Environmental performance of additive manufacturing process – an overview

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Abstract

Purpose – The purpose of this paper is to overview the literature about the environmental performance of additive manufacturing (AM) and to evaluate the use of life cycle assessment (LCA) on these studies.

Design/methodology/approach – This study was based on the systematic literature review.

Findings – The investigation found that most authors were concerned about the energy consumption of the AM equipment, which is the subject studied by 87% of articles. In addition, 25% of the studies used LCA at least in some level, making a global environment assessment to evaluate the environmental impacts of AM. By analyzing research studies, it was possible to find signs that AM could be a lower environmental impact process, when compared with traditional manufacturing. However, this assumption is not valid in all cases because there are many variables that may affect environmental results.

Originality/value – Due to the increase on the usage of this type of technology by industries, studies on the environmental performance of this process became relevant.

Keywords Energy consumption, 3D printing, Environmental performance, Life cycle assessment (LCA), Additive manufacturing (AM)

Paper type Literature review

1. Introduction

The additive manufacturing (AM) process, or 3D printing, as it is usually known, has been gaining more followers due to the readiness, speed and pre-production model low costs when compared with conventional methods (Lan, 2009). The use of AM on engineering industry such as R&D and start-up companies has been significantly growing as it enables converting computer-aided designs into physical parts without molding or other pre-fabrication steps (Upcraft and Fletcher, 2003). Due to the increase on the usage of this type of technology by industries, studies on the environmental impacts produced by this process became relevant.

There are several tools and methodologies directed to evaluate the environmental management of a production process, such as cleaner production, defined by Glavič and Lukman (2007) as a systematic methodology focused on the activities of the production, aimed at minimizing resources usage, increase the material productivity and improve the energy efficiency of processes. Another approach to the sustainability of production systems is the Eco-design, or design for environment, a product development process that considers the whole life cycle, assessing the environmental impacts in all production stages and application, aiming at reducing impacts (Glavič and Lukman, 2007). One of the most comprehensive tools for analyzing environmental aspects and impacts is the life cycle assessment (LCA), defined by SETAC (Society of Environmental Toxicology and Chemistry, USA and Europe) as a methodology for assessing the environmental impacts involved with the usage of a product, production process or activity within specified limits from the extraction of raw material, through the processes of production, transportation, usage, reuse, maintenance, recycling and final disposal. This study aimed to analyze the progress of studies that evaluate the environmental performance of additive manufacturing processes, their main authors, journals/congresses that most published articles related to this subject, the tools being used by researchers to measure the AM-generated environmental impact factors and, in particular, the main characteristics of the studies that use the LCA as a way of evaluating aspects and environmental impacts of the AM.

2. Theoretical background

2.1 Additive manufacturing

AM is defined as the process of merging materials, usually layer by layer, to build an object from data of a 3D computer model

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(Zein *et al.*, 2002; Mellor *et al.*, 2014). There are many different AM technologies, each one with its particularity regarding the equipment operation. According to ASTM 52900:2015, AM processes can be classified into seven distinct categories: vat photopolymerisation, material jetting, binder jetting, material extrusion, powder bed fusion, directed energy deposition and sheet lamination.

Although AM has been considered a technology that generates lower environmental impacts when compared with conventional methods, studies that demonstrate such benefits are still scarce (Faludi *et al.*, 2015; Malshe *et al.*, 2015). One of the main reasons is that AM reduces the consumption of raw material, using only the necessary for each piece, not generating runners/burrs/shavings as in conventional methods (Malshe *et al.*, 2015; Paris *et al.*, 2016). However, there are some aspects to be considered, such as energy consumption, transportation and emissions. A methodology that may evaluate and quantify the impacts generated by this technology is the LCA (Kreiger *et al.*, 2014; Faludi *et al.*, 2015; Malshe *et al.*, 2015; Barros and Zwolinski, 2016; Paris *et al.*, 2016), either individually analyzing the AM process and the impacts caused by the use of the technology (Kreiger *et al.*, 2014; Malshe *et al.*, 2015; Paris *et al.*, 2016) or by comparing the processes in a way that tries to establish the best alternative with an environmental focus (Faludi *et al.*, 2015; Barros and Zwolinski, 2016).

2.2 Life cycle assessment

According to the International Organization for Standardization ISO 14040:2006 (ISO, 2006a), the increasing awareness about the environmental protection and its implications, both in production and consumption, increased the interest on developing methodologies aimed at quantifying such impacts, being the LCA one of the best alternatives.

The LCA allows identifying opportunities to improve the environmental performance of products and processes, subsidize information for decision makers on industry and government organizations, select environmental performance indicators, helping on green marketing, among others (ISO, 2006b).

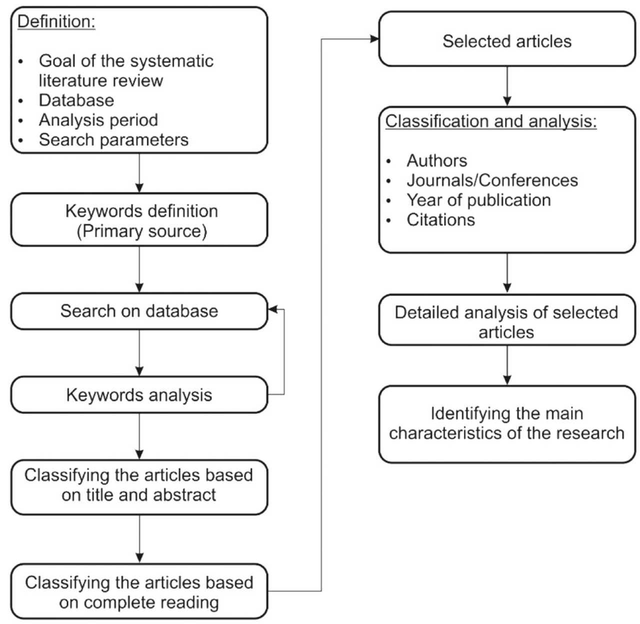
According to ISO (2006b), the LCA study consists in four phases: goal and scope definition, inventory analysis, impact assessment and interpretation of results. The conclusions obtained with LCA can be presented at the end of the life cycle inventory (LCI), or the life cycle impact assessment (LCIA). The purpose is to organize the results and convert them into understandable and meaningful information for decision makers.

3. Materials and methods

The adopted methodology used in this study was based on the systematic literature review (SLR), which was defined by Kitchenham (2004) as a study that aims to interpret and evaluate the relevant literature available about a subject, phenomenon or area of interest. To develop an SLR, three basic steps were followed: planning, execution of the theoretical review and demonstration of results (Brereton *et al.*, 2007). A detailed perspective of the adopted methodology can be seen in Figure 1.

Many articles found through the SLR, besides containing some of the keywords used for the research, such as "Sustainability" and "3D printing", showed not to be relevant to the purpose of the review, and therefore the steps of reading the title, abstract and whole articles were performed. A total number of 240 articles were found at Web of Science (WoS) and Scopus databases. After title and abstract analyzes of each one, it was selected 75 articles for a detailed evaluation of each publication. Moving on to the complete reading of the publications, a total of 43 articles showed to be relevant for the analysis, which represents almost 18 per cent of the articles found.

Figure 1 SLR detailed procedure



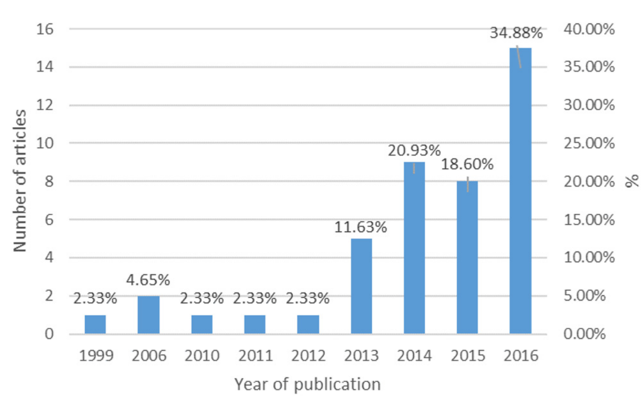
Source: Adapted from Kitchenham (2004), Brereton *et al.* (2007)

4. Outcomes and discussions

4.1 Bibliometric mapping

Figure 2 shows the evolution of the scientific production involving environmental performance in AM from 1999 (first publication found) to 2016.

Figure 2 Evolution of AM publications and environmental management



As of 2010, studies started to become more frequent, with annual publications, allowing to trace a trend line that showed a considerable growth in the number of publications. By analyzing the period between 2012 and 2016, it should be noted that approximately 75 per cent of articles were published in the past three years. Although AM is not a recent technology, with the first equipment being commercialized in 1987 (Wohlers *et al.*, 2014), only in recent years, with the reduction of equipment costs, this technology became more accessible, with industry growth of 26 per cent in 2015 (Wohlers *et al.*, 2016) and 17.5 per cent in 2016 (Wohlers *et al.*, 2017). The increase on AM processes application can explain the growing number of articles published in the area in recent years, especially when related to the environmental performance of the process, as the interest about environmental impacts became significant with the mass use of the technology.

As for the source of the publications, an analysis of the main countries that published on the theme can be observed in Figure 3. Publications were found in 17 countries, the USA being the head country in number of publications, with 15 articles published, representing more than a quarter of all scientific production in the area. The UK, France and Canada also show great interest on the subject. The overall analysis shows that Europe is the region that publishes the most, with 20 published articles, representing 39.2 per cent of the total. North America stands out with 19 publications, or 37.3 per cent of the total, and Asia with seven published articles, 13.7 per cent of the total. In addition, South America had one published article, with Brazil being the only country to publish in the area; two articles published in Australia and one article in the African continent. The obtained results were expected, as the AM technology is located in developed countries (Europe and North America), where the main research centers are based and where the main AM equipment manufacturers are installed.

In total, 29 journals/conferences were identified, 17 journals (58.6 per cent) and 12 conferences (41.4 per cent) that published about the subject. The *Rapid Prototyping Journal* and the *Journal of Cleaner Production* published most articles, with six (15.4 per cent) publications each.

A total of 145 different authors published on the topic. Table I presents the three authors who published the most, who are also the authors with the largest number of GCS (Global

Table I Authors that published the most

Authors	Countries	Articles Total	Articles (%)	GCS Total	GCS (%)
Joshua Pearce	USA	3	7.0	52	4.6
Pascal Mognol	France	3	7.0	49	4.4
Nicolas Perry	France	3	7.0	49	4.0
Others	Multiples	34	79.1	971	87.0

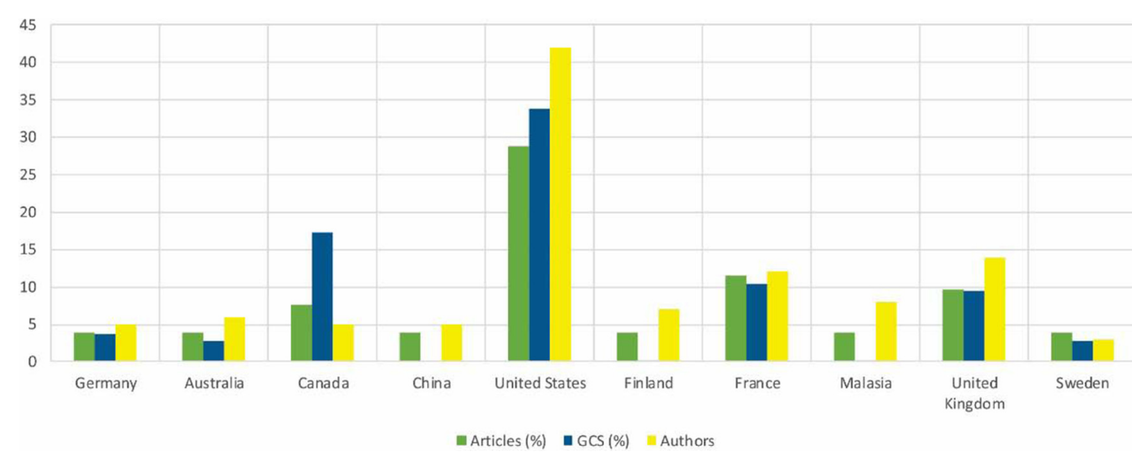
Citation Scores), which measures the number of citations that the article has in the WoS or Scopus database.

The presence of two French authors is noteworthy, with France being the second largest country regarding the number of publications. Is also possible to observe that 86.9 per cent of the CGS citations are scattered among other authors.

Figure 3 shows the countries with the highest number of publications. For each country, the percentage of publications, the percentage of GCS citations and the total number of authors were counted. Through this analysis, it was possible to reaffirm the USA as the major research center in this area. Besides being the country with the largest number of publications and where the most proficient authors are, it is also the country with the highest GCS index. China, Finland and Malaysia, despite being among the most published countries, obtained almost no representativeness when the numbers of global citations were considered. China, for example, despite having 3.8 per cent of the total number of publications, did not obtain any global citation. On the other hand, there are countries whose number of publications is low, but have a higher citations index, like Canada, that owns 7.7 per cent of the total publications, but obtained 17.2 per cent of the total citations.

Two countries that are not among the main centers of research but showed a relevant number of GCS citations are The Netherlands and South Korea. These two countries published one single article each but showed considerable citation percentages, The Netherlands with 4.73 per cent and South Korea with 6.72 per cent. In The Netherlands, Gebler *et al.* (2014) projected impacts of the use of AM for the year 2025. In South Korea, the article by Yoon *et al.* (2014)

Figure 3 Relation between the number of authors, total of publications and GCS of each country



compared AM with conventional manufacturing, focusing on energy consumption.

4.2 Literature analysis

Table II reviews the 43 articles that evaluated the environmental performance of the AM process. Drizo and Pegna (2006) and Gebler *et al.* (2014) carried out theoretical studies, the first article being an overview of the literature, based on the only article available on the subject at that time (Luo, Leu and Ji, 1999), an analysis of the impacts related to health, waste, raw material consumption and energy consumption in Vat Photopolymerization (SLA), and the second one, in addition to a brief literature review, also presented a modeling out of data found in the literature to estimate cost variation, energy consumption and CO_2 emission projected for the year of 2025.

Baechler *et al.* (2013) performed an LCI and studied the amount of energy and raw material used on an AM process, material extrusion, to compare the processes using virgin high-density polyethylene (HDPE) and recycled HDPE obtained through the process proposed by the article, resulting in a reduction of energy consumption with the use of recycled material. In Kreiger and Pearce (2013), an LCIA was performed to compare the impacts of the Material Extrusion with the conventional manufacturing method of injection molding, using ABS (acrylonitrile butadiene styrene) and PLA (polylactide) as raw material. In this LCIA, the energy consumption and the material used were considered as inputs and the cumulative energy demand (CED) and the Greenhouse Gas Emission (GWP) were the outputs, apparently showing an advantage for the AM process regarding the analyzed impacts. Faludi *et al.* (2015) compared two AM technologies, namely, material extrusion and material jetting, with the conventional machining manufacturing process. Through the LCA, the authors concluded that, in addition to the impacts, the material extrusion process was the least aggressive, but the comparison between material jetting processes with the machining depends on the size of the production.

The material extrusion technology was covered by five different articles, being the most studied AM process on the selected articles. This interest can be explained by the lower cost of equipment, making this technology also popular outside industrial and academic areas. The powder bed fusion technology placed in second, with four articles covering equipment that uses this process. This technology is mostly used to manufacture components using metal as raw material, which is an area of great interest. The material jetting technology was used by Mognol, Lepicart e Perry (2006), who experimented the three technologies mentioned, selecting manufacturing parameters to reduce the energy consumption of each process. Faludi *et al.* (2015) also compared the material extrusion and material jetting technologies with conventional manufacturing (CNC). In addition, Drizo and Pegna (2006) presented a review based on one article that explores Vat Photopolymerisation technology.

Some of the articles found do not suggest the kind of raw material employed, focusing only on the energy consumption of the equipment rather than making a complete environmental analysis of the AM, including a view of the life cycle of the product. Baechler *et al.* (2013), Baumers *et al.* (2011), Kreiger and Pearce (2013), Sreenivasan *et al.* (2010) and Faludi *et al.* (2015) mention ABS, HDPE and PLA as the raw materials employed in Material Extrusion and Material Jetting processes, and PA-12 (polyamide) the one used in the Powder Bed Fusion process.

The energy consumption was the main environmental aspect studied, being approached by 87 per cent of the articles, focusing on the environmental performance of the AM. Table III presents the results of energy consumption addressed in these articles. All selected articles make some kind of comparative or descriptive study of energy consumption in AM processes. Even articles that use the LCA methodology, such as Baechler *et al.* (2013) and Kreiger and Pearce (2013), focused on energy consumption. Kreiger and Pearce (2013) and Gebler *et al.* (2014) also analyzed the GWP, with a focus on CO_{2eq} emission; an analysis of the social impact caused by the AM in the industry concluded that AM may cause social insecurity regarding the number of jobs, especially on emerging countries, as the use of AM causes changes on the working structure. Another focus presented by Drizo and Pegna (2006) analyzes aspects related to health safety and the potential impacts, depending on the raw material, that may generate toxic gases, causing eye and skin rash.

It is possible to observe in Table III that the values and units presented on the selected studies are many and diverse, being impossible to establish a comparison between them. Parameters such as geometry, orientation, filling percentage, layer thickness and orientation, support and others indicators make the comparative analysis imprecise.

Some authors studied the influence of these parameters on environmental aspects and their impacts in the use of AM. Barros and Zwolinski (2016) studied the influence of the AM user profile on generating impacts, analyzing how the expertise and the way someone operates an equipment can affect the generation of impacts. Ding *et al.* (2016) carried out a study on the deposition path and its implications on raw material consumption. Griffiths *et al.* (2016) analyzed the effects of the slice orientation, the components infill and the layer height on the consumption of energy and raw material. Mognol *et al.* (2006) studied the reduction of energy consumption when changing orientation parameters of components, such as height, layer thickness and use of printing support.

For a better discussion of the environmental aspects and impacts caused by the AM processes and the conventional methods, articles that aim to establish a comparison between this two manufactures or between AM processes should be analyzed, as the interference of the variables can be minimized in one single study.

Regarding the studies that made comparisons between different AM technologies, it is possible to highlight Baumers *et al.* (2011), which compared two models of the same technology (Powder Bed Fusion) to analyze the consumption differences of the stages on the printing process (heating, printing and cooling), concluding that for this technology, the printing phase is responsible for the highest energy consumption. Jackson *et al.* (2016) compared an equipment that uses direct energy deposition with powder bed fusion and concluded that the total energy consumption, considering the production stage of the raw material and deposition, was practically the same.

Table II Review of articles about AM environmental performance

Authors	AM technology	Goal	Feedstock	Aspects analyzed	Impacts analyzed
Baechler *et al.* (2013)	Material Extrusion	To develop, test and analyze (Quality, Energy Consumption and Time) the use of recycled filaments in RepRap printer	HDPE	Feedstock. Energy Consumption. Embodied Energy	
Balogun and Oladapo (2016)	Material extrusion	To improve the direct electrical energy model of FDM strategy with a view to develop mathematical model or framework for a 3D printing process	ABS	Energy Consumption	
Barros and Zwolinski (2016)	Material extrusion	To compare AM and Injection Molding through LCA and analyze the influence of the user profile on the results	PLA	Table IV	Table IV
Baumers *et al.* (2011)	Powder bed fusion	To compare the Energy Consumption of two printer models (Powder Bed Fusion), dividing the Energy Consumption between the several steps of the printing process (Heating, Printing and Cooling)	PA 12	Energy Consumption	
Baumers *et al.* (2013)	Powder bed fusion	To develop a tool that estimates the energy flow of the AM process		Energy Consumption	
Le Bourhis *et al.* (2013)	Powder bed fusion	To present a LCA based methodology to assess the environmental impacts of AM, in particular on Powder Bed Fusion processes	Steel	Feedstock Energy Consumption	
Burkhart and Aurich (2015)	Powder bed fusion	To work as a guide of how companies can evaluate the reduction of the environmental impacts caused by their products, through the components obtained through the AM, analyzing, as an example, the life cycle of commercial vehicles, through LCI	Steel	Transport	
Chen *et al.* (2015)	Powder bed fusion	To analyze the AM in different aspects, comparing it with the traditional manufacturing; To detail a case study, comparing AM Energy Consumption (SLS) with the Injection Molding		Energy Consumption. Embodied Energy	
Despeisse and Ford (2015)		To describe several kinds of products and industries that can, using AM, improve the sustainability of their products			
Ding *et al.* (2016)	Wire and Arc additive manufacturing (WAAM)	To Present a new strategy for the path of deposition on the AM processes of metallic filaments, to reduce the amount of raw material (buy-to-fly ratio)		Feedstock	
Drizo and Pegna (2006)	Vat Photopolymerization	To Review the literature on environmental impact assessment of AM to identify opportunities for future research		Feedstock Energy Consumption	
Faludi *et al.* (2015)	Material extrusion Material jetting	To compare the environmental impacts of two different types of AM with conventional manufacturing (CNC) through a LCA	ABS	Table IV	Table IV
Gebler *et al.* (2014)		To design the aspects and impacts caused by the use of the AM by the year of 2025		Energy Consumption	CO_2 Emission Social
Griffiths *et al.* (2016)	Material extrusion	To optimize the AM process to compare and relate the constructed piece weight, the amount of disposed material, the Energy Consumption and the production time	PLA	Energy Consumption Feedstock Waste	
Hapuwatte *et al.* (2016)		To compare conventional manufacturing with the AM, in a holistic way, considering the entire life cycle, through the Product Sustainability Index (ProdSI)			Economic Social Environmental

(*continued*)

Table II

Authors	AM technology	Goal	Feedstock	Aspects analyzed	Impacts analyzed
Huang *et al.* (2016)	Powder bed fusion Direct energy deposition	To analyze, through an LCI, the differences between conventional and additive manufacturing on the production of aircraft parts	Titanium Aluminium	Feedstock Energy Consumption	
Ibrahim *et al.* (2014)	Material extrusion	To investigate the use of a biodegradable PLA on the AM	PLA	Feedstock	
Jackson *et al.* (2016)	Direct energy deposition Powder bed fusion	To compare the Energy Consumption of the wired-based and Powder-based AM processes	Steel	Energy Consumption	
Kai *et al.* (2016)	Material extrusion Vat Photopolymerization Material jetting Sheet lamination Powder bed fusion Binder jetting	To investigate the metrics applied to identify the advantages and disadvantages of the AM		Water Consumption Feedstock Energy Consumption Waste	Global Warming Potential (GWP)
Kellens *et al.* (2014)	Powder bed fusion	To perform a LCI based on CO2PE! methodology to estimate the environmental footprint of the SLS process	PA 12	Energy Consumption Feedstock	
Kianian and Larsson (2015)	Vat photopolymerization	To perform an LCI comparing the AM (SLS) with the conventional one (Injection)	PS	Feedstock Energy Consumption	
Kreiger *et al.* (2014)	Material extrusion	To Perform an LCA to verify the best scenario for HDPE recycling to be used as raw material on the AM	HDPE	Table IV	Table IV
Kreiger and Pearce (2013)	Material extrusion	To perform a comparative LCIA between the AM process and conventional manufacturing (injection molding)	ABS PLA	Table IV	Table IV
Le Bourhis *et al.* (2014)	Direct energy deposition	To Suggest a methodology to evaluate the Energy Consumption, raw material and fluids on the AM Direct Energy Deposition (Atomization and printing) stages	Metal	Energy Consumption Feedstock Water Consumption	
Liu *et al.* (2016)	Direct energy deposition	To evaluate Energy Consumption of Direct Energy Deposition process considering the laser power, speed and deposition rate of feedstock	Metal Alloy	Energy Consumption	
Luo, Leu and Ji (1999)	Vat photopolymerization	To present a methodology for the evaluation of environmental performance of the AM (SLA) considering the many stages of the process	Epoxy Resin	Feedstock Energy Consumption Waste	
Malshe *et al.* (2015)	Vat photopolymerization	To conduct a LCA to analyze the environmental performance of a new kind of SLA (Fast MIP-SL)	Epoxy Resin	Table IV	Table IV
Mani *et al.* (2014)		To Suggest a methodology to characterize the sustainability of the AM processes			
(Meteyer *et al.* (2014)	Binder jetting	To conduct an LCI to serve as basis for a LCA on the AM process		Energy Consumption Feedstock	

(*continued*)

Table II

Authors	AM technology	Goal	Feedstock	Aspects analyzed	Impacts analyzed
Mognol *et al.* (2006)	Material jetting Material extrusion Powder bed fusion	To discuss the Energy Consumption of the AM, analyzing three different AM technologies, comparing the Energy Consumption by changing the parameters, aiming to reduce the Energy Consumption		Energy Consumption	
Nagarajan *et al.* (2016)	Vat photopolymerization	To conduct an environmental impact assessment (EIA) of the novel fast MIP-SL process using a LCIA approach	Resin	Table IV	Table IV
Nyamekye *et al.* (2015)	Powder bed fusion	To determine sustainability gains on the supply chain using AM and offering a methodology to conduct an LCI comparing AM and the CNC		Feedstock Energy Consumption Waste	
Paris *et al.* (2016)	Direct energy deposition	To perform a LCA as a decision criterion on selecting the manufacturing process (MA × Milling)	Titanium	Table IV	Table IV
Peng (2016)		To provide models to estimate and optimize the AM Energy Consumption based on the division of this consumption, primary (change the phase of the raw material) and secondary (printing itself)			
Ramli *et al.* (2015)	Material extrusion	To develop an integrated raw material recycling system on the 3D printer itself	ABS	Feedstock	
Santos *et al.* (2012)	Material extrusion	To carry out a case study, performing a LCA based on its own computational tool	ABS	Feedstock Energy Consumption Waste Transport	
Senyana and Cormier (2014)	Direct energy deposition	To compare the environmental impact of the AM in relation to the conventional manufacturing (Forging)	Titanium	Feedstock Energy Consumption Transport	
Sreenivasan *et al.* (2010)	Powder bed fusion	To perform an Energy Consumption analysis on several components of the SLS process in order to compare and discuss with other processes	PA 12	Energy Consumption Feedstock	
Tang *et al.* (2016)	Binder jetting	To propose a general framework which can integrate a design stage in LCA for minimizing the product environmental impact of AM process		Energy Consumption Feedstock Waste	Climate Change Human Toxicity
Ullah *et al.* (2013)	Vat photopolymerization	To develop a sustainability index for AM process considering volumetric quantity, CO2 footprint and resource depletion of primary production, energy consumption and CO2 emission		Energy Consumption	CO_2 Emission
Vinod *et al.* (2016)	Direct energy deposition	To focus on reducing lead-time and energy consumption for laser-based metal deposition and investigate the effect of process parameters on microstructure, density, surface roughness, dimensional accuracy and microhardness	Metal Alloy	Energy Consumption	
Xu *et al.* (2015)	Binder jetting	To create a model to analyze the Energy Consumption of the Binder Jetting process		Energy Consumption	
Yoon *et al.* (2014)	Material extrusion Powder bed fusion	To compare conventional (subtractive) and additive manufacturing regarding energy consumption		Energy Consumption	

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Table III AM energy consumption results found on the selected articles

Articles	AM technology	Material	Energy consumption	Unit
Jackson *et al.* (2016)	Direct energy deposition	Steel	8.97	kWh/kg
Le Bourhis *et al.* (2014)	Direct energy deposition	Steel	12-109	kWh/piece
Paris *et al.* (2016)	Direct energy deposition	Titanium	26.05	kWh/piece
Griffiths *et al.* (2016)	Material extrusion	PLA	0.007-0.03	kWh/piece
Kreiger and Pearce (2013)	Material extrusion	ABS e PLA	0.1-0.52	kWh/piece
MOGNOL *et al.* (2006)	Material extrusion	–	0.5-1.25	kWh/piece
Baumers *et al.* (2011)	Powder bed fusion	PA 12	56.75-66.02	kWh/kg
Baumers *et al.* (2013)	Powder bed fusion	–	0.54-1	kWh/cm^3
Le Bourhis *et al.* (2013)	Powder bed fusion	Steel	21.48-24.2	kWh/kg
Jackson *et al.* (2016)	Powder bed fusion	Steel	18.58	kWh/kg
Mognol *et al.* (2006)	Powder bed fusion	–	32-56	kWh/piece
Sreenivasan *et al.* (2010)	Powder bed fusion	PA 12	14.5	kWh/kg

Considering only the printing stage, direct energy deposition technology consumed half of the energy required when compared with powder bed fusion. The equivalence in total consumption is due to the higher energy consumption for the production of the wire used in the direct energy deposition equipment in relation to the powder used by powder bed fusion technology.

In the article by Mognol *et al.* (2006), a comparative analysis was performed between three different technologies: material extrusion, material jetting and powder bed fusion. The results showed that the most important feature for reducing the energy consumption was related to the printing time, stating that it is possible to reduce the equipment energy consumption in 45 per cent (material jetting), 61 per cent (material extrusion) and 43 per cent (powder bed fusion) with some adjustments on the parameter set. Barros and Zwolinski (2016) performed an LCA to compare material extrusion AM technology with the conventional injection molding processes, analyzing the influence of the user experience of the AM with the generated environmental impacts generated. Nine impact categories were analyzed, emphasizing the global warming and non-renewable energy impacts, which, according to the authors, are key categories of impacts for companies today. For these two categories, when the AM user profile is classified as a beginner, the result on the evaluated impacts is favorable to conventional manufacturing; however, when handled by an advanced user, the analysis shows that the AM impact can be up to 45 per cent lower when compared to the conventional manufacture. Chen *et al.* (2015) compared powder bed fusion technology with the conventional injection molding process and concluded that the embodied energy of the two processes is similar for productions of up to 100 items, but advantageously for injection molding for productions over 1,000 items. The relation between the size of the production and the impact caused by the process was also approached by other authors. In the work by Kianian and Larsson (2015), a comparative analysis was carried out between the Vat Photopolymerization process and the conventional injection molding manufacture. The authors concluded that, for the production of up to 1,000 items with the AM process, the energy consumption is lower than on the conventional one, but for a production above this amount, there is an advantage for the injection molding process. Senyana and Cormier (2014) compared direct energy deposition technology with the conventional forging process and also the environmental performance to the quantity of items produced. Yoon *et al.* (2014) related the volume of the produced items to the energy consumption, in which the energy consumption of the AM (material extrusion) process, by mass deposited, was higher than the conventional injection molding process, when the volume of the production increases. Huang *et al.* (2016) compared the additive manufacture (powder bed fusion and direct energy deposition) with conventional (forging, casting and machining) through LCIA, and concluded that the use of AM can reduce energy consumption by up to three times. Paris *et al.* (2016) analyzed ten impact categories, comparing the AM with the conventional machining, and concluded that the AM can be environmentally better in all analyzed categories, as long as the ratio between the volume of material needed for the production of an item through the machining process divided by the final volume of the item is greater or equal to 7. Hapuwatte *et al.* (2016) compared the AM with the conventional forging process using the Product Sustainability Index (ProdSI) method and concluded that the total impact (environmental, social and economic impacts) caused by the AM process (environmental sub-index score) is lower than the impacts caused by the conventional manufacturing, mainly because of the better efficiency on the use of raw material. Kreiger and Pearce (2013) also analyzed the consumption of raw material on the AM process; unlike conventional manufacturing methods, such as injection molding, the AM allows the production of items with no full infill, which reduces the need of raw material, a factor that may lead the AM to have a lower environmental impact over conventional methods.

As mentioned, many authors used the LCA in their studies. Table IV presents an overview of all articles that conducted the LCA to assess the environmental impacts caused by AM process. Considering all 43 articles, at least 25 per cent used the LCA, some of them performed the study until the inventory stage. In addition, all articles that used LCA are recent (an average of two years of publication), indicating the importance of this methodology on AM studies, and also showing the researchers' growing interest in recent years.

Regarding the technologies studied through the LCA, has been identified the predominance of Material Extrusion which, as previously seen, is one of the most studied technologies

Table IV Review of articles that performed LCA

		AM			LCA		
Authors	**Goal**	**Technology**	**Raw material**	**Functional unit**	**Dimension**	**Software**	**Method**
Barros and Zwolinski (2016)	To compare the Additive and Conventional Manufacturing (injection molding) through ACV and analyze the influence of the user profile on the results	Material extrusion	PLA	Mug that holds 250 ml of cold water, used 4 times a day, for 3 years	Gate-to-grave	SimaPro	Impact 2002+
Faludi *et al.* (2015a)	To compare the environmental impacts of two distinct types of AM with the conventional one (CNC) through a LCA	Material Extrusion Material Jetting	ABS	Manufacture of two different plastic parts – one complex, usually made by AM, and a flat perforated surface, made by conventional milling machines	Cradle-to-grave	SimaPro	ReCiPe Impact 2002+
Kreiger *et al.* (2014)	To perform a LCA to verify the best scenario for the recycling of HDPE used as MA raw material	Material Extrusion	HDPE	1 kg of HDPE compatible recycled by AM and conventional methods	Gate-to-gate	SimaPro	IPCC 2007 CED
Kreiger and Pearce (2013)	To perform a comparative LCIA between the AM process and conventional manufacturing (injection molding)	Material Extrusion	ABS PLA	Kilograms required to create each individual product	Cradle-to-gate	Simapro	IPCC 2007 CED
Malshe *et al.* (2015)	To conduct an LCA to analyze the environmental performance of a new type of SLA equipment (Fast MIP-SL)	Vat Photopoly-merisation	Epoxy Resin	1000 unities of 6 different pieces	Cradle-to-gate	SimaPro	ReCiPe
Nagarajan *et al.* (2016)	To conduct an environmental impact assessment (EIA) of the novel fast MIP-SL process using a LCIA approach	Vat Photopoly-merisation	Resin	1000 units of each manufactured part	Gate-to-gate	SimaPro	ReCiPe
Paris *et al.* (2016)	To perform a LCA as a decision criterion for the choice of manufacturing process (MA x Conventional Manufacturing (machining)	Direct Energy Deposition	Titanium	Titanium Turbine composed of 13 blades with nominal size of 130 mm × 30 mm	Gate-to-grave	SimaPro	CML 2 Baseline 2000 CED

because of the low cost of equipment, hence its widespread use. As for the materials used, a great variety was observed, and it was not possible to highlight the use of a particular raw material.

Regarding the software used to perform the LCA, all articles used SimaPro, one of the most used software for LCA (Speck *et al.*, 2016). The most used methods were ReCiPe, CED and Impact 2000+. The ReCiPe method is the successor of the Eco-indicator 99 and the CML-IA methods, analyzing a total of 18 impact categories at the midpoint level and three categories at the endpoint level. The CED method is classified as Single Issue and performs energy source analysis. Impact 2000+ combines the midpoint and Damage categories, summarizing all inventory analysis data into 14 midpoint and four Damage categories.

Faludi *et al.* (2015), Malshe *et al.* (2015) and Nagarajan *et al.* (2016) demonstrated the results through the endpoint type categories of impact. Malshe *et al.* (2015) evaluated the Vat Photopolymerization process, specifically a new kind of SLA (Stereolithography) equipment, also through an LCA. The authors produced different pieces for analysis and concluded that the greatest impacts are related to damage to human health and resource depletion. Nagarajan *et al.* (2016) performed a LCIA of the novel fast MIP-SL process and identified energy consumption as the dominant impact factor. Kreiger *et al.* (2014) used the LCA to evaluate the best scenario for recycling HDPE to be used as raw material on the AM, and concluded that the recycling performed in a decentralized way is better on the perspective of environmental impacts, being the lowest values presented by *Energy demand* e *Greenhouse gas emissions*.

5. Conclusions

From the results obtained through this literature review about the environmental performance of the AM, it was possible to observe the growing number of studies about the subject in recent years, especially on North America and Europe.

With the increase use of AM, the need and the interest of researchers in studying and evaluating the environmental aspects and impacts that this technology can cause to the environment also increases. In addition, there is a great concentration of research on developed countries, as they are the ones with technology expertise, where the largest manufacturers are located and the where the concern with environmental issues is also rising. As the AM is still a new technology, the number of consolidated researchers in the area is still small, but about to grow as the use and the studies about this technology become more popular.

As for the published articles, it is possible to observe a great concern, by some of the authors, in addressing the questions about the energy consumption of the equipment. This concern is because when compared to conventional techniques, the AM has an advantage regarding raw material consumption and waste generation, as it uses only the volume of material needed to construct the item. However, because of the characteristics of the additive manufacturing and its long processing time, it consequently lower the productivity, as the dilution of the energy consumed by the equipment *per* item produced becomes a concern for the researchers. This fact also explains the intense researches to evaluate and reduce the energy consumption of such equipment.

Despite the existence of numerous articles focusing on energy consumption was observed a recent growth on the number of articles using more advanced tools to analyze aspects and environmental impacts of the process, such as LCA.

The LCA was used, in general, by a considerable number of authors, especially in recent years, demonstrating the increasing need for studies about AM by analyzing aspects and environmental impacts of manufactured products. Because of the small number of researches, it was not possible to determine the categories of environmental impacts that AM causes, but it can be inferred that the energy consumption stood out on the AM analysis.

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