Environmental performance modeling for additive manufacturing processes

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Abstract:

Sustainability means considering economic, social and environmental aspects. In the mechanical product design field, sustainability means thinking about eco-design and life cycle analysis, when the whole life cycle of the product (from raw material extraction to end of life) is concerned with environmental impacts. Nowadays, most of the manufacturing methods are driven only by money, and the environmental and social aspects are not taken into account. The goal of this paper is to propose an environmental assessment methodology of the manufacturing processes. In this methodology, all flows consumed and produced (material, fluids, electricity) are considered. A predictive model of flow consumption is defined from the CAD model of the product and the manufacturing program. The aim is to be able to minimize the environmental impacts of the manufacturing during the design stage. In this paper, the focus is put on additive manufacturing.

Keywords: environmental management, advanced manufacturing technology, manufacturing strategy, sustainable manufacturing

1. Manufacturing processes and eco-design

1.1. Definition and aim of eco-design

Under the standard ISO 14050, eco-design is defined as "the integration of environmental considerations during the whole process which transform a demand to specifics characteristics or specifications for a product, a process or a system" [1].

As it is shown on Figure 1, the whole product life cycle is generally split into four distinct steps: raw material extraction, part manufacturing, product usage and end of life. Such a study is often called "from cradle to grave" analysis.

Between two different life cycle steps, transport phases have to be considered during the environmental evaluation of the product. For example, raw material transport, supplier's provision, consumer's expedition, end of life product collection has to be integrated.

Usually, inputs can be classified into two categories: materials and energy. Materials inputs are linked with different kind of environmental aspects such as, resources utilization, people and ecosystem contaminant exposition, etc. Energy inputs are necessary in most of product life cycle. Each kind of source of energy (fossil fuel, nuclear, hydraulic, geothermal, solar, wind source, etc.) contains identifiable environmental aspects.
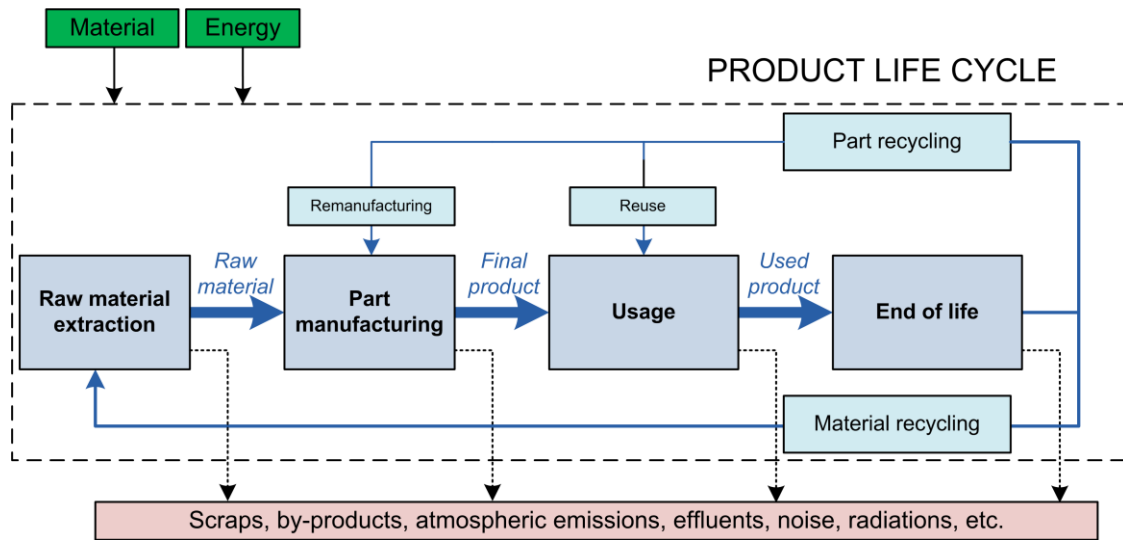
Figure 1. Product life cycle steps.

The outputs created during product life cycle are related to [2]:

- Scraps, which are generated during each life cycle step,

- By-products and co-products,

- Atmospheric emissions (gas emissions, vapors and particle in the air),

- Effluents (substances emission in superficial water or in the phreatic table),

- Noise,

- Radiations,

- Electromagnetic fields, etc.

Following the generic framework of the Life-cycle assessment methodological tool, after goal and scope has been determined, data has been collected during the inventory step. This inventory result is usually a very long list of emissions and consumed resources. Then the long list of Life Cycle inventory results should be transformed into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category.

Different methods can be used to classify the impacts caused on the environment. In this study, the method is Eco-Indicator 99 [4], which is a method oriented damage and translate all the impacts into a unique *point* value, a non-dimensional number used to compare the different source of impacts. 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 1kg of stainless steel is around 900 *mPts*. The choice of this method has been done because it was the one that most of studies on environmental assessment of additive processes that have been analyzed in the state-of-the-art used.

The environmental performance of a product includes, on one hand, to quantify the environmental impacts for the life cycle studied, and in the other hand, to identify and evaluate in which measure the different parameters, characteristics and functionalities of the product life cycle are behind the measured environmental impacts [3]. The environmental evaluation required precise knowledge about environmental sciences (basics, naturals and socials), working experiences knowledge linked to the studied product and its application, as well as data sources allowing to help in the environmental evaluation process. The environmental evaluation is a complex step of eco-design and the environmental evaluation tools have to be developed with the specialists of the different fields considered. Nevertheless, engineers of mechanical products, especially designers, cannot pride to be an expert in raw material extraction processes, manufacturing processes or end of life processes. From this observation, it seems necessary to propose simplify tools in order to evaluate the environmental impact for the different life steps of the product, usable from the design step.

1.2. Manufacturing phase in eco-design tools

Recently, some editors of CAD software have integrated simplified tools of life cycle assessment in order to make easier the access to eco-design for their users. For example, we can find the module called

Sustainability in the software Solidworks®. Even if these tools are helpful to make comparisons between some parts design within control of all the life cycle steps, they are not adapted to characterize with accuracy manufacturing steps. They are not able to express the progresses realized on environmental considerations in the manufacturing industries.

In case of life-cycle assessment, most of currently available data bases (for example Ecoinvent) and LCA tools (for example Simapro) generally focus on unit process like milling, casting, and forming and provide statistic estimation of the environmental impacts of each process. Data for additive manufacturing processes are still not available.

It seems necessary to develop tools in order to evaluate the environmental impacts with sufficient accuracy in order to take into account links between inputs (material and energy), outputs (scraps and others) characterizing the environmental impacts due to manufacturing step. Such tools could allow the engineers controlling the eco-efficiency of their product from the design step. Figure 2 summarizes these expectations focalizing on the manufacturing step.
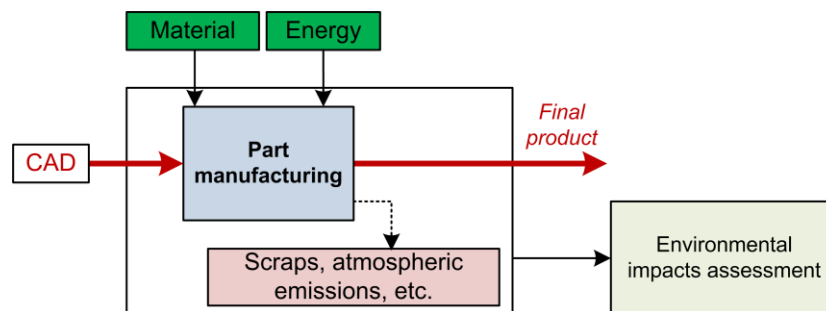

Figure 2. Environmental evaluation of manufacturing step.

2. Sustainability development as a competitiveness factor

For years, the reduction of the environmental impacts has been seen as impracticable for manufacturers. In fact, most of the manufacturing choices concern the definition of a process (machine-tool, strategy, trajectories, and manufacturing parameters) and rely only on the economic aspect. Nowadays, normalization (ISO 140XX) and the European Community encourage the manufacturers to respect some environmental criteria. The potential benefits could include:

- A cost decrease, according to the optimization of the quantity of material and energy consumed, most efficient processes and the reduction of scraps;
- The stimulation of innovation and creativity
- The definition of new products from recycled materials
- A better brand image
- Different financial opportunities, especially from investors aware of sustainability
- A better employees motivation
- The reduction of risks

That is why it can be considered that the assessment, and reduction, of the environmental impacts of the manufacturing phase of a mechanical part should have two main advantages:

- To provide accurate data for a complete life-cycle assessment of the product
- To become more competitiveness, in economic and environmental points of view

Even if the manufacturing phase have not the most impact considering the whole life-cycle of a product, to take into account the environmental impact during the manufacturing choices (process, machine-tool, trajectories of the tool, …) can help manufacturers to be more competitive.

3. Application to additive manufacturing

3.1. Is it an adapted process to eco-design?

Additive manufacturing is an innovative process which is now being considered as mature. This process allows obtaining shapes which will be difficult to manufacture with another process (complex shapes, unblocking empty internal shape, internal right angle, etc.). Furthermore, this process is able to shape an important range of materials such as colored ABS, chrome-cobalt alloy, titanium or multi-materials. Taking into account the environmental aspect in additive manufacturing processes is identified as one of the eight major priorities of development in the next 10 years for these processes to grow up significantly [5]. At the same time, additive manufacturing of metallic parts has been identified as one of the fourth technological keys for the international experts from consortium 2020, which present an outlook of research field for the next two years in order to lead to a sustainable manufacturing and more energy efficiency manufacturing processes in 2020 [6]. Additive manufacturing and sustainable development are cited in the strategic datebook from the European platform Manufuture [7], and taking into account the environmental aspect in additive manufacturing processes is identified as one of the eight major priorities of development in the next 10 years for these processes to grow up significantly [8].

Additive manufacturing processes are often seen as cleaner processes, allowing using the exact amount of material, minimizing significantly manufacturing scraps contrary to usual processes such as machining or punching. Moreover, the possibilities given by these processes such as optimized design allow producing lighten parts. Another advantage is to manufacture without tool, such as milling instrument and mold. So there are many advantages which need to be quantified in order to know what the real environmental benefits of these processes are.

3.2. Additive manufacturing and environment : state of the art

In additive manufacturing, parts are obtained with a successive addition of material. In each layer, the material is aggregated with the help of an energy source displacement or with a nozzle which ejects molten material. All the technologies are following a programmed manufacturing path. The final shape of the part is directly link to the trajectory chosen [9]. The impact of the path strategy on the part's geometrical characteristics is due to the important influences of the Multiphysics phenomena during the manufacturing [10, 11]. That is why the case study proposed in this paper is focused on the path strategy (see section 3.3).

The first studies dealing with environmental impacts of manufacturing processes have been conducted in the 90's [12]. The goal of these studies was to determine the impact of selective laser sintering and fused deposition modeling machines based on Eco-Indicator 95 for the environmental evaluation. Thereafter, studies have been conducted allowing comparing conventional processes with additive manufacturing. Morrow et al. [13] propose a study which compares the manufacturing of an injection mold realized either by conventional machining or by additive manufacturing. Serres et al. [14] have published a study comparing the additive manufacturing CLAD process with machining for a specific part in Ti_6Al_4V. In this study, they show that additive manufacturing is better with an environmental aspect than machining because this process use less material and no lubricant fluid (toxic for human). Recently, Faludi et al. have compared additive manufacturing versus traditional machining via life-cycle assessment [15] and Yoon et al. did a comparison of energy consumption in bulk forming, subtractive and additive processes [16]. They characterized 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.

Another methodology called "C02PE! Initiative" allows realizing an analysis following by systematic amelioration of processes, including some additive manufacturing processes, is currently in development [17] [18]. If those studies show the possibilities given by this innovative technology and give some elements in order to compare these processes with conventional processes, they are not taking into account the possibilities of manufacturing strategy and manufacturing parameters optimization, to minimize the environmental impact due to energy consumption or material consumption. Other studies are focused on electrical consumption of additive manufacturing processes and give some ideas for improvement [19, 20]; they are not taking into account all the inputs (material and energy).

Taking into account these considerations, it seems interesting to propose a new methodology allowing evaluating the environmental impact for the set part-process, from the path strategies, taking the whole inputs and outputs to characterizes the environmental impact of the manufacturing step and giving some improvements advices, either on the design of the part or on the manufacturing parameters. This global

methodology is presented on Figure 3. In this methodology, outputs are limited to the part produced and the environmental impact of the manufacturing phase. In fact, no emissions or pollutions are taken into account because their quantitative evaluation was not in the scope of our study. Few papers present analyses on particles emissions associated to additive manufacturing (for example: Stephens et al. on desktop 3D printers [21]).
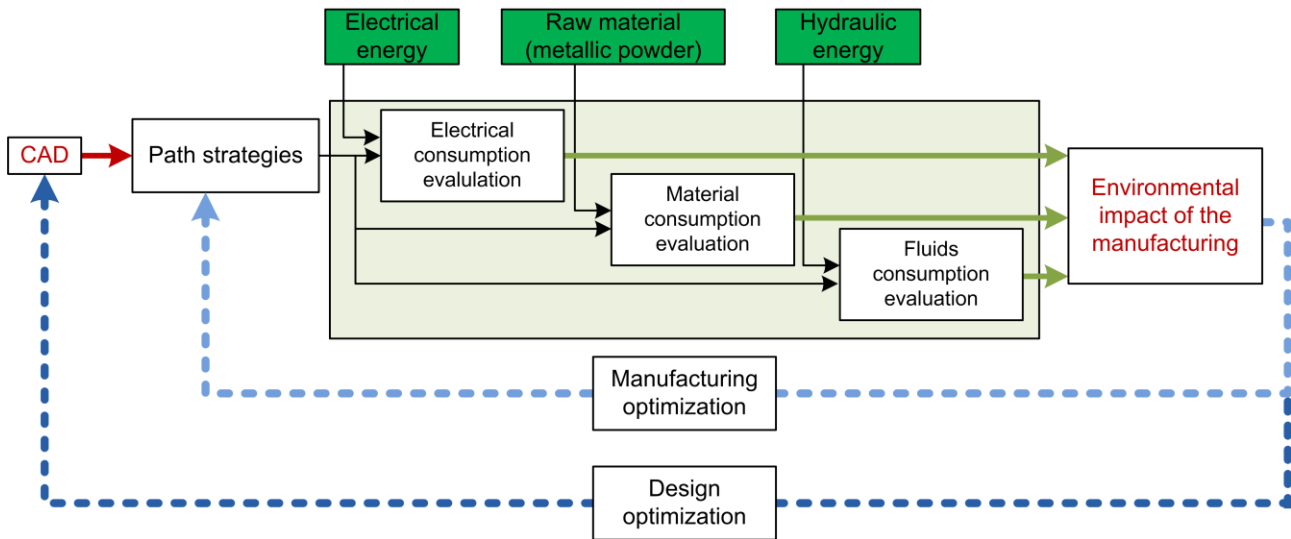

Figure 3. Environmental impact of the manufacturing assessment methodology.

3.3.   Strategies paths choice example with environmental considerations

The methodology presented on Figure 3 was developed for metallic powder projection technology, determining accurate models for a quantitative evaluation of electrical, material and fluids consumption from path strategies [22]. From experimental acquisitions of electrical power, a model was created allowing determining the environmental impacts due to the electrical consumption of the different features of the machine (displacement axis, laser, stand-by mode, cooling system, etc.). The experiments were carried out measuring current and voltage in the different features of the machine. This model is completed with the impacts due to powder consumption and fluids consumption (projecting gas, cooling fluids) during the manufacturing. These consumptions were measured directly on the machine via flowmeters. The mass of the part is given by the CAD software and a ratio is measured between the mass in CAD model and the total amount of material that was needed to produce the part. With the inventory data (electrical power, time, gas flow rate, water flow rate, mass of material consumed), the environmental impacts are determined from the factor given by the Eco-Indicator 99 method. This method allows comparing different strategies from environmental considerations.

Figure 4 presents the CAD model use to illustrate the methodology with two examples of path strategies for one layer. The acceleration and deceleration are more important for the strategy called Zig Zig, so the electrical consumption of the axis is 2.9 time more important. However, this electrical consumption has to be qualifying in regard to the laser electrical consumption which is less important for the Zig Zig strategy due to switch-off mode during way back (dot points on Figure 4). This strategy is slower than the other (12.5% slower) and consumes 11.5% more material. So, in order to compare effectively both strategies, it seems necessary to do an exhaustive assessment, material and energy, translating those consumptions into environmental impacts. The results are shown in Table 1 and Figure 5.

Finally, if we only consider the electrical consumption, both strategies have the same impact. Nevertheless, taking into account material and fluids consumptions, the Zig Zag strategy is better. This example allows illustrating the use of environmental impact evaluation models during manufacturing step. This example shows the consequence to take into account all the inputs and outputs for this methodology. In fact, it is not interesting to decrease the electrical consumption (laser consumption for example) and increase the consumption of other inputs (such as gas consumption). The predictive model developed allows getting a global approach minimizing the impacts transfers.
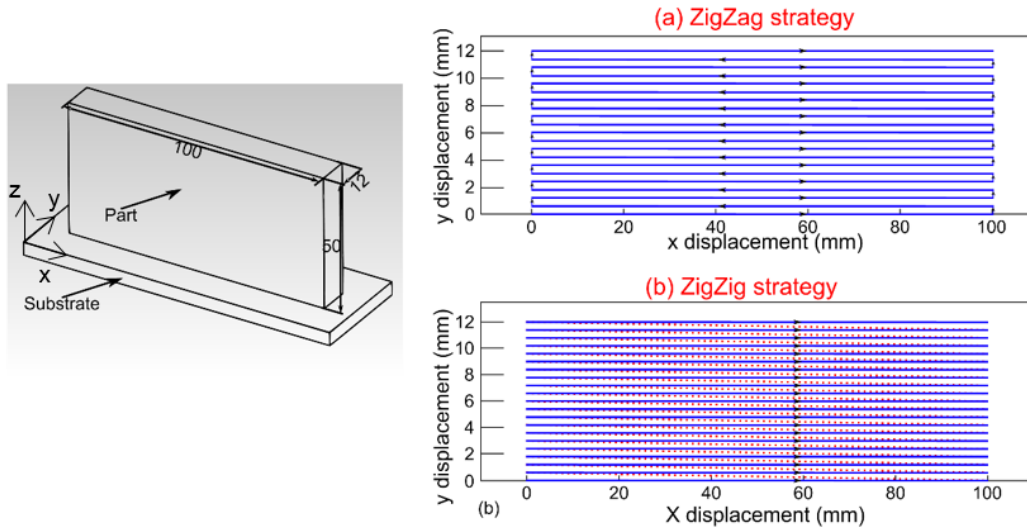
Figure 4. CAD model of part example and both strategies ZigZag (a) and ZigZig (b).

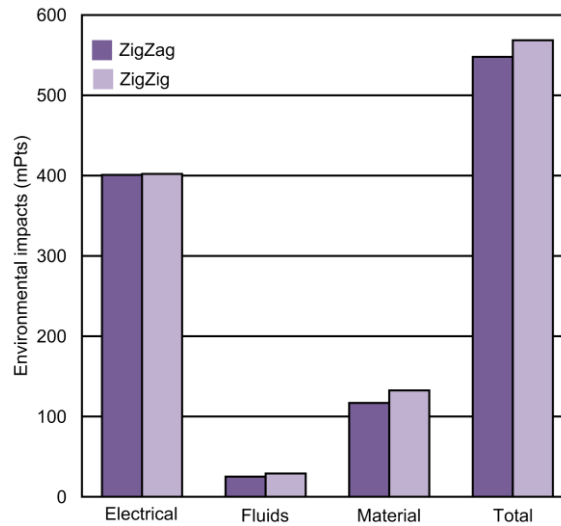|	ZigZag	ZigZig	Difference	Translation in mPts
Ee_{axis} (kWh)	0.0506	0.1465	+189 %	12 mPts/kWh
Ee_{laser} (kWh)	6.3	6.24	-1 %	12 mPts/kWh
Ee_{cool} (kWh)	24.9	24.66	-1 %	12 mPts/kWh
Ee_{cste} (kWh)	2.16	2.46	+14 %	12 mPts/kWh
V_{fluids} (l)	2134.1	2436.3	+14 %	7.2 mPts/kg
$m_{material}$ (kg)	1.38	1.56	+13 %	86 mPts/kg
t_{man} (min)	427	487	+14 %	

Table 1. Results for both strategies.

Figure 5. Environmental impacts comparison from both strategies.

4. Results, conclusion and future work

The main result of the work presented in this paper is the framework of an environmental impact assessment methodology. The Figure 5 illustrates the results that can be obtained within the methodology. In this paper, it has been applied on metallic powder projection technology. Other case studies has been done by Le Bourhis et al. [23].

In this paper, the environmental impacts assessment as an indicator to help manufacturers taking a decision has been investigated. Such an indicator has to be considered as a way to improve the competitiveness of the manufacturers. It must be integrated in a whole methodology, considering all the environmental impacts and

not only the electric consumption. Moreover, accurate models are defined to provide accurate indicator that can be implemented in a whole life-cycle approach.

The proposed assessment methodology could be generalized for all range of additive manufacturing processes when considering every machine as an assembly of several technological features and creating predictive models for electrical, fluid and material consumptions for all features, as it has been done in the application on metallic powder projection technology.

To be used in a complete optimized design and manufacturing procedure, the environmental performance assessment methodology should be integrated in a design for manufacturing approach. The aim will be to define a design for green manufacturing methodology.

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