Eco-design and Additive Manufacturing: Analysis and proposals

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Résumé :

Aujourd'hui, de nouvelles technologies de fabrication sont apparues, telles que la fabrication additive (FA) qui permet de créer des formes complexes sans recourir à des outils spécifiques. En outre, la fabrication pour l'environnement est devenue une obligation pour les fabricants afin de maintenir leur position sur le marché. Il est donc nécessaire d'évaluer écologiquement ces nouvelles technologies depuis la phase CAO dans le but de choisir le procédé de fabrication le plus écologique pour une pièce donnée. Cet article présente une revue de la littérature de différents travaux reliant la FA à l'éco-conception. Nous introduisons d'abord des recherches évaluant de manière environnementale les différentes méthodes de fabrication additive. Deuxièmement, nous présentons un examen critique des travaux présentant des processus de conception pour la FA. Enfin, nous proposons une approche d'éco-conception pour la fabrication additive depuis la phase CAO.

Abstract:

Today, new manufacturing technologies has emerged such as the additive manufacturing (AM) that allows creating complex shapes without resorting to specific tools. Also, Environmentally Conscious Manufacturing Process (ECMP) has become an obligation for manufacturers to maintain their market position. Hence it is necessary to assess environmentally these new technologies till CAD phase in the aim to choose the most ecological manufacturing process for a chosen part. This paper presents a literature review of different works relating AM to eco-design. First we introduce researches assessing environmentally the different additive manufacturing methods. Second, we present a critical review of works presenting design processes for AM. Finally, we propose an approach for eco-designing products for AM in CAD phase.

Mots clefs: Eco-design, Additive manufacturing, Environmental Impacts, CAD

1 Introduction

The concept of Industry 4.0, also called industry of the future, has been formalized since 2011 by the Germans [1]. The concept is based on the vision of connected factories, made flexible and intelligent thanks to the networking of machines, products and individuals. Processes can be modeled at all scales and "cyberphysics systems" are optimized to provide customized products for each customer at the cost of mass production. The Internet of Things makes it possible to follow the life and the use of the product and to offer additional complementary services.

New technologies, such as additive manufacturing (AM) and various process and material improvements, improve the efficiency of smart factories processes and reduce their environmental impact and the workload.

Today, 19% of the world's greenhouse gas emissions are due to manufacturing activities [2], and that the additive manufacturing is more and more mastered to pass from the use only for the prototyping towards the industrial production of the small series [3]. Hence, its impacts on the environment should be assessed.

The goal of this paper is to propose an approach for eco-designing products for AM in the CAD phase by exploring works done before in this context. This preventive methodology would allow the designer to make an informed choices in the design phase knowingly the environmental impacts (EI).

2 Additive Manufacturing Process Chain: An overview

According to ASTM F2792 [4], additive manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. There are many different types of AM processes; which can be classified either by:

- The nature of the materials used: plastic, metallic, ceramic or composite [5]
- The principle associated with the process: Laser melting, Laser Polymerization, Thermal Extrusion, Material Jetting, Material Adhesion and Electron Beam [6]
- The status of the material used to create the object during the process (1)

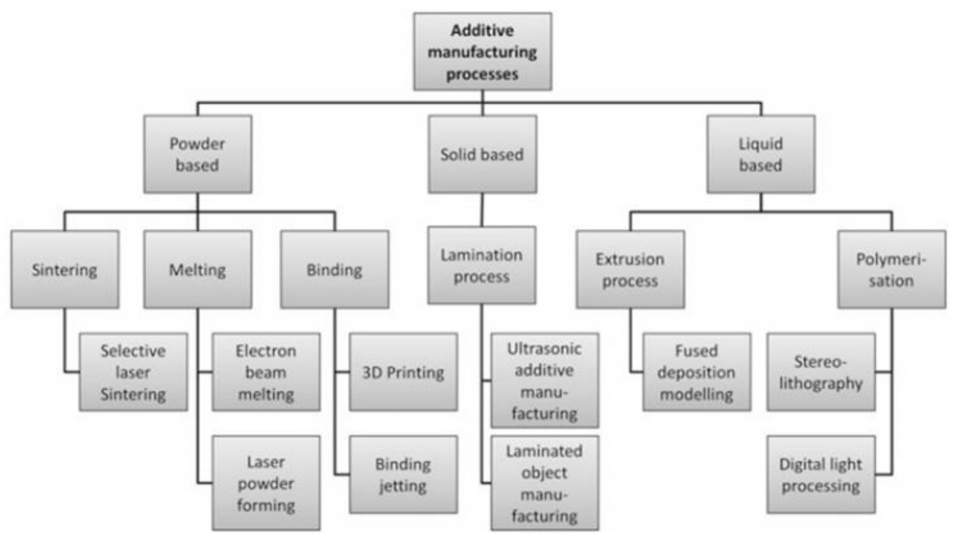


Fig. 1 Additive manufacturing processes classification according to status of the material [9]

Gibson et al. explain in their work [7] these AM processes and technologies with details. According to them, AM process sequence consists in eight key steps (figure 2).

It has been raised by these authors eight key steps in the AM process sequence. Additive manufacturing starts with a three-dimensional CAD product. The stereolithography format (STL) is generated to continue then through an additive process manufacturing step of successive deposit layers of trajectory-controlled material. Once the product is obtained, it is necessary to clean it or/ and to post-process it before it can be functionally used.

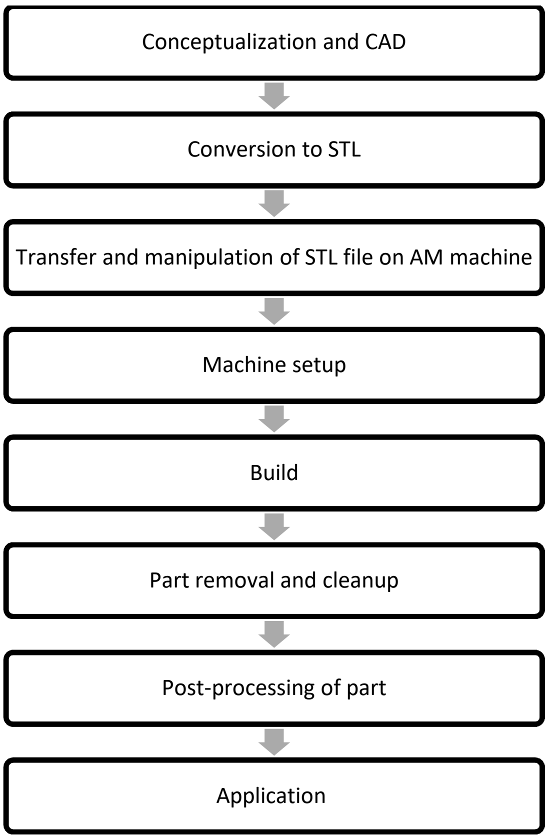


Fig. 2 Eight key steps in the AM process sequence

The design of a new product intended to additive manufacturing therefore has direct impacts on traditional logistics chains. 3D printing technology for example enables organizations to bypass the conventional supply chain and manufacture their own products (Fig. *3*). The main impacts [8, 9] of additive manufacturing on supply chain management are:

- Faster production cycle based on sending digital files
- Reduced time to market
- More simple manufacturing processes : reduction of tools even total elimination of specific tools
- Production of a very customized products and assembly
- Decrease of the production of waste in the stages of production
- Decrease of the weight of the finished parts thanks to the topological optimization [10]

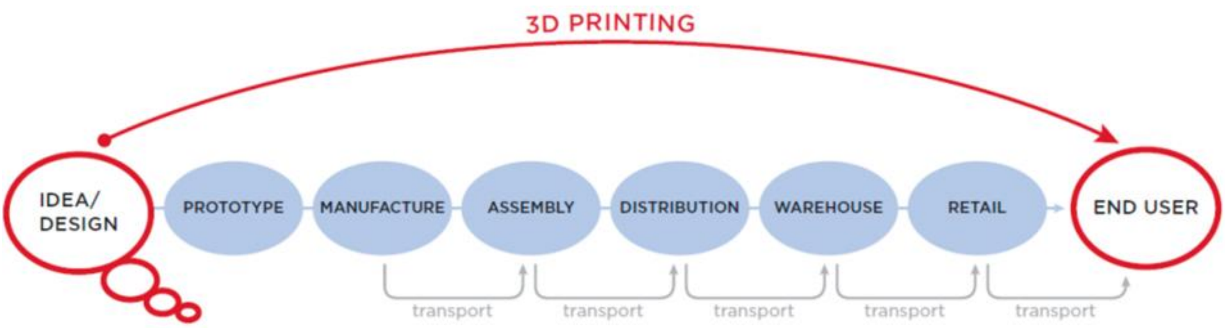


Fig. 3 A comparison between traditional and 3D printing supply chain [11]

3 Environmentally conscious AM: state of the art

On a purpose to recommend environmentally clean machining processes, Byrne and Scholta [12] presented three principal methods for minimizing environmental impact. The first one was to modify existing processes. The second was to replace existing ones by alternative processes. Or, as a third method to develop a new manufacturing process technologies to replace conventional machining. AM could be considered part of the last one.

The characterization of the AM processes sustainability dealt with three aspects: economic, social and mainly environmental one. From a common economic and environmental point of view, the AM processes could be considered in favor of sustainable development in so far as they imply:

- Less transportations efforts, than a more efficient supply chain
- Greater material utilization
- A reduced amount of material loss and waste
- Direct recycling is possible
- Suitable process for zero stock management
- Most of the time, no specific tools are needed (molds, etc.)

But there are not only advantages, unfavorable aspects has been identified such as:

- The high energy consumption
- Some artefacts may need a rework to enhance their quality therefore more impacts will be generated
- A higher manufacturing time than conventional processes ones

Studied technology	Machines	Materials	ECR (kWh/kg)	Environmental impact (mPts/kg)
Stereolitho-graphy	SLA-250	Epoxy resin SLA 5170	32.48	18.51
	SLA-3000	Epoxy resin SLA 5170	41.41	23.60
	SLA-5000	Epoxy resin SLA-5170	20.70	11.80
Selective Laser Sintering	Sinterstation DTM 2000	Polyamide	40.01	22.81
	Sinterstation DTM 2500	Polyamide	29.77	16.97
	Vanguard HiQ	Polyamide	14.54	8.29
	EOSINT M250 Xtended	Metalic Powder (Bronze + Ni)	5.41	3.09
	EOSINT P760	Polyamide PA2200 Balance 1.0	36.50	20.81
		Polyamide PA2200 Speed 1.0	39.80	22.69
		Polyamide PA3200GF	26.30	14.99
Fused Deposition Modeling	FDM 1650	ABS Plastic	346.43	197.47
	FDM 2000	ABS Plastic	115.48	65.82
	FDM 8000	ABS Plastic	23.10	13.16
	FDM Quantum	ABS Plastic	202.09	115.19
Selective Laser Melting	MTT SLM 250	Metalic Powder SAE 316L	31.00	17.67
Electron Bean Melting	Arcam A1	Metalic Powder Ti-6AI-4V	17.00	9.69

Fig. 4 Environmental impacts of different AM machines using Eco-Indicator 95 [13]

The AM processes social impacts has been qualitatively studied by some authors. Indeed it has been noticed by [4] that some AM technologies is accessible to a wide communities in developing and developed countries. Since the 3D printing is cheap, it becomes a widespread technology in different applications, fields and societies. This ease to access to this type of AM technology could be seen in two different and contradictory points of view. In one hand, it is considered as an opportunity of equal chance in access to technology and an ease in added value generation for a better customer satisfaction by the fabrication of a user-oriented products. In the other hand, the greater accessibility to 3D printing could cause spurious prototype-making as was the case to desktop printers which have generated a significant consumption of papers.
Studies done on the impacts of the AM technologies (Fig. ***7***): consider: energy use, material toxicity and waste.

- **Energy use**

One of the major environmental concerns for AM in the literature is energy consumption. More specifically the electrical consumption of the AM machine during the process [13, 14, 15]
The massive energy *ECR* used during the process is calculated by dividing the electric power consumed during manufacturing by the process productivity. The environmental impact is then calculated by multiplying this ECR by a factor issue from the Eco-Indicator method database (Fig. **4**).

- **Material toxicity**

According to Malshe et al. [16] the majority of the material safety data sheets data recognize that handling or inhaling vapor from epoxy resin materials used in AM machines can lead to skin irritation, severe eye irritation and possible allergic skin reactions

- **Waste**

Based on some case studied it has been raised up that using additive technologies could reduce up to 40 % the waste of raw material in comparison with subtractive technologies. It has also been noticed that 95 % to 98 % of the remaining material may be recycled [17].

3.1 LCA models for AM

Considering the environment only as a constrained function during the early design phase, which is qualitatively evaluated, till now is considered a very restrictive approach. Indeed, nowadays we talk about eco-design, which is a design approach taking into account all the environmental impacts of a product on its whole life cycle phases, not only qualitatively but even quantitatively through a Life Cycle Analysis (LCA). The ISO 14040 LCA framework [18] is used by several researches [16, 17, 19, 14] to quantify the environmental impact assessment (Fig. ***5***).

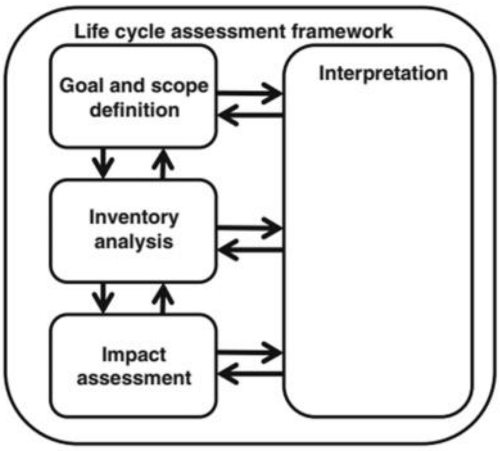


Fig. 5 Stages of an LCA according to ISO 14040 [18]

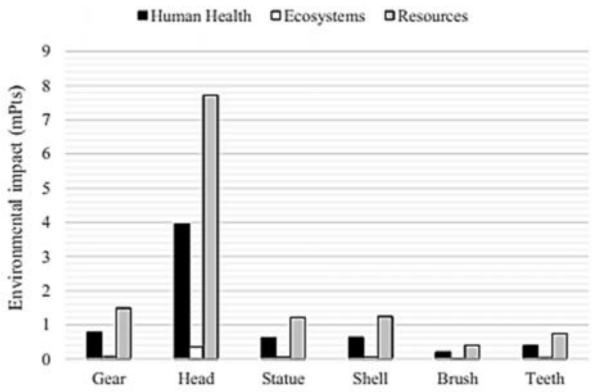


Fig. 6 Environmental impacts of six parts studied by Malshe et al. [16]
(METHOD: RECIPE ENDPOINT (H) V1.03/WORLD RECIPE H/A)

As showing by **Erreur ! Source du renvoi introuvable.**, six different parts produced by the fast mask-image-projection based stereolithography (Fast MIP-SL) AM process has been studied. The life cycle inventory has been developed, the ReCiPe 2008 method was selected to determine the environmental impacts of the process. This results show that huge damage is made to resource depletion (64%) and to human health (33%). the brush, with the lowest mass and second shortest build time, exhibit the lowest impact, whereas the head causes the main environmental impact, with his greatest mass and longest build time.

3.2 Environment comparison between AM vs traditional machining

LCA, based on the ReCiPe EndPoint H methodology, was conducted by Faludi et al. [17] using SimaPro software to evaluate environmental impact of a chosen two parts. Embodied impacts, has been evaluated in the whole life cycle phases:

- Transportation
- Energy used during manufacturing
- Energy used while idling and in standby
- Material used in final parts
- Waste material generated
- Cutting fluid for CNC
- Disposal

Therefore, they have compared quantitatively the environmental impacts of AM with CNC machining. Fossil fuel depletion, climate change, acidification, eutrophication, human toxicity, ecotoxicity and other impact categories has been evaluated and the following conclusion has been made: the main impacts, for CNC and AM machines, were detected during the machine's usage. Looking closer to this production phase, it was found out that [17]:

> *"For three-dimensional (3D) printers, electricity use is always the dominant impact, but for CNC at maximum utilization, material waste became dominant, and cutting fluid was roughly on par with electricity use"*

It is largely knowing that energy use during processing is one of the largest impacts of machining [20], but it has been showing by some other researchers [17] that it is not always true. When comparing various manufacturing parameters of different rapid prototyping systems, Mognol et al. [21] find out that the manufacturing time is the most important parameter. Therefore, in order to reduce the electrical energy consumption, we have to minimize the duration of the production phase. An optimization of the process parameters, in order to reduce the manufacturing time, whether for AM or traditional machining should be done.

Impacts of CNC milling machines	
	energy use
	tool utilization
	embdied energy
	cutting fluid
	injury
	machine end-of-life
	chips and scarps: material waste

Impacts of AM	
	energy use
	material toxicity
	material waste (support material, leftover mass)

Fig. 7 Environmental impacts of AM and CNC technologies

4 Design methodologies for AM

4.1 Methodologies for Early Design Stage (EDS)

A methodology for conceptual design stage has been introduced by Markou et al. [22] in a context of a Design to Environment approach. The implementation of the proposed methodology (Fig. ***8***) is based on creativity session where dedicated supports in terms of environmental decisions are needed to guide the choices. Supports like a LiDS wheel adapted for additive manufacturing, a table describing the different AM processes in terms of AM category, AM technology, Material capability (metal/polymer), Material state (powder/liquid), Energy consumption rate (ECR) (kWh/kg), Inert gas, Post-processing method and need in Water (Yes/No) has been used successfully to support environmental decisions in creativity sessions.

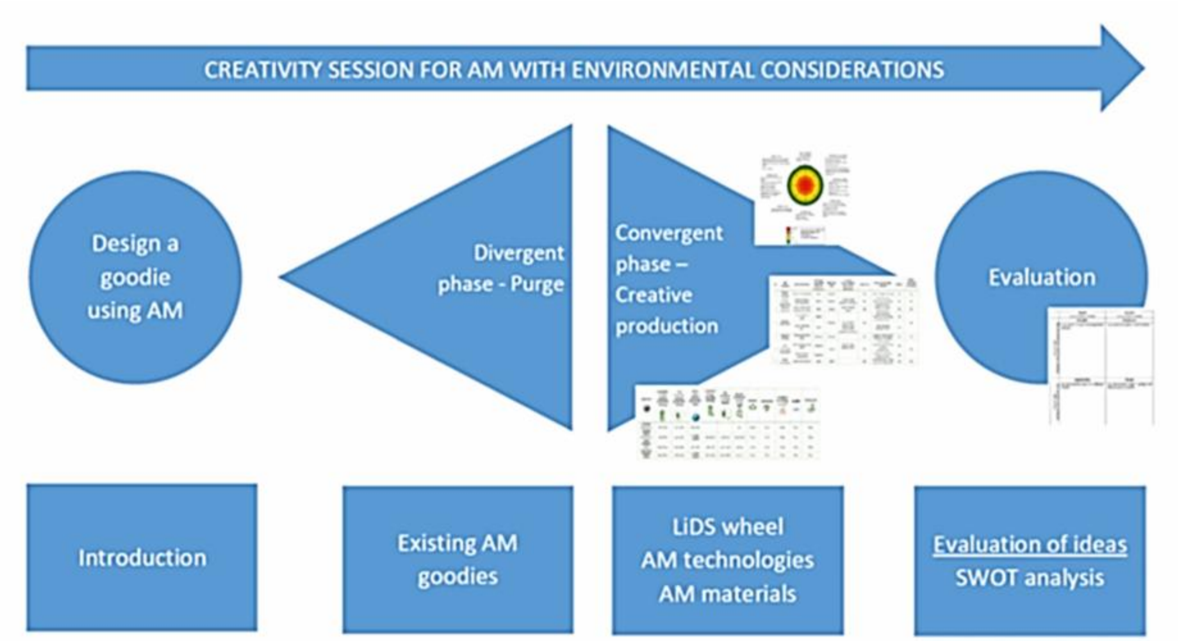


Fig. 8 New methodology for creativity session [22]

4.2 Methodologies for Detailed Design Stage (DDS)

In his thesis, Ponche [23] proposed a novel methodology organized in four main stages:

- The definition of a design domain: which has to be defined taking into account the manufacturing orientation or directions to be used to manufacture the part and the general characteristics of the machine
- The definition of the final theoretical geometry of the product
- The definition of the corresponding realistic geometry: on this step the selection of a trajectory strategy is going to be required

- The estimation of the geometry: optimal geometry and the corresponding manufacturing strategy can then be identified and proposed to the user

As for Gaha et al. [24, 25], they proposed a features-based model to integrate CAD and LCA systems. Their methodology (Fig. ***9***) consists on exploring features technology to calculate the environmental impact of an artifact till the detail design phase. This methodology is general and can be applied in all manufacturing processes; among others the AM ones.

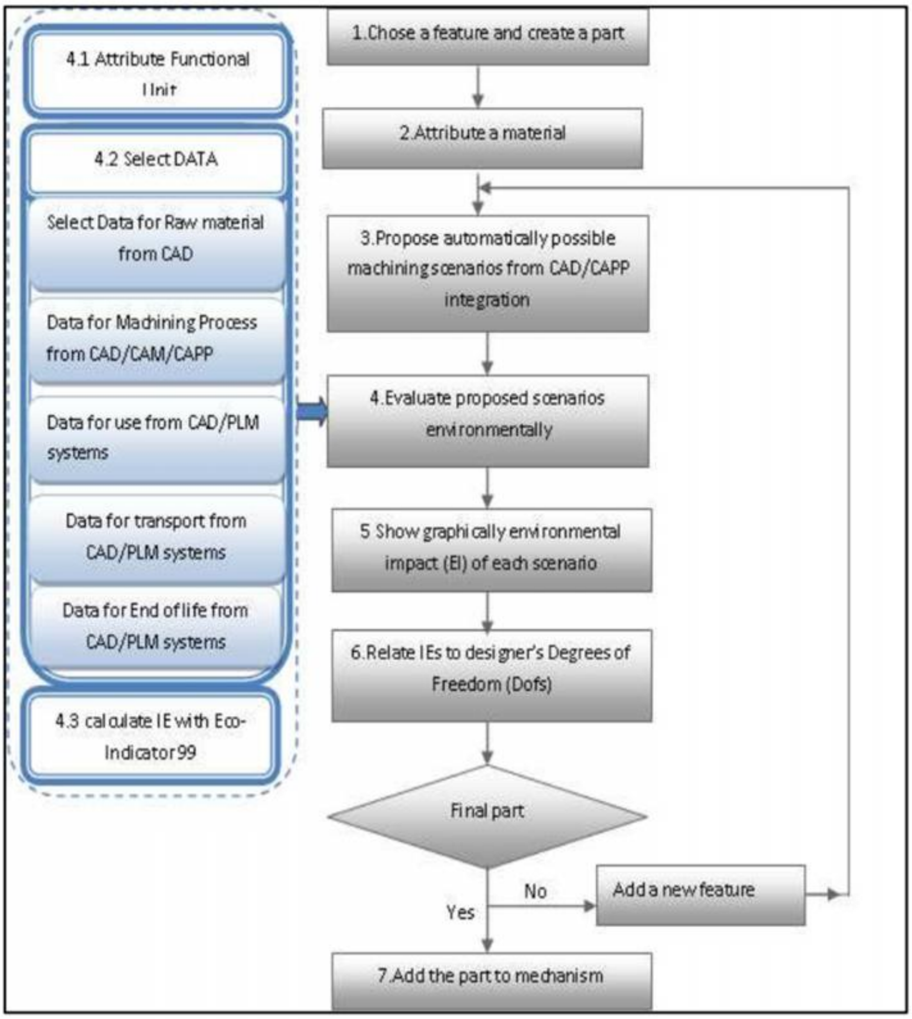


Fig. 9 Gaha methodology for Eco-designing products based on feature technology [24]

In the purpose to help designer to decide which process could generate the reduced environmental impact, Kerbrat et al. [26] have proposed a four steps methodology:

- Numerical programme generation
- Extraction of the command parameters
- Construction of process database
- Environmental impact assessment

For each of the three input's consumption (electrical, material and fluids consumption), the evaluation of the global environmental impact of the part from its CAD model using empiric model or analytical one can be made. Fig. ***10*** explains this environmental performance assessment methodology more explicitly.

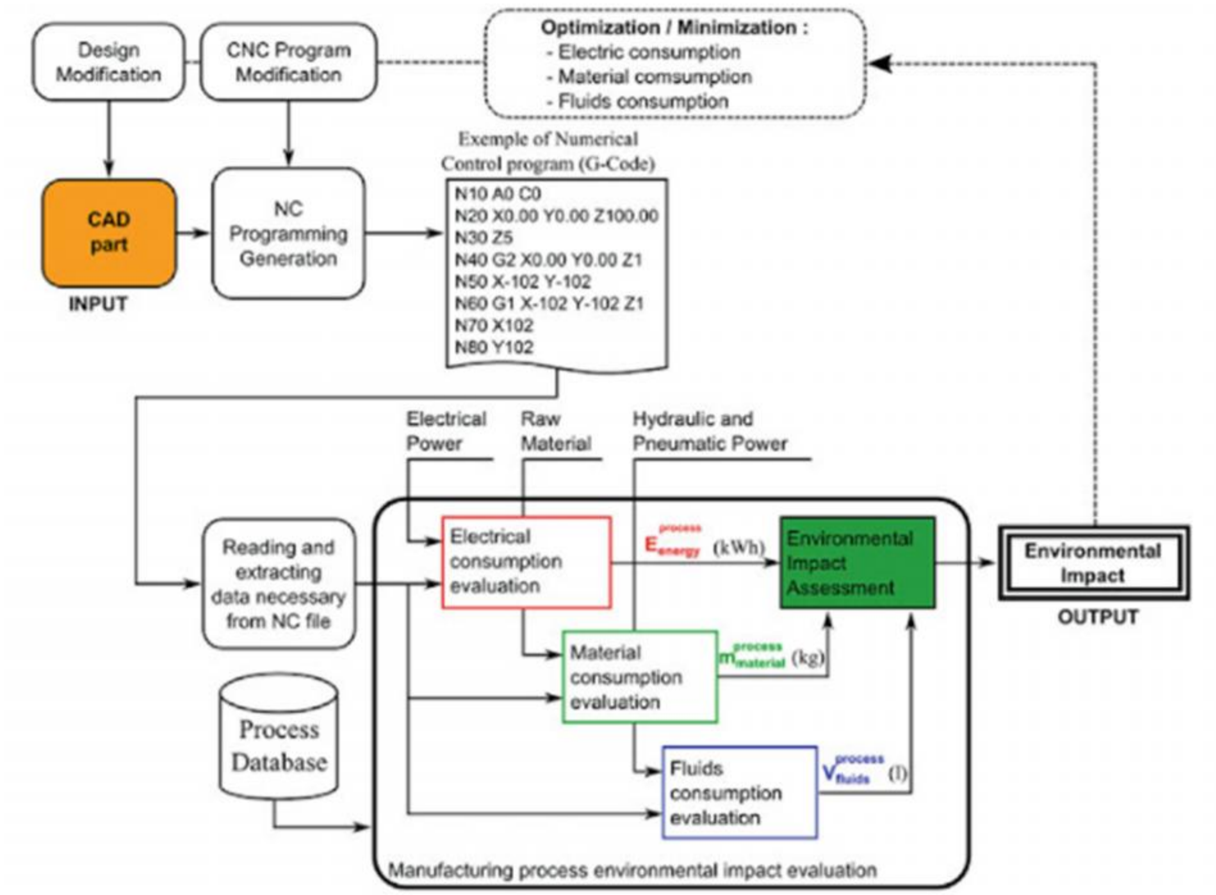
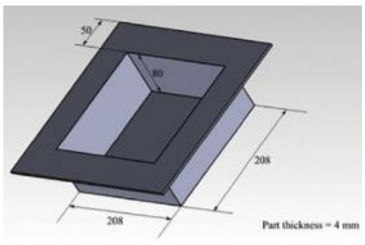


Fig. 10 An environmental performance assessment methodology [4]

An industrial case study has been conducted using the Kerbrat methodology. Two different manufacturing strategies depending on the nozzle type has been considered: the smallest nozzle needs smaller laser power (about 250W) opposed to the bigger one whose demand on laser power will be very high (about 3 kW). The part (Fig. ***11***) has been built by the directed energy deposition process, which is a 3D metallic AM.



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		

(a) Part model (b) Study Results

Fig. 11 Case study results [4]

The used methodology enables the evaluation of the environmental impact (Fig. ***11***) of each manufacturing strategy: MacroCLAD relative to the big nozzle and MesoCLAD relative to the small one. This work allowed to Kerbrat et al. to concluded that:

> *"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"*

5 Discussion and critical review

AM production systems can be located in the consumer's premises. The user thus becomes both producer and consumer. Designers, meanwhile, can indifferently work in the same premises or work distantly. In the latter case, the designer sends the CAD file by mail or via the cloud to the manufacturer who converts it to an STL file before transferring it via Wi-Fi or USB key or cable to the 3D printer. As it is schematically explained in the **Fig.** ***12***, in the CAD phase a computer is used for a period of time that may be low or high depending on the product /system being designed. After sending this CAD file, the generation time of the STL file using a computer is very low. Then the production layer by layer of the product/system begins.

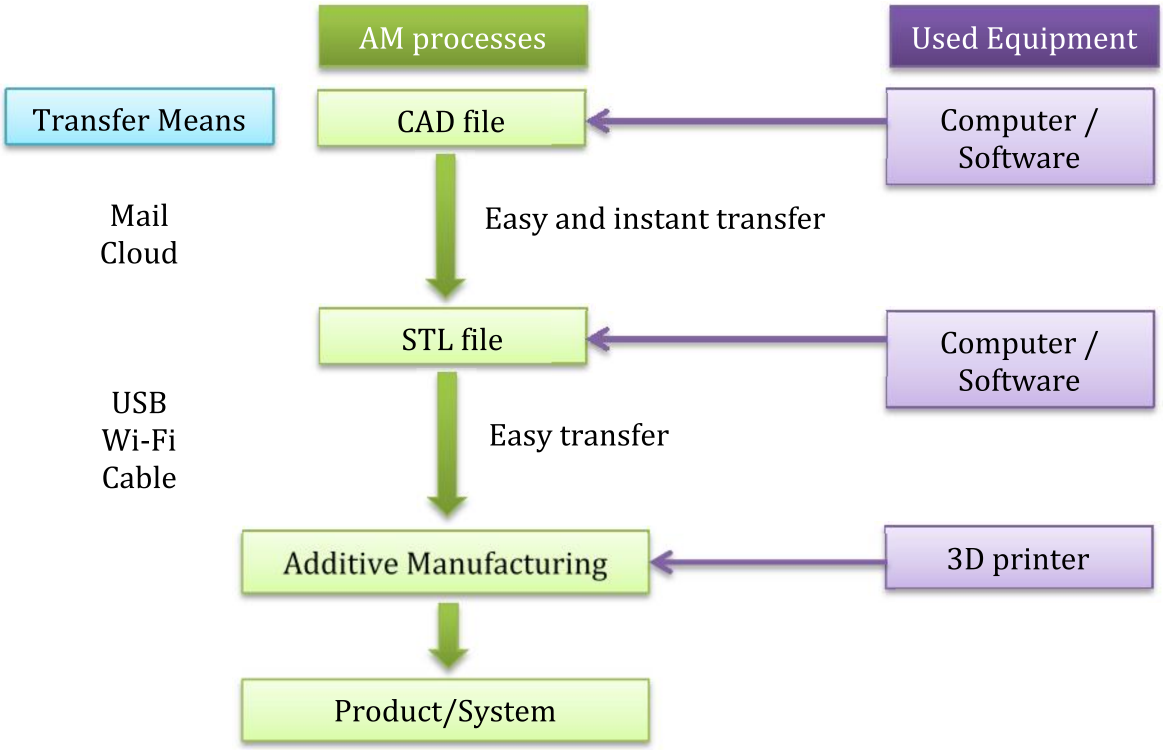


Fig. 12 AM production logistic chain in the case of the designer is working remotely from the manufacturer

During the phase of process and flow identification, we have noticed that the CAD phase, in relation to the used equipment, is based on computers. Innovation now imposes a speed on the market like a real need. Computers are becoming more and more efficient, in a very low time, given the rapid technological evolution. In order to take advantages of the computers new performance, the user is led either to abandon his old computer or to resell it. We are then talking about obsolescence, which is a real risk for companies, with non-negligible impacts. The lifetime of a computer was four and a half years in 1992, to three years in 1998 and two years in 2006 [27].

In the case where the computer is resold, the environmental impact will always be evaluated in the usage phase. On the other hand, if it is considered obsolete then it should be treated as a waste, although it may still be functional. The relative environmental impact will have to be evaluated.

Compared with conventional manufacturing means where the average lifetime of a machine is ten years and is considered two times larger [17] than a 3D printer and if we estimate that computers have a two years lifetime, than environmental impact is expected to rise.

6 Proposals

Based on the eight key steps proposed by Gibson [7] in the AM process sequence, we propose to cluster these steps into three phases (Fig. **13**) that we will call:

- CAD phase: which corresponds to the phase of conceptualization, the work is done in the virtual world on computers through software
- AM building: this is the phase that includes all the steps of using the machine
- Part post processing: this final phase is relative to the part and its finalization

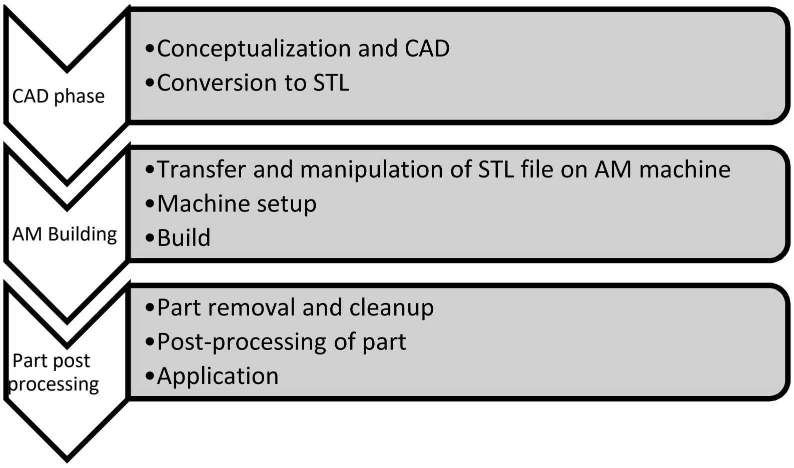
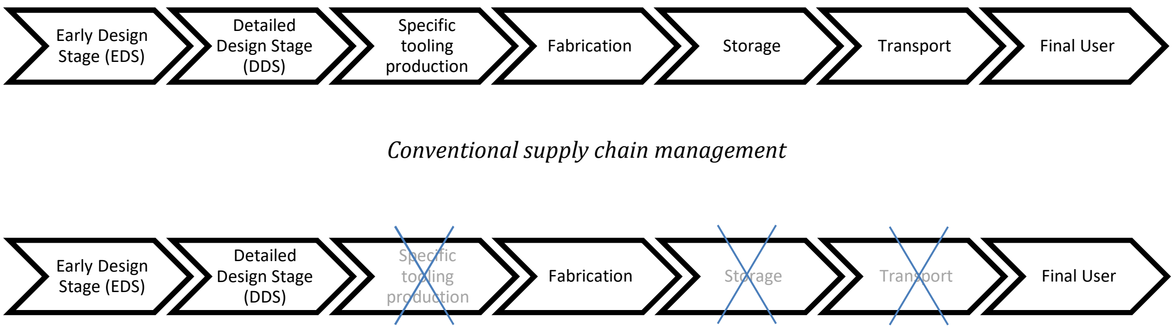


Fig. 13 Three key steps in the AM process sequence

As for the supply chain management we talked about before, we highlight that the new product development cycle is accelerated: the extreme case of a final user who has own means of production and the know-how of a designer shows that the supply chain in additive manufacturing can really become minimal (Fig. ***14***). In comparison with conventional process steps: specific tools construction, storage and transport steps will be deleted, and therefore the assembly cost and the inventory management costs will be decreased



AM supply chain management

Fig. 14 Comparison between conventional production processes vs AM one's

While introducing environmentally assessed methods researches for additive manufacturing, we have noticed the lifetime obsolescence of the used machines in the CAD phase hasn't been taking into account. Hence, we propose a novel approach for eco-designing products for AM in CAD phase that consider le machine obsolescence evaluation as explained in Fig. **15**.

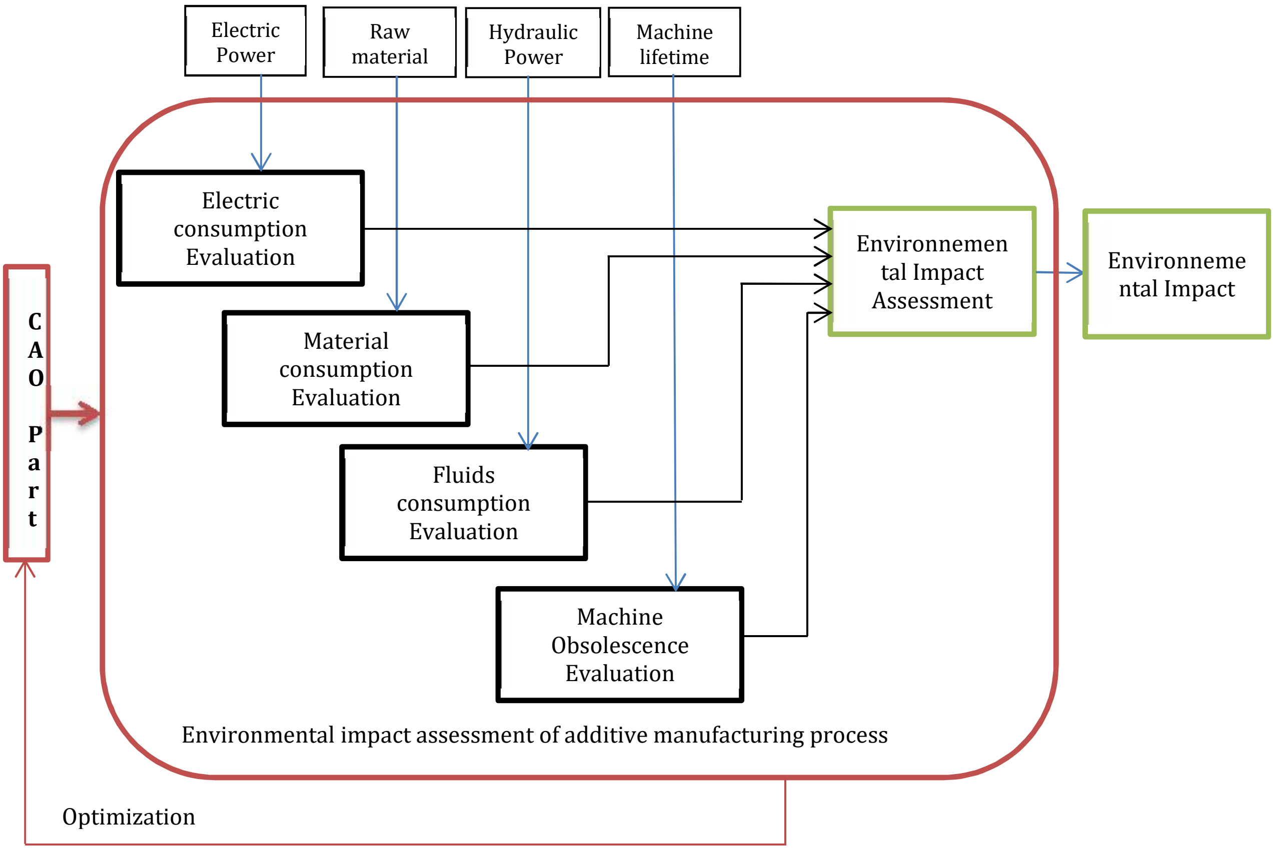


Fig. 15 Proposed Eco-design methodology for AM process

7 Conclusion

Despite the number of studies that explore the AM sustainability in CAD phase, the disposal analysis of used equipment in this detailed design stage, mainly computers obsolescence has not yet been performed. Through our literature review, it appears that environmental impacts of the used equipment in the CAD phase could be quantified from the moment that 3D printers and computers life times could be estimated with a relative accuracy.

We have presented a process analysis of the AM production logistic chain in the case of a designer is working remotely from the manufacturer and discerned the importance of the quantification of the environmental impact of the used equipment in the CAD phase taking into account the obsolescence lifetime.

In our future research work, a quantitative evaluation of the EI using LCA sofware will be established through a case study.

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