switch-on time such as $t_{\text{man}} = t_{\text{laser}} + \overline{t_{\text{laser}}}$	Second	Monitored
$Pc_{\text{stand-by}}$	Power consumed by the cooling system in standby mode	Watt	Monitored
Pc_{on}	Power consumed when the cooling system works	Watt	Monitored
Pe_i	Electrical power consumed by the *i*-axis	Watt	Monitored
Pe_{idle}	Constant electrical power demand	Watt	Monitored

$$E.I._{\text{fluids}} = [dc + df] * t_{\text{man}} * fc_{\text{argon}} \tag{4}$$

4.3.2 Material Consumption

Now, the focus is put on the determination of the powder consumption during part manufacturing. In fact, an advantage of the additive manufacturing process is to project and fuse exclusively the necessary powder. However, this is not the reality and an amount of powder will not be fused in the directed energy deposition process.

In the studied machine, two different kinds of nozzles can be used to project the powder. Their efficiency is not the same. Moreover, the efficiency of each nozzle depends on the desired powder flow rate.

An analytic model is proposed for the material consumption estimation during part manufacturing, according to Eq. (5):

$$EI_{\text{material}} = [en + k * (1 - en)] * dp * t_{\text{man}} * fc_{\text{material}} \tag{5}$$

4.3.3 Electric Consumption

In each machine, electric components can be classified into two categories. Some features have constant energy consumption such as electrical cabinet and hydraulics components. For the other components, their electrical energy consumption depends on the part design but also on machine parameters.

The modelling of each feature of the directed energy deposition machine has been done and published by Le Bourhis et al. [39]. In this section, the results are summarised with Eq. (6) in which can be found the environmental impact of each component.

$$E.I._{\text{electricity}} = \left(g(Pl) * t_{\text{laser}} + Pc_{\text{standby}} * t_{\text{man}} + (Pc_{\text{on}} - Pc_{\text{standby}}) * t_{\text{on}} + \left(\sum_{i=1}^{5} \int_{0}^{\text{tman}} Pei(t) * \mathrm{d}t \right) + Pe_{\text{idle}} \right) * fc_{\text{elec}} \tag{6}$$

4.3.4 Lost Powder Recycling

In this process, a nonnegligible amount of material is projected but not fused. It seems important to propose a method to recycle this powder. In fact, AM processes could be seen as environmentally friendly only if all the powder projected is used.

The lost powder cannot be used without treatment. In fact, this powder could cause several damages to the machine and needs to be sieved and dried before being reused. Some studies have been conducted to determine that this recycled powder has the same mechanical properties as fresh powder.

4.4 Industrial Example

4.4.1 Case Study Introduction

The example below illustrates the possibility of the environmental impact assessment methodology. It is based on a case study presented by Le Bourhis et al. [40].

This example is an aeronautic part which is at this time produced by conventional machining. More than 80 % of raw material is machined to produce this part. In this example, the focus is on nozzle choice. As it has been previously mentioned, this directed energy deposition process uses two kinds of nozzle. Which one is more ‘environmentally friendly’? The methodology helps to answer this question.

4.4.2 CAD Part

The part presented (Fig. 23) is composed, amongst others, with a pocket 200 mm square and 80 mm in depth. The part thickness is 4 mm. In this study, the answer is how to know which nozzle is better to manufacture the pocket. In fact, is it possible to choose in the NC programme generation which nozzle will be used?

4.4.3 Different Manufacturing Strategies

In this case, with the nozzle called MacroCLAD, the part can be produced in one trajectory by layer but the laser power demand will be very high (around 3 kW). However, if the smaller nozzle, called MesoCLAD, is used, the part needs five trajectories of 0.8 mm width by layer with a smaller laser power demand (around 250 W). The methodology developed allows us to choose which nozzle must be used to minimise the environmental impact of the manufacturing process.

4.4.4 Environmental Impact Results

The model used enables the evaluation of the environmental impact of each manufacturing strategy. This methodology is formalised on an informatics tool for designers. The first step is to read the G-code of the CAD model and extract all the values that are needed to evaluate the environmental impact such as laser power, trajectories, axis speed, and so on. From these values it is possible to calculate and preprocess the expected consumption. The results are given either in scientific units (kWh, litre, or kilogram) or in environmental units (mPts). The second unit allows comparing the different flow consumptions amongst them.

The results are shown in Fig. 24 and Table 5.

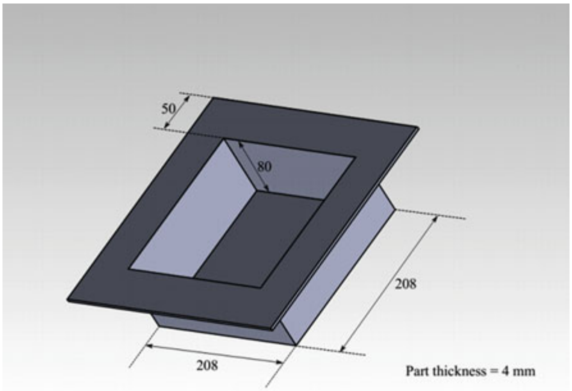


Fig. 23 Part model

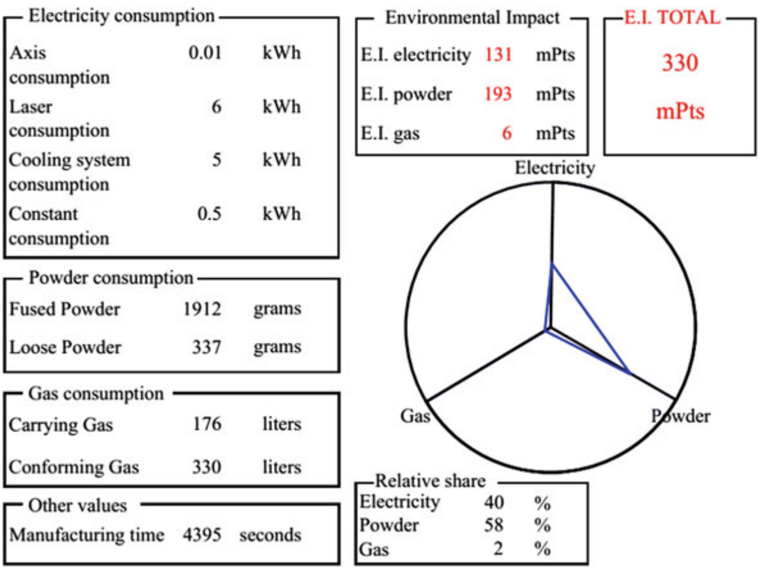


Fig. 24 MacroCLAD results

Table 5 Complete study results

Input consumption	Scientific units		Environmental impact (mPts)	
	MacroCLAD	MesoCLAD	MacroCLAD	MesoCLAD
Electricity	12 kWh	109 kWh	131	1332
Powder	2.249 kg	3.824 kg	193	328
Fluids	0.5 m^3	9.5 m^3	6	122
Time	4395 s	78,872 s		

These results show two different kinds of consumption. In fact, even if the power laser demand is more important for MacroCLAD than for MesoCLAD, the total energy consumption to build the same part is less important for MacroCLAD. That is because the time to manufacture the part is drastically reduced when using the MacroCLAD nozzle (in this case study, it obviously depends on the CAD model). Furthermore, the efficiency of the MacroCLAD nozzle is more efficient, around 80 % contrary to 35 % for MesoCLAD. Thus the powder consumption is less important too.

To conclude, the methodology would help the designer to determine, directly from its CAD model, which process could generate the lesser environmental impact. For this part, it should be interesting to manufacture it with the MacroCLAD nozzle, from an environmental point of view.

5 Conclusion

In this chapter, two main points are developed. First, the literature on all the studies led to characterising the environmental impact of AM processes. The studies on electric energy consumption of these processes are analysed, and then some studies taking into account raw material and all the flows through the process are detailed.

Second, a new methodology in order to evaluate, with accuracy, the environmental impact of a part from its CAD model is presented. In this methodology, the work is not focused only on electrical consumption but also on fluids and material consumption which also contribute to the environmental impact. In addition, the inputs of this methodology correspond to the set part process, which allows taking into account different manufacturing strategies and their influences on the global environmental impact. The methodology developed is based on both analytic models (validated by experiments) and experimental models.

And finally, an industrial example shows that for some manufacturing strategies, the environmental impact due to electrical consumption is not the predominant one. In this case study, material consumption has an important impact and has to be taken into consideration for a complete environmental impact assessment.

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http://www.springer.com/978-981-10-0604-3

Handbook of Sustainability in Additive Manufacturing
Volume 2
Muthu, S.S.; Savalani, M.M. (Eds.)
2016, VIII, 114 p. 73 illus., Hardcover
ISBN: 978-981-10-0604-3