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Thematic Section

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Systematic analysis of comparative studies between additive and conventional manufacturing focusing on the environmental performance of logistics operations

Análise sistemática de estudos comparativos entre a manufatura aditiva e convencional com foco no desempenho ambiental das operações logísticas

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Abstract: Based on the promise to revolutionize the entire supply chain, additive manufacturing is seen as an alternative to conventional manufacturing processes, since it simplifies the production of small batches, shortens the distances between production and consumption and generates new distribution models. Due to its huge potential to spread more sustainable environmental practices, investigations on the environmental assumptions, concerning the application of additive manufacturing technologies, are required. Therefore, based on a systematic literature review, this study aimed to analyze the studies that addressed the environmental performance of logistics operations in a comparison among conventional and additive manufacturing, using the Life Cycle Assessment technic (LCA). Although there are few available studies that quantitatively analyze and compare the environmental performance of the additive manufacturing process with traditional process from a transport perspective, it has been concluded that reducing the distances and the quantity of transported products, carbon dioxide emissions and the consumption of energy resources are reduced.

Keywords: Life cycle assessment; Additive Manufacturing (AM); Decentralized Manufacturing System (DMS); Transport.

Resumo: Com a promessa de revolucionar toda a cadeia de suprimentos, a manufatura aditiva apresenta-se como uma alternativa aos processos de manufatura tradicionais, pois facilita a produção de pequenos lotes, encurta as distâncias entre produção e consumo e gera novos modelos de distribuição. Devido ao seu grande potencial de difundir práticas ambientais mais sustentáveis, estudos sobre as implicações ambientais do uso de tecnologias de manufatura aditiva são necessários. Diante disso, a partir de uma revisão sistemática da literatura, este trabalho teve o objetivo de analisar os estudos que abordaram o desempenho ambiental das

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operações logísticas em um comparativo entre a manufatura convencional e a manufatura aditiva, por meio da metodologia de Avaliação do Ciclo de Vida (ACV). Embora existam poucos estudos disponíveis que analisam e comparam, em termos quantitativos, o desempenho ambiental do processo de manufatura aditiva e de manufatura convencional, sob a perspectiva do transporte, foi possível concluir que, ao reduzir as distâncias e a quantidade de produtos transportados, diminui-se as emissões de dióxido de carbono e o consumo de recursos energéticos.

Palavras-chave: Avaliação do ciclo de vida; Manufatura aditiva; Sistema de manufatura descentralizada; Transporte.

1 Introduction

The manufacturing context is constantly developing. The rise of advanced manufacturing technologies significantly enhances the development and enables an effective production relating to costs and resources (Ford & Despeisse, 2016). In this scenario, the use of Additive Manufacturing (AM) could promote shorter, localized, collaborative, and more sustainable supply chains (Gebler et al., 2014).

According to Pour et al. (2016), the accelerated growth rate of studies on AM, among researchers and professionals working in different areas of the industry, indicates that this technology has the potential to be an effective methodology in the manufacturing process. This fact highlights the need to examine the advantages of AM. Previous research highlights the benefits of AM in the supply chain, which are: shorter manufacturing time, reduced inventory, reduced production batch, lower transportation costs, less production waste, and better sustainable practices (Attaran, 2017; Li et al., 2017; Cerdas et. al., 2017). Based on this context, since the environmental impacts related to AM logistics are not clearly presented, this study aimed to carry out a Systematic Literature Review (RSL) on the studies that discussed the environmental performance of logistics operations in a comparative analysis between conventional or traditional manufacturing (CM) and additive manufacturing, using the Life Cycle Assessment (LCA) technique.

Since the life cycle approach includes all activities related to the production of products, transportation is considered one of the fundamental stages of the processes of a product system. The transportation of materials and products, as well as the transportation that covers the final disposal of the product after the customer's use, is usually estimated during the data collection for Life Cycle Inventory (LCI).

This article initially provides an overview regarding the change of the supply chain with the advent of the Industry 4.0. Then, the main characteristics and advantages of additive manufacturing were presented. In addition, the methodology approach was presented and a bibliometric analysis was performed to verify the worldwide research scenario on the topic. After conducting the bibliometric analysis, the articles that investigated the environmental impacts of the logistics operations were selected for a systematic analysis. Finally, research gaps were identified in order to provide directions for future research and practices.

2 Industry 4.0 and innovations in logistics operations

The fourth industrial revolution is represented by the increase of intelligent automation technologies, the integration of production systems, and the advancement of information technologies, giving rise to smart factories (Ibarra et al., 2018).

In Industry 4.0, manufacturing systems allow monitoring of physical processes and decision making through real-time communication. Information on products, machines, or production lines generates a huge amount of statistical data that helps to ensure intelligent manufacturing when analyzed (Dilberoglu et al., 2017).

Industry 4.0 is transforming the entire supply chain, allowing full real-time transparency between suppliers and customers, small batches production, a variety of products, connected processes, and decentralized and autonomous management (Vaidya et al., 2018). However, these benefits cannot be achieved by the production without smart logistical processes, and, according to this fact, there are many reasons to consider the impacts of the fourth industrial revolution on logistics (Kayikci, 2018).

Rüßmann et al. (2015) point out that the fourth revolution regards the integration between production processes, logistics, and their corresponding information technology systems, including all exchange of information about products, production within companies, and between customers and suppliers. Dilberoglu et al. (2017) complement this concept by highlighting that this communication occurs in real-time and the processing and storage of this information occur in the cloud to increase its availability and accuracy. In view of these transformations, the supply chain becomes more flexible, allowing quick action in the face of changes in production processes (Kayikci, 2018).

Thus, the goal of smart industries is to use emerging technologies to deeply integrate manufacturing and logistics processes, making production operate efficiently, with high quality, low cost, and sustainable (Wang et al., 2016).

3 Additive manufacturing

In addition to smart factories, Industry 4.0 brings a concept of greater flexibility in manufacturing, combining mass customization and productivity (Huang et al., 2015). This aids companies to deal with the challenges of manufacturing customized products, including high quality, and in shorter delivery time (Kayikci, 2018). In this context, additive manufacturing, also known as 3D printing, is considered a crucial ingredient in this disruptive movement of the conventional manufacturing, since it allows the printing of customized products to meet the requirements of the final consumer (Dilberoglu et al., 2017).

Additive manufacturing encourages innovation and is on the list of recent disruptive technologies. Furthermore, it is a technology that can produce anything, eliminating many restrictions imposed by conventional manufacturing methods (Huang et al., 2015). In the beginning, AM was encouraged by prototyping companies, which have printed products without regard to the accuracy of the projected design (Ford & Despeisse, 2016). However, the possibility of "printing everything" made this production model receive notoriety and relevance in the manufacturing industries. Currently, 3D printing allows relatively easy production of complex products, which can reduce overall production time as a result of consolidating several stages of manufacture and assembly (Gao et al., 2015).

According to Gao et al. (2015), one of the benefits of this technology is the need for fewer components inside the company. The consolidation of the manufacturing and assembly steps results in a reduction of components in a product's BOM. Product simplification, on the other hand, reduces the number of suppliers or tools needed for the production, labor, movement of components during the manufacturing process, and the stock of materials in the process (Harlalka et al., 2016).

Rejeski et al. (2018) also highlight that, since AM allows the production of small quantities, it will no longer be required to produce unnecessary quantities, which is not possible in conventional manufacturing processes with economically viable batch concepts. In addition, according to Huang et al. (2015), AM's flexibility provides the printing of products or parts only when demanded, in other words, at the time they will be utilized in production. This fact transforms the production chain, enabling manufacturing on-demand, reducing inventories and waiting times and contributing to just in time practices.

AM not only changes the way products are designed and manufactured but also changes the product distribution network to the final consumers (Gao et al., 2015). In conventional manufacturing, the production is fixed in a single place, to facilitate large-scale production and distribution through transportation. Meanwhile, the production process can be decentralized in the AM, meaning that the product is designed in a specific location and produced closer to the place of consumption (Santos et al., 2017). This type of approach eliminates the long distances that products move within the supply chain, reducing logistics and storage costs (Rüßmann et al., 2015).

Decentralized or distributed production suggests an alternative to conventional production that differs in scale, location, and producer-consumer relationship (Kohtala, 2015). In Table 1, Li et al. (2017) present the differences between the conventional supply chain and the AM supply chain.

Table 1. Differences between a conventional supply chain and one adopting AM.

Parameter	Conventional supply chain	Supply chain adopting AM
Production methods	Conventional manufacturing – Subtractive manufacturing	AM equipment – Additive manufacturing
Supply chain configuration	Supplier – Manufacturer – Distributor – Service location	Centralised structure: Supplier – Distributor (Manufacturer) – Service location Decentralised structure: Supplier – Service location
Members' responsibilities	Supplier: Provide raw materials Manufacturer: Manufacturing and holding inventory Distributor: Distributing and holding inventory	Supplier: Provide raw materials and manufacturing STL (stereolithography) files Distributor (Manufacturer)/Service location: Manufacturing and distributing based on demand and holding inventory

Source: Li et al. (2017).

The entire transformation makes the supply chain more flexible, making it react to market changes periodically (Kayikci, 2018). This increases manufacturing productivity, improves the economy and promotes industrial growth (Rüßmann et al., 2015). In the future, manufacturers will understand that it will no longer be viable or efficient to ship products worldwide because AM will make manufacturing possible anywhere and at the same cost (Durão et al., 2017).

While traditional manufacturing processes generate considerable waste due to material removal (called subtractive processes), another advantage of AM is the reduction in the generation of the amount of waste, as it builds the final shape of the product by adding material layer by layer (Huang et al., 2015). On the other hand, similar to conventional processes, AM is a productive process that also consumes materials, energy and contributes to emissions to the environment, which must be considered in life cycle assessments (Rejeski et al., 2018).

4 Methodology

First, based on the emergence of additive manufacturing, it was assumed that there was a trend in the reduction of potential environmental impacts, focused on logistical operations. This fact could influence in modifications of the transportation mode since the transport of products over long distances would be replaced by the transportation of materials to AM companies considering a short distance (Kohtala, 2015). Thus, two research questions were asked:

- **(Q1)** What are the most relevant comparative studies on environmental performance between additive and conventional manufacturing, focusing on the differences of the logistics operations?
- **(Q2)** What are the environmental impacts (positive and negative) of the additive manufacturing and decentralized transport?

Thus, the purpose of the selection of articles was to identify discussions about a probable change in the results of the potential environmental impacts of transport operations in scenarios where traditional manufacturing is compared with additive manufacturing. The profile of these studies was also questioned, regarding the applied methods and characteristics of the studies.

Based on this, in order to answer the research questions, a systematic review of the literature was carried out. Therefore, the researches that discussed the potential environmental impacts of additive manufacturing and addressed the impacts of transport or the environmental performance of logistics operations were selected according to the steps described in Figure 1.

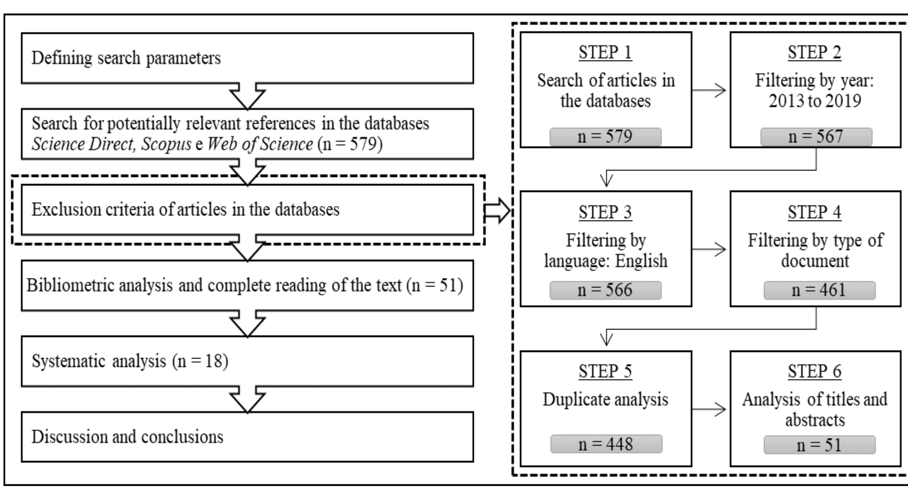

Figure 1. Steps of research process. Source: The authors (2020).

For the selection of articles, the defined strategy covered three databases: *Science Direct*, *Scopus* e *Web of Science*. In each database, the keywords were combined among the search strings "AND" and "OR", as shown in Table 2.

Table 2. The search parameters applied in databases.

Search term	Database	Search boundaries	Results
("Additive manufacturing" OR "3D printing") AND ("Life Cycle Assessment" OR "environmental performance") AND ("Logistics" OR "transport")	*Science Direct*	Full text	298
	Scopus	Full text	272
	Web of Science	Topic	9

Source: The authors (2020).

Based on a total result of 579 articles (1st step), the filtering steps were carried out. As an exclusion criterion, the articles published between 2013 and 2020 (2nd step) were selected, due to the fact that the studies on the environmental impacts of additive manufacturing emerged in 2010 and began to grow from 2013 (n = 567).

Next, documents in languages other than English (3rd step) were excluded from the search (n = 566) and research article, review articles and conference paper were selected (4th step) (n = 461).

Then, using the Mendeley® software, the results found in the databases were exported in the BibTeX extension format and the duplicated articles (5th step) between the databases were analyzed. Thus, 13 articles were excluded in this step (n = 448).

In order to refine the results regarding the subject of interest, the 6th step consisted in the analysis of title and abstracts, based on the confirmation of the search keywords in the 448 documents. In this step, 51 articles were selected, and then a bibliometric analysis was carried out to highlight the pertinent aspects of the theme.

Finally, these articles were read in full (n = 51), to verify whether, in fact, these publications were related to the research topic. Hence, priority was given to the studies that discussed the environmental effects of additive manufacturing and presented the environmental impacts of transportation in a life cycle approach, resulting in a database with 18 articles (Table 3).

5 Results and discussion

This section consists of two main stages: bibliometric analysis and systematic analysis. The results of these steps, as well as the exclusion criteria for articles, are presented in detail in topics 5.1 and 5.2.

5.1 Bibliometric analysis

At this stage, the 51 studies analyzed were produced by the authors (Abdulhameed et al., 2019; Afshari et al., 2019; Agrawal & Vinodh, 2019; Ahmad & Enemuoh, 2020; Arrizubieta et al., 2020; Attaran, 2017; Böckin & Tillman, 2019; Campitelli et al., 2019; Caviggioli & Ughetto, 2019; Cerdas et al., 2017; Chen et al., 2015; Barros & Zwolinski, 2016; Esmaeilian et al., 2016; Faludi et al., 2019; Ford & Despeisse, 2016; Fruggiero et al., 2019; Garg & Lam, 2015; Ingarao et al., 2018; Kek et al., 2016; Kellens et al., 2017a, b; Kohtala, 2015; Kothman & Faber, 2016; Kunovjanek & Reiner, 2020; Li et al., 2017; Liu & De Giovanni, 2019; Ma et al., 2018; Maciel et al., 2019; Mele et al., 2020; Minetola & Eyers, 2018; Mrazović et al., 2018; Nagarajan & Haapala, 2018; Niaki et al., 2019; Nyamekye et al., 2015; Nyman & Sarlin, 2014; Paris et al., 2016; Peng et al., 2018; Peng & Sun, 2017; Pour et al., 2016;

Priarone & Ingarao, 2017; Priarone et al., 2018; Saade et al., 2020; Santander et al., 2020; Savolainen & Collan, 2020; Schutter et al., 2018; Sinclair et al., 2018; Torres-Carrillo et al., 2020; Tziantopoulos et al., 2019; Yeon et al., 2020; Yusuf et al., 2019; Zhang et al., 2019).

Thereby, in the first analysis (Figure 2), the evolution of the theme was verified based on the number of articles published per year. It is worth mentioning that the search for articles published in 2020 was carried out until March 2020.

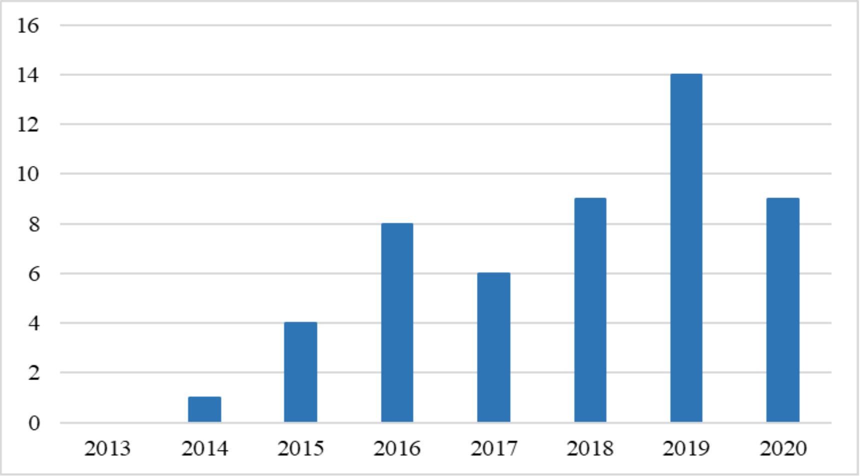

Figure 2. Number of articles per year. Source: The authors (2020).

Although studies on the environmental impact of additive manufacturing are in a preliminary phase, according to the number of publications over the years, there is a remarkable growth in research that mentions the transportation in the last few years.

Only with the quantitative analysis of the data, it is possible to prove that the interest in analyzing the sustainability and the environmental impacts of disruptive technologies, such as 3D printing, has grown, mainly, in the last 3 years.

In the second analysis (Figure 3), the number of papers on the research topic, as well as the h-index, were listed according to the articles' publication journals. The h-index is proposed by Hirsch (2005), which points to the number of articles (h) that have a number of citations greater than or equal to h. These indexes were consulted on the website Scimago Journal & Country Rank and describe the impact factor of journals and conference papers.

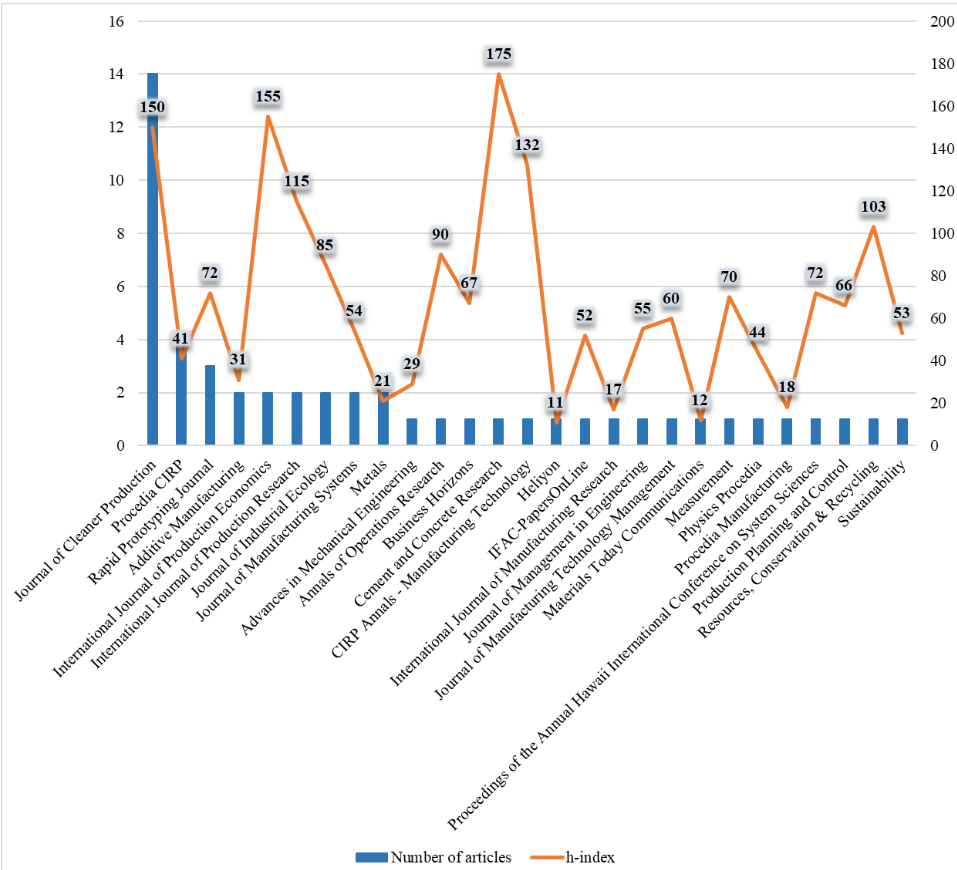

Figure 3. The most relevant journals. Source: The authors (2020).

The scientific journals “Journal of Cleaner Production” (27.45%), “Procedia CIRP” (7.84%), and “Rapid Prototyping Journal” (5.88%) represent 41.18% of the publications evaluated in this analysis, that is, 21 of the 51 articles. For the 52.82% of articles, only five journals had 2 articles published in each of them, and the rest had a single publication on the topic. Regarding the impact factor of the journals, it was found that the “Journal of Cleaner Production” presented the third highest value of the h-index, with 150, and also is the journal including more publications that discuss the environmental issues of additive manufacturing. Also, according to Figure 3, the highest h-index among the journals belong to “Cement and Concrete Research” (175) and “The International Journal of Production Economics” (155), but they do not represent a significant part of the number of articles selected for this analysis.

Finally, the third analysis represents the geographical distribution of the authors of the analyzed articles (Figure 4).

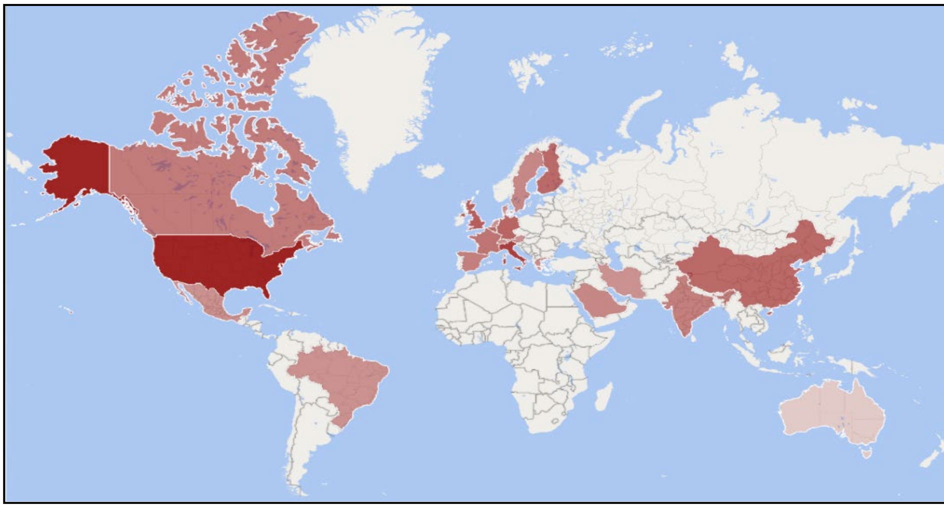

Figure 4. The geographical distribution of the author's research centers. Source: The authors (2020).

In this analysis, the authors' research centers were collected, and the number of authors, localized in the countries around the world was calculated. As shown in Figure 4, the color grading in each region increases, according to the concentration of authors in the countries on the map. The countries with the highest number of authors were the United States (18.39%), Italy (13.79%), United Kingdom (8.62%), Germany (7.47%), China (6.90%), Finland (6.90%), Belgium (6.32%) and France (5.17%), corresponding to 73.56% of the research centers of the analyzed authors. The other authors, who represent 26.44% of the total authors of the analyzed documents, have research centers in Canada, India, Spain, Saudi Arabia, Sweden, Greece, Austria, Brazil, Denmark, Iran, Mexico, the Netherlands, Switzerland, Australia, and Singapore.

In addition, the countries of publication of each article were also analyzed. Some articles had the characteristic of shared research. In other words, they were written by authors and co-authors from different countries of the world. Thus, Italy (14.49%), the United States (14.49%), the United Kingdom (11.59%) and Belgium (7.25%) have great influence in research on the environmental performance of disruptive technologies, representing 47.83% of the selected publications.

In conclusion, the remaining 52.17% of publications were spread among different countries, such as China, Finland, Germany, France, Canada, India, Spain, Australia, Brazil, Denmark, Greece, Mexico, Saudi Arabia, Iran, Singapore, Sweden, Switzerland, and Austria.

5.2 Systematic analysis

In this topic, the content analysis of the 51 articles selected in the bibliometric review was carried out. After the analysis, the articles that were excluded did not present evaluations or discussions about the environmental impacts of additive manufacturing focusing on transportation. In addition, most of the articles were focused on other types of applications, presenting limited discussions about the supply chain.

Thus, the selection process of the articles prioritized studies that performed the environmental LCA of products from additive manufacturing and presented results of the evaluation of transport in the life cycle. Furthermore, studies that did not assess the transport, but addressed topics on centralization and decentralization of the supply chain, were also selected with the aim of enhancing the debate on the possible environmental impacts.

During the selection process, the number of publications decreased from 579 to 18. The systemic analysis procedure was performed to provide the main characteristics of the studies, as well as the necessary discussions to answer the research questions. Thus, Table 3 presents the characteristics of the evaluated studies, reporting the objective of the article, the object of study, method, and the environmental impacts of the contained analyzes.

Table 3. The main information and characteristics of the studies.

Author	Title	Journal	Objective	Object of study	Method	Environmental impacts
Cerdas et al. (2017)	Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System	Journal of Industrial Ecology	Compares a conventional mass scale centralized manufacturing system (CMS) against a 3D printing-supported distributed manufacturing system (DMS) on the basis of the production of one frame for eyeglasses using the life cycle assessment methodology	Frame for eyeglasses	LCA-based approach	The greatest contribution of DMS corresponded to printing electricity (70% of the life cycle for Climate Change, Acidification, and Depletion of Abiotic Resources). For CMS, the largest contribution was the production of acetic acid and acetic anhydride
Kellens et al. (2017a)	Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental NImplications	Journal of Industrial Ecology	Provides an overview of currently available studies analyzing the environmental dimensions of AM, encompassing life cycle stages from material production to the part manufacturing and use phase up to the waste treatment of the AM production waste	Articles	Literature review	AM requires a higher demand for specific energy because it has a longer cycle time, and the need for support structures, generating environmental impacts in the manufacturing phase
Peng & Sun (2017)	Energy modelling for FDM 3D printing from a life cycle perspective	International Journal of Manufacturing Research	Analyze the energy consumption of FDM processes and analyze the potential for energy efficiency of 3D printing from a life cycle perspective	Plastic materials	LCA-based approach	N/A

Table 3. Continued…

Author	Title	Journal	Objective	Object of study	Method	Environmental impacts
Ingarao et al. (2018)	Environmental modelling of aluminum based components manufacturing routes: Additive manufacturing versus machining versus forming	Journal of Cleaner Production	Perform a comparison of manufacturing approaches (Selective Laser Sintering, SLM, conventional machining and forming processes) for aluminum-based components	AA-7075 T6 aluminum alloy, with 4 different geometries	LCA-based approach	N/A
Li et al. (2017)	Additive manufacturing technology in spare parts supply chain: a comparative study	International Journal of Production Research	Investigate the effects of AM to produce spare parts and compare the total costs and carbon emissions of a supply chain that uses AM (centralized and distributed) with a conventional.	Spare parts supply chain	Simulation method SD (*System dynamics*)	Most of the carbon emissions come from the preparation of raw material for production, as AM requires greater energy demand (314 MJ/kg compared to 209 MJ/kg)
Mrazović et al. (2018)	Guiding building professionals in selecting additive manufacturing technologies to produce building components	Materials Today Communications	Develop an evaluation method with the aim of informing construction professionals about the multicriteria comparative logic between AM and CM for the production of specific construction components	Window frame and a bracket	LCA-based approach	LCA studies have shown an environmental impact up to 87% lower in AM, for water and energy consumption, human health, ozone depletion, and acidification impacts
Ford & Despeisse (2016)	Additive manufacturing and sustainability: an exploratory study of the advantages and challenges	Journal of Cleaner Production	Answer the question: how does additive manufacturing allow for more sustainable models of production and consumption?	A case study in 16 companies that use AM	LCA-based approach	Material and energy savings in production, reduction of material processing toxicity, reduced energy intensity and reduction of waste generation
Kohtala (2015)	Addressing sustainability in research on distributed production: an integrated literature review	Journal of Cleaner Production	Examines what aspects of distributed production researchers are studying when they aim to establish links to sustainability beyond simply economic sustainability	Articles	Literature review	AM has benefits such as reduced electricity consumption and reduced waste

Table 3. Continued…

Author	Title	Journal	Objective	Object of study	Method	Environmental impacts
Chen et al. (2015)	Direct digital manufacturing: definition, evolution, and sustainability implications	Journal of Cleaner Production	Analysis of direct digital manufacturing from different perspectives in comparison to various traditional manufacturing paradigms, in order to provide a basis for manufacturers to use in improving their manufacturing systems	N/A	N/A	The selective laser sintering process is significantly more energy-intensive than the injection molding process.
Peng et al. (2018)	Sustainability of additive manufacturing: An overview on its energy demand and environmental impact	Additive Manufacturing	Provide an overview of the sustainability of additive manufacturing	Articles	Literature review	AM has the potential to reduce the amount of raw materials needed in the supply chain, reduce the need for energy-intensive, waste, and polluting manufacturing processes, and allow for more efficient and flexible product design
Attaran (2017)	The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing	Business Horizons	Identify and highlight the challenges of implementing additive manufacturing. Discuss the advantages compared to traditional manufacturing and explore the impact on the supply chain	N/A	N/A	AM contributes less to the environmental footprint. The technology generates less waste since only the necessary materials are consumed
Pour et al. (2016)	Additive Manufacturing Impacts on Productions and Logistics Systems	IFAC-PapersOnLine	Present analysis to represent how AM's industrial applications could create distinctions between conventional technologies and explain the need to reconfigure production, distribution and logistics processes	N/A	Literature review	The advantages in relation to the sustainability aspects of the AM are still uncertain since the research was restricted to analyze case studies and general discussions. However, the main effort has been to emphasize the MA's strengths and make them more achievable

Table 3. Continued…

Author	Title	Journal	Objective	Object of study	Method	Environmental impacts
Saade et al. (2020)	How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies	Journal of Cleaner Production	Evaluate studies on the environmental impacts of the MA life cycle and identify the main challenges and trends in load measurements	Articles	Literature review	Relative to the values of the global warming potential (GWP) in comparison with conventional manufacturing (CM), the AM processes were presented as advantageous in the most part of the cases
Fruggiero et al . (2019)	The load of sustainability for Additive Manufacturing processes	Procedia Manufacturing	To estimate energy consumption in Additive Manufacturing (AM) for relevant technologies such as Direct Metal Laser Sintering (DMLS) and Selective Laser Sintering (SLS) under different products and process specifications. A comparison among subtractive and additive technologies was made to weigh the impact of direct and indirect consumption of the new technology	Different geometric shapes (called ID1, ID2, ID3)	LCA-based approach	AM is more efficient, regarding consumption and environmental impact due to large amounts of waste material in the MC
Kunovjanek & Reiner (2020)	How will the diffusion of additive manufacturing impact the raw material supply chain process?	International Journal of Production Research	Simulate the reduction of material stocks through the adoption of AM in the manufacturing industry and point out the implications for supply chains	Different scenarios	Systems dynamics – Monte Carlo Simulation	AM has the potential to directly reduce raw material inventories near to 4%
Niaki et al. (2019)	Why manufacturers adopt additive manufacturing technologies: The role of sustainability	Journal of Cleaner Production	Identify which factors motivate the adoption of the AM and understand the role of your sustainability benefits	Respondents' responses	Empirical data collection and questionnaire application	The MA can result in a non-polluting value chain. The lightweight opportunity can also result in energy and raw material savings, offering economic benefits while sustaining

Table 3. Continued…

Author	Title	Journal	Objective	Object of study	Method	Environmental impacts
						resource and energy conservation throughout the entire product life cycle
Tziantopoulos et al. (2019)	Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era	Production Planning and Control	Discuss the main decisions concerned in the design and management of supply chains specified by the technologies of the AM principles and identify the predominant factors that establish the viability of related networks	Articles	Literature review	The supply chains defined by the adoption of AM technologies need to be investigated based on a technological perspective, of raw material, and market aspects, because although there is less waste of materials, the types of materials are restricted
Afshari et al. (2019)	The role of eco-innovation drivers in promoting additive manufacturing in supply chains	International Journal of Production Economics	Develop an original mathematical model to investigate the influence of eco-innovation factors on supply chain performance	Different parameters used for the optimization	Mathematical modeling	Market share is not the main factor that promotes the implementation of AM in supply chains. In economies of scale, AM still needs technological improvement. In small-scale markets, AM is more suitable for supply chains, since total cost and environmental impact are lower than in the CM

N/A: Not available. Source: The authors (2020).

5.3 Discussion

After a more detailed analysis of the information contained in the articles, it was possible to identify the changes in transport generated by AM and its environmental impacts. Based on the systematic analysis, the potential to improve supply chain dynamics with the adoption of AM technologies was highlighted. Regarding environmental impacts generated by the AM, it was recorded that these impacts have occurred based on three different perspectives: the material yield variance, energy consumption, and emissions. Furthermore, when assessing in more detail the environmental impacts caused by AM in the transport stage, the decentralization of the supply chain was the main point addressed.

Distributed/decentralized manufacturing systems (DMSs) are generally presented with several advantages over a centralized manufacturing system (CMS)

(Cerdas et al., 2017). The DMS can, in fact, decrease the environmental impact of reducing the global transportation, because of the nearness of the points of sale of the products to customers (Mrazović et al., 2018), indicating a decrease in the carbon dioxide emissions by around 5% until 2025 (Gebler et al., 2014).

In addition, AM can reduce indirect consumption, such as energy consumption and emissions, due to the transport phase (Fruggiero et al., 2019; Niaki et al., 2019; Tziantopoulos et al., 2019). However, the demand for direct energy for productive time is still very high in 3D printing, compared to conventional manufacturing processes. This fact occurs because the embodied energy of the additive manufacturing is lower than conventional manufacturing, only when the production batch is small (Chen et al., 2015). Consequently, additive manufacturing processes would need to become significantly faster through technological improvements (Cerdas et al., 2017), so that they also present more benefits of high volume production.

The research carried out by Cerdas et al. (2017) evaluated, through LCA, a product manufactured using AM in two fictitious scenarios: a decentralized manufacturing system and a centralized manufacturing system. Although the global participation of the transportation phase remained under 5% in all impact categories, the decentralization caused a significant decrease in the potential impacts of the categories climate change, acidification, depletion of abiotic resources, and marine ecotoxicity. This result for DMS is a consequence of the production with customers and the simplification of the supply chain.

Kohtala (2015) identified in her review that the articles that discussed location concerns have mentioned that the most important environmental benefit of DMS is the reduction of activities and the decrease of environmental impacts related to the transportation phase. Also, AM could reduce the demand for product transportation by digitally transferring designs, leading to a decentralization of manufacturing. The manufacturing of products near to the final consumer, logistical costs, and environmental impacts are minimized (Attaran, 2017).

Another benefit of AM was mentioned by Li et al. (2017) when carbon emissions were examined in the stages of the processing of raw material, manufacturing, and transportation. For the transportation of materials and products, the conventional system corresponded to 5.59% and 5.24% of carbon emissions, centralized AM to 6.78% and 6.77% and decentralized AM to 7.27% and 0%. According to the authors, conventional subtractive manufacturing requires a large number of raw materials compared to the supply chains that adopt MA, leading to a significant increase in carbon emissions during transportation. This occurs based on the potential that AM has of bringing the right products, in the right quantity, close to the customers, which makes it possible to reduce the energy demand of transportation on a global scale (Chen et al., 2015).

Thus, by changing the long-distance transportation to a short-distance transportation (Ford & Despeisse, 2016; Mrazović et al., 2018) and reducing the weight of the transported products, it is possible to create environmental advantages that support the reduction of carbon emissions (Peng et al., 2018).

In addition, Li et al. (2017) compare the transportation costs between CM, centralized AM, and decentralized AM. According to the authors, transportation cost was the predominant factor in all systems, representing 57% of the total cost in the MC, 49% in the centralized AM, and 44% in the decentralized AM. This result is a consequence of the configuration of the supply chain, which considers the transportation of raw materials and products for centralized conventional manufacturing and centralized additive manufacturing. Meanwhile, in decentralized AM, only the transportation of raw materials is estimated, causing cost reduction to this configuration of the supply chain (Attaran, 2017). Regarding economic reasons, Niaki et al. (2019) support the argument that environmental benefits have low relevance in the decision to adopt AM since few companies are motivated by these factors. For this reason, it is essential to connect the economic and environmental advantages of additive technologies, including the arrangement of the supply chain.

On the other hand, for the authors Peng & Sun (2017), Kellens et al. (2017a), Ingarao et al. (2018) and Pour et al. (2016), the central point of the discussions presented in the articles was the environmental dimensions of the additive manufacturing process. Peng & Sun (2017) performed a life cycle assessment of products for additive manufacturing, nevertheless, the effects of the energy consumption of the transportation stage were not mentioned. According to Pour et al. (2016), even though the shorter supply chain reduces the need for transportation, due to the possibility of bringing production centers closer to customers, this factor is barely held in AM studies and no conclusion could be extracted.

Furthermore, the literature review made by Saade et al. (2020) already indicated that among 12 articles that addressed LCA from cradle to grave, only three carefully detailed the transportation stage (Cerdas et al., 2017; Huang et al., 2017; Li et al., 2017), while the others performed average calculations of the distance per ton transported. In this context, although the aim of the most part of the evaluations did not focus on transportation, the authors highlighted the importance of including in the assessment of environmental impacts, the reduction of distances, and the reduction of the weight of products forward the supply chain.

Based on the scenario revealed above, this study found that the environmental impacts of decentralized AM are still in the exploratory phase, reinforcing the need for further integrated studies between additive manufacturing and the decentralized supply chain. As a result of the lack of studies on this topic, further LCA studies must be fulfilled to estimate the environmental impacts of AM technology (Yusuf et al., 2019) on production processes and on the supply chain.

6 Conclusions

The literature review presented in this article aims to compare, from a global perspective, the environmental impacts caused by the transportation stage of additive manufacturing and conventional manufacturing. Based on this, it is evident that the current research scenario has few studies that discuss this approach. The most provide only an overview of how the distribution scenario would impact on the environment. Some indicate that AM technologies have more environmental advantages than conventional manufacturing. However, the studies that performed the LCA of AM products demonstrated intensive energy consumption during its processing, making the reduction of the potential impacts of other processes, such as transportation, proportional to the impacts generated by the CM, in a global analysis.

The systematic review of the literature pointed out that, in fact, decentralized additive manufacturing systems decrease the need for transport over long distances, but clearer approaches and assertive researches on the effects of this change on environmental impacts are still required more. So far, it is known that 3D printing does not replace conventional manufacturing, but it is an alternative manufacturing technology toward sustainable development. The reduction of distances and the number of products transported consequently decrease carbon dioxide emissions and the consumption of energy resources. Moreover, decentralized AM is the most suitable alternative when small batches are produced, as it reduces energy consumption. It is also worth highlighting that this scenario could be modified depending on the energy sources applied, which must be presented in detail in the analysis (such as the use of renewable and non-renewable energy).

However, the results achieved in this study reveal that the long-term environmental advantages of a decentralized manufacturing system over a centralized one are still uncertain. Few studies have been carried out that prove the benefits of using additive manufacturing technologies, making brief discussions concerning the topic. The situation is even more uncertain when it comes to thoroughly assess the relationship between the transportation and distribution of products and materials. Unfortunately, transportation is often under-explored due to its low contribution to the results of the life cycle assessment.

It is also interesting to highlight that currently there are not many types of research that discuss the concept of decentralized and centralized supply chains in the environmental performance assessments of AM, being a field not deeply explored in LCA researches.

Thus, for future research, it is recommended to carry out life cycle assessments that present substantial data on the transportation processes, in order to enable a more detailed analysis of the environmental effects of AM in logistical operations. It is also suggested to simulate distribution routes for the quantification, documentation and comparison of data on the potential environmental impacts of the two systems.

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