A Framework to Compute Carbon Emissions Generated from Additive Manufacturing Processes

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Abstract. Additive Manufacturing (AM) is an emerging and promising technology increasingly adopted from Industry. However, Industry is responsible for the majority of global carbon emissions (CEs), heavily contributing to greenhouse effect. Therefore, it is important to define the environmental impact of all processes, including AM carbon footprint. This work aims at reviewing literature for the equations for CE calculations of AM and developing a framework for CEs calculations generated from all the types of AM. Literature was found for some AM types, with each type of AM described stepwise and categorized per Process, Machine and System level. At each step, the equations for CEs, based on carbon emission factor and energy spent, were allocated. At process level, CEs come exclusively from the energy spent for curing. At the machine level, CEs are related to the process, auxiliary equipment and consumables. At system level, additional CEs are derived from material used, pre-processing and post-processing steps. Total carbon emissions are the sum of CEs at machine level and additional CEs from system level. Generalization of this approach led to a framework that can be used for all types of AM, to calculate CEs of each AM type based on the steps included.

Keywords: Additive Manufacturing · Carbon Emission Calculation · Carbon Footprint

1 Introduction

Additive Manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer [1] and it is one of the fundamental elements of the fourth industrial revolution [2–4]. However, industrial advantages often come with increased carbon emissions (CE), leading to increase of global temperature. This is why the term of carbon footprint has been developed, in order to measure the environmental impact of products, processes, infrastructures, individuals, mainly all human related activities. Carbon footprint is the total amount of greenhouse gases, including dioxide and methane, that are generated by our actions [5]. As the role of ecological constraints

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is increasing affect manufacturing technologies [6], it is imperative that AM is examined from an environmental point of view.

Previous literature presents the environmental impact of AM [7–9] and how to reduce it [10]. Optimization models have also been suggested regarding the energy efficiency of AM [11], while others try to approach it from a sustainability point of view [12, 13]. However, a holistic analysis regarding the carbon footprint of every AM method is yet to be done.

The aim of this study is to develop a framework for computing carbon emissions generated from additive manufacturing processes using appropriate energy equations.

2 Materials and Methods

This study focuses on summarizing the methodologies used for calculating the CE of AM processes, on the type and the amount of energy that these processes require, as well as the necessary materials. Databases of Google Scholar, ResearchGate and ScienceDirect were researched for relevant papers. Keywords used were: "additive manufacturing", "CO_2 emission", "environmental impact", "carbon emission". In order to be considered for the review, the papers had to fulfill the following selection criteria: (a)Type of process and (b)Calculation of CE using mathematical equations. At the end, the papers were categorized as follows:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Electron Beam Melting (BEM)
- Laser Engineered Net Shaping (LENS)
- Fused Deposition Modeling (FDM)

Each AM approach has multiple steps, starting from auxiliary equipment switching on, all the way to the equipment being shut down when operations are over. For this, the three-level approach was used as proposed by *Fysikopoulos et al.* (2014) [14] in the case of machining, where steps were grouped per process, machine tool and system level. Process concerns the energy interactions related to the physical mechanisms of the process itself". The machine level focuses on the auxiliary equipment and the consumables (fluids etc.). System is about the material consumption and the actions that take place before or after the processing.

3 Results

Literature review was done to figure out how much work was already done regarding the carbon footprint calculation of AM processes. Precisely, Stereolithography (SLA) [15], Selective Laser Sintering (SLS) [16], Electron Beam Melting (EBM) [17], Laser Engineering Net Shaping (LENS) and Fused Deposition Modeling [18], each had one paper estimating, however, their energy consumption instead of the carbon footprint. Then the CE was calculated through the following equation:

$$CE = CEF \cdot E \tag{1}$$

where *CE* is the carbon emitted due to consumption, *EC* the energy consumed, measured in (GJ), and *CEF* the Carbon Emission Factor, measured in $\left(\frac{kgCO_2}{GJ}\right)$. The aforementioned techniques were described step-by-step and then categorized into levels as seen in Table 1. In SLA the object is created by selectively curing a polymer resin layer-by-layer using an ultraviolet (UV) laser beam. SLS is a powder bed printing technology. It uses a high-power laser to sinter small particles of polymer powder into a solid structure, tracing the geometry of digitally sliced CAD models layer by layer and working from the bottom of the part upwards. EBM [19] is a process where high-velocity electrons concentrated into a narrow beam that are directed towards the work piece, creating heat, and vaporizing the material. LENS [20] uses computer-controlled lasers that, weld air-blown streams of metallic powders into custom parts and manufacturing molds. In FDM [21] an object is built by depositing selectively melted material in a predetermined path, layer by layer. Further description of these techniques is presented in Table 1.

The three-level approach [5] was adapted to the AM techniques as seen in Fig. 1. Process level includes CE from the energy consumed during the process and are mainly caused by the electrical energy consumption of the laser. At Machine level, the emissions of the process level increase by the emissions of the auxiliary equipment and the consumables, namely every action that the printer has to perform in order to function properly, depending on the AM process. Lastly, the System level includes CE from the Machine level plus CE from pre and post-processing along with the ones of the material consumption.

4 Framework for CE Calculation for AM

A framework is proposed, to allow for CE calculation for every AM method. This will derive from the generalization of the "Levels method" used above in the previous techniques. Thus, it can be said that the CE at the Process level ($CE_{process}$) come exclusively by the energy spent for curing ($E_{process}$):

$$CE_{process} = CEF_{process} \cdot E_{process} \quad (2)$$

In the Machine level the carbon footprint depends on the energy spent at the process level, by the auxiliary equipment $\left(CE_{auxiliary}\right)$ and by the consumables $\left(CE_{i,cons}\right)$.

$$CE_{machine} = CE_{process} + CE_{aux} + \sum_i CE_{i,cons} \quad (3)$$

Which can also be written as:

$$CE_{machine} = CE_{process} + CE_{auxiliary\ equipment} + \sum_i CE_{i,cons} = CE_{process} + CEF_{aux} \cdot E_{aux} + \sum_i CEF_{i,cons} \cdot Q_{i,cons} \quad (4)$$

where (CEF_{aux}) is the CE factor of the auxiliary equipment consumption, (E_{aux}) the energy required by the auxiliary equipment, and ($Q_{i,cons}$) the quantity of the consumables used for the creation of the final product.

Table 1. Level categorization of AM techniques (P-Process, M-Machine, S- System)

AM technique	Levels	Steps
SLA	P	• Laser beam will harden actual part geometry
	M	• Resin dispensation • Build platform is lowered • Laser unit directs UV beam to a reflective mirror • Galvo motor system directs beam at the bottom of the resin tank • Support structures layer is hardened • Build platform rises peeling the part from the bottom of the tank • Re-coater sweeps the surface
	S	• Design • Print preparation software • Instructions sent to printer • Chemical bath • Post-curing
SLS	P	• Focused beam directed to the powder surface a cross-section of the part geometry
	M	• Powder pre-heating • Roller dispenses the powder • Laser unit directs a beam to a reflective mirror • Powder delivery system moves up • Platform lowers by one layer • Re-coater distributes the next layer of powder and excess powder is captured in the collection container • Part and chamber cool down
	S	• Design • Print preparation software • Instructions sent to printer • Part cleaning
EBM	P	• The electron beam moves selectively causing the powder particles to fuse together
	M	• Build platform is pre-heated • Roller dispenses the powder • Electromagnetic coils point the beam towards the desired points of the build platform • Build platform is moved down one layer • Powder delivery system moves up • The re-coater distributes a new layer of powder
	S	• Design • Print preparation software • Instructions sent to printer • Polishing of the part

(*continued*)

Table 1. (*continued*)

AM technique	Levels	Steps
LENS	P	• The metal melts at the focal point of the laser
	M	• Inert shroud gas distribution • A laser beam created by a laser generator is focused through a lens onto the workpiece • The powder-feed system regulates the mass flow • The metal solidifies • The head moves in the *z-axis*
	S	• Design • Print preparation software • Instructions sent to printer • The part is heat-treated/ machined etc
FDM	P	• The material is distributed to create the part
	M	• The extrusion head is automatically fed by the system • Build chamber is pre-heated • Build platform rises to initial position • A few layers of material are distributed as a support • The build platform moves down
	S	• Design • Print preparation software • Instructions sent to printer

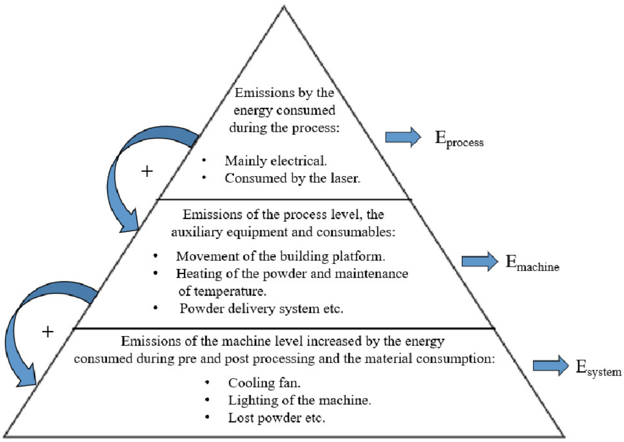

Fig. 1. Levels of AM processes.

The consumables can either be liquid (CE_{fluid}) or gas (CE_{gas}):

$$\sum_i CE_{i,cons} = CE_{gas} + CE_{fluid} \tag{5}$$

Regarding the auxiliary equipment, any of the followings can be included depending on the AM method used

$$CE_{auxiliaryequipment} = CE_{materialdispenser} + CE_{buildplatformmotor} + CE_{galvomotorsystem} + CE_{recoater} + CE_{heater} + CE_{laserunit} + CE_{pressure} + CE_{gasdispenser} + CE_{headmotor} + CE_{lighting} \quad (6)$$

Thus, every method needs a material dispenser whether it is liquid, powder or solid ($CE_{materialdispenser}$). Some methods have a moving building platform ($CE_{buildplatformmotor}$) on which the product is being built, while in others it is the head that moves layer by layer ($CE_{headmotor}$). To ensure the smoothness of each layer recoaters are sometimes necessary ($CE_{recoater}$). Accordingly, there are methods that need a heater (CE_{heater}) for the right composition of the material, while most of the printers have some light for the easier use of the machine ($CE_{lighting}$). Regarding the laser-based methods, CE are created by both the galvo motor system ($CE_{galvomotorsystem}$) and the laser unit ($CE_{laserunit}$). Lastly, special conditions may require the use of gas ($CE_{gasdispenser}$) or pressure ($CE_{pressure}$) in the building environment.

Table 2 presents the aforementioned framework, as described.

Table 2. CE framework for AM (P-Process, M-Machine, S- System)

Level	Procedure	Equation
P	Energy spent during curing	$CE_{process} = CEF_{process} \cdot E_{process}$
M	Energy spent at the process level and by the auxiliary equipment and the consumables	$CE_{machine} = CE_{process} + CE_{aux} + \sum_i CE_{i,cons} = CE_{process} + CEF_{aux} \cdot E_{aux} + \sum_i CEF_{i,cons} \cdot Q_{i,cons}$
S	Energy spent at the machine level, for the material production, transport, and disposal and by pre/post processing	$CE_{system} = CE_{machine} + \sum_i (CE_{i,transp} + CE_{i,prod} + CE_{i,disp}) + CE_{pre-process} + CE_{post-process}$

5 Discussion

Carbon emissions in AM are caused mostly due to the energy consumption that this technique requires at process, machine, and system level, by the auxiliary equipment and the consumables, by the production, transportation and disposal of materials, as well as by the pre and post processing. The framework presented in this work suggests a simple, yet effective approach of estimating the CE of every AM technique. The most common source of CE for all three levels is the electrical energy spent. The amount of energy spent for every step multiplied by a specific Carbon Emission Factor (CEF) results into the CE of this step.

This paper examines AM from a different point of view, the one concentrating on the carbon footprint of the process, in contrast with the majority of energy-spent focused research that has been done this far. It suggests a holistic framework estimating the carbon emission of every AM technique and doesn't focus on just one process. This is necessary, especially now that green manufacturing plays such an important role due to the increasing climate change. Nevertheless, being at an early stage the aforementioned framework comes with some limitations. Only the electrical energy spent for every task is taken under consideration.

6 Conclusions and Future Outlook

Nowadays, a framework estimating the CE of every AM technique should be considered not only helpful but also necessary to ensure the sustainability of the process. This can be done by dividing the processes into steps which will then be categorized into levels. Once the energy spent is estimated, then the carbon footprint can be calculated.

In future works, a more detailed determination of carbon emission factors should be included to find which level of AM is the most environmentally harmful. Additionally, some ways of reducing the carbon emissions should be suggested. The same applies for the materials used. Thus, examining all the required parameters we will see which one, if changed, will give the desired outcome.

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