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Review

A Systematic Literature Review on Additive Manufacturing in the Context of Circular Economy

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Abstract: Additive Manufacturing (AM) is, undoubtedly, one of the most promising and potentially disruptive technologies of the Industry 4.0 era, able to transform the traditional manufacturing paradigm and fuel the generally accepted and necessary shift towards the conceptualisation, design and adoption of sustainable and circular business models. The objective of this paper is to contribute to the structure of the scientific field residing in the intersection of AM and Circular Economy (CE), by determining the status of its current state-of-the-art, proposing an initial typology in an attempt to contribute to the existing efforts of structuring this rather novice research area and pinpointing research gaps where more focus should be put, and highlighting areas with a significant potential for added-value future research. To that end, a sample of 206 papers, published from 2014 to 2020, was retrieved from the Scopus and Google Scholar databases. After studying and critically evaluating their content in full, contributions were classified into six thematic categories, providing a first typology of the current literature, followed by a detailed section highlighting and taxonomizing existing review studies. Next, contributions of the three categories of interest are discussed followed by a critical evaluation of the study's contribution, inherent limitations and future research potential.

Keywords: additive manufacturing; circular economy; sustainable manufacturing; Industry 4.0; 3D printing

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1. Introduction

The proliferation of the Fourth Industrial Revolution, referred to as Industry 4.0, has undoubtedly transformed the manufacturing industry by driving dramatic increases in productivity and flexibility, enhancing strategical and operational decision-making and contributing to an improved overall industrial performance [1,2]. AM, also known as three-dimensional (3D) printing, has been presented as an essential driving force behind Industry 4.0. AM uses digital 3D models to create parts by adding material in layers [3], offering the beneficial ability to build parts with geometric and material complexities [4], as opposed to conventional subtractive manufacturing, where a product is shaped by removing material in order to achieve a desired shape [5]. The consumer driven nature of this manufacturing paradigm, in that it inherently provides opportunities for mass customization by facilitating the production of personalized products [6], justifies its growing utilization by industrial companies, which strive to meet the ever-growing customer demand and eventually blossom in this modern, continuously changing, competitive landscape.

Nevertheless, despite its economic benefits, the development of industrialization has indisputably led to serious ramifications, several of the most significant of which pertain to the deterioration of the environment. In fact, industrialization is deemed responsible for a multitude of deleterious consequences undermining the integrity of natural ecosystems, such as water [7], air [8] and soil pollution [9], resource depletion [10] and excessive land use [11]. Under these conditions, the need to ensure companies' environmental compliance without jeopardizing their production and, therefore, financial prosperity, is now more imperative than ever. In light of the intrinsic mechanics of the conventional linear economy, in which resources are considered to be unlimited, and economic benefits are placed above all other criteria [12], the transition to a sustainable CE business model appears as a priority. The CE concept and its 3R principles, i.e., "reduce, reuse, recycle", are fully aligned with combining economic growth and environmental protection by promoting the extension of the useful life of products which have exhausted their physical and/or functional service life and would otherwise be discarded, thus maximizing their utilization capacity and maintaining their value for as long as possible [13].

This paper aspires to investigate the possibilities provided by the use of AM as an enabler of CE. A systematic literature review is carried out in an attempt to propose an initial typology of scientific contributions in the specific research area, establish a foundation of knowledge through describing the output of the relevant scientific literature and to synthesize the different perspectives on the matter, assess the research progress, highlight future research directions and shed light on the prospects of adoption of this innovative combination model by the industry. The remainder of the paper is organized as follows: Section 2 presents the methodology followed in this study and provides the details of the selection process for the papers included in the study sample. In Section 3, a concise and coherent study on precedent review efforts is carried out in order to assess research progress and facilitate our systematic literature review process, the results of which are discussed in Section 4. Finally, the paper concludes with Section 5, summarizing the study's findings, while highlighting research limitations and future research potential.

2. Methodology

A systematic literature review was carried out in order to identify and critically appraise the findings of relevant peer-reviewed studies while ensuring impartiality, meticulousness and transparency. The data collection process was conducted on 31 March 2020 using the bibliographic databases of Scopus and Google Scholar (Figure 1). Therefore, additional papers added on a later date to the two databases are not included in this study.

For Scopus, the authors used the following keyword string: "("Additive manufactur*" OR "3d print*" OR "rapid prototyp*" OR "additive production" OR "generative manufactur*") AND ("recycl*" OR "circular economy")". The asterisk (*) at the end of a key word ensures the inclusion of the term in both singular and plural forms as well as its derivatives. This query was entered into Scopus's default tab (Document Search form) and the initial search of all document fields generated 615 results. Then, three inclusion criteria were imposed to filter our results, the first of which was the selection of the search field "Article Title, Abstract, Keywords". Second, the time frame of our review was selected to include studies dating from the last seven years, namely from 2014 to 31 March 2020, given that AM and 3D printing are recently emerging scientific fields. In particular, all search results dated after 2000, 97.0% of them after 2014 and 84.3% after 2017. Due to the rapid development of the field, the chances of results dating from 2000 to 2013 (3%) containing vitally useful information were slight. Third, in terms of document types, the authors decided to only include articles, book chapters, reviews, conference papers and conference reviews published after 1 April 2018. The reason for excluding conference publications published prior to that date lies in the fact that if significant ideas had been proposed, they would have already been published in journals during the last two years. Our search, after excluding other document types and imposing the aforementioned search field and time span constraints, yielded 446 results. Table 1 demonstrates the number of publications per journal, for journals containing equal to or more than five publications. The journal with the majority of studies was "Additive Manufacturing" with 24 publications (5.38%).

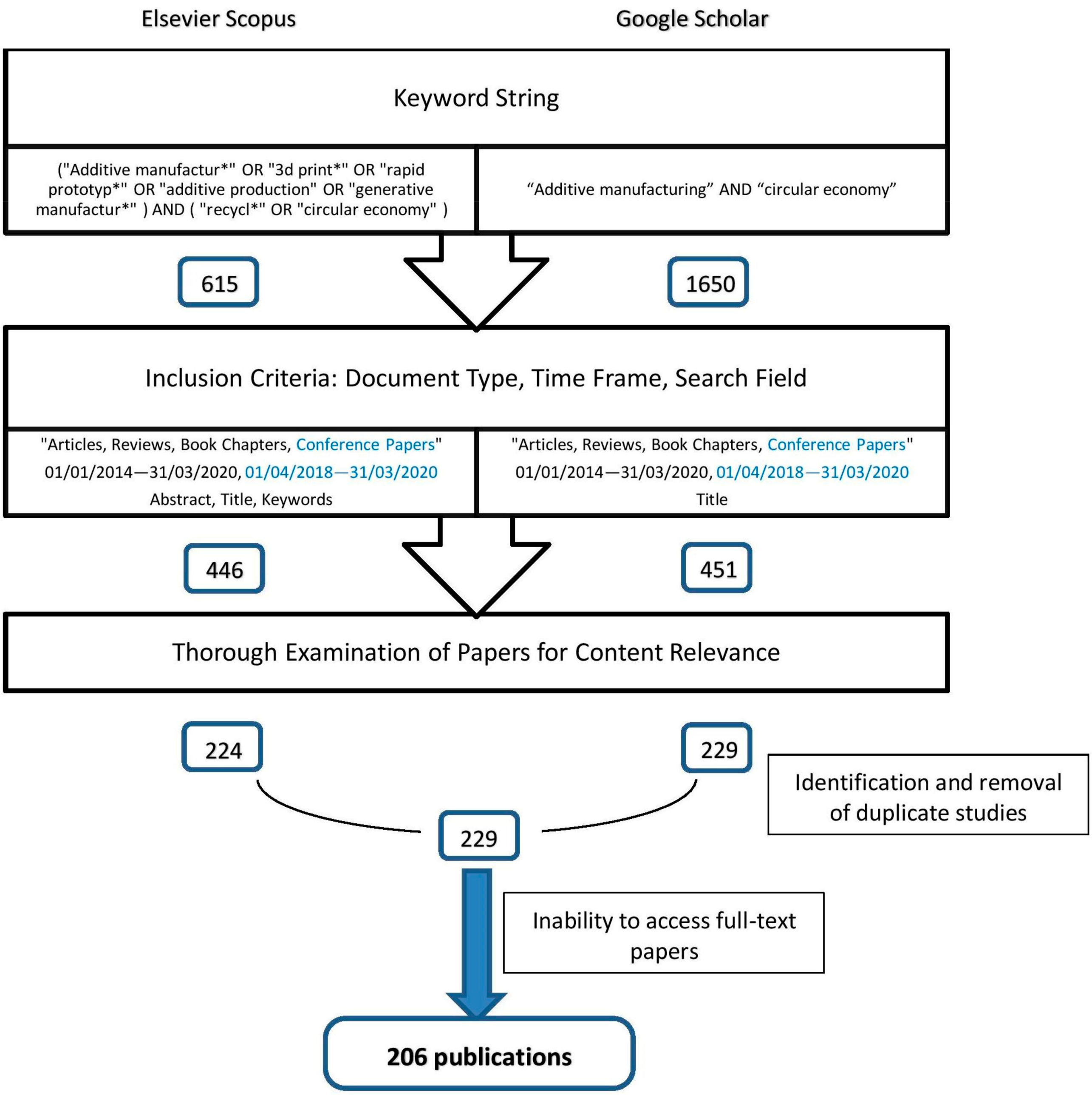

Figure 1. The Data Collection Process.

Table 1. Number of Publications per Journal.

Journal	# * of Publications
Additive Manufacturing	24
Journal of Cleaner Production	13
IOP Conference Series: Materials Science and Engineering	11
Proceedings of the International Astronautical Congress, IAC	10
Composites Part B: Engineering	8
Procedia Manufacturing	7
ACS Applied Materials and Interfaces	6
Construction and Building Materials	6
JOM	6

Table 1. *Cont.*

Journal	# * of Publications
Polymers	6
Procedia CIRP	6
3D Printing and Additive Manufacturing	5
ACS Sustainable Chemistry and Engineering	5
Key Engineering Materials	5
Materials	5
Minerals, Metals and Materials Series	5
Powder Technology	5
Resources, Conservation and Recycling	5

* Number of Publications.

After thoroughly examining their content, namely their abstract, keywords, table of contents and main body, 222 papers were considered inadmissible on account of failing to meet the subject criteria, thus resulting in 224 papers.

As for Google Scholar, since it includes scholarly articles from a wider variety of sources compared to Scopus, keywords had to be more focused, so that results could be controlled and manageable. Therefore, the keyword string used in this case was selected to be the following: "("Additive Manufacturing" AND "Circular Economy")". The initial search of the query on documents' full text yielded 1650 results. As opposed to Scopus, Google Scholar only provides the option to search a query on a document's title, a feature embraced by the authors to limit the number of the results. After imposing the same time frame criteria as before and rejecting document types deemed unreliable, such as undergraduate dissertations, the sample from Google Scholar amounted to 451 results, 446 of which had already been retrieved in Scopus, ultimately diminishing the sample to 5 publications. Overall, we were not able to retrieve the full text of 20 papers from Scopus and 3 from Google Scholar, thereby decreasing the final sample size from both bibliographic databases to 206 publications.

Figure 2 illustrates the number of publications over the selected time frame (1 January 2014–31 March 2020). It is remarkable that the first spark of notable scientific interest in the field was observed in 2017, followed by an impetuous surge during the ensuing years. In particular, publications seem to have almost tripled from 2017 to 2018, continued to increase almost three and a half times during 2019 and are expected to almost quadruple during 2020.

Next, the papers included in the sample of publications were extensively studied and classified based on research subjects. AM and its interaction with, and contribution to, CE is the core theme of the present study. For this reason, in an effort to classify the final sample of publications into subject categories, the two thematic axes of "Additive Manufacturing" and "Circular Economy" were divided into five smaller subcategories of interest, namely (1) Additive Manufacturing Methods, (2) Additive Manufacturing Materials, (3) Recycling, (4) Reuse and (5) Remanufacturing & Repair. It must be noted that initially, a sixth category was used, so as to include publications which seemed relevant to the topic and contained general information about the environment and CE; however, it was not clear into which subject area they should be classified. Second, most papers can fall into more than one category. Third, the classification was initially carried out by studying the papers' abstracts. Nevertheless, at a later stage, after examining each document's full text, it was made clear that they could be classified into more than one category. This is of course to be expected when dealing with largely interrelated concepts. Last but not least, for the classification to be achieved, further deliberations were conducted among the authors where necessary, until unanimity was reached. With the aim of achieving unbiased results, the selected publications were studied individually. The grouping decisions were then juxtaposed, in order to discuss controversies and, eventually, eliminate them.

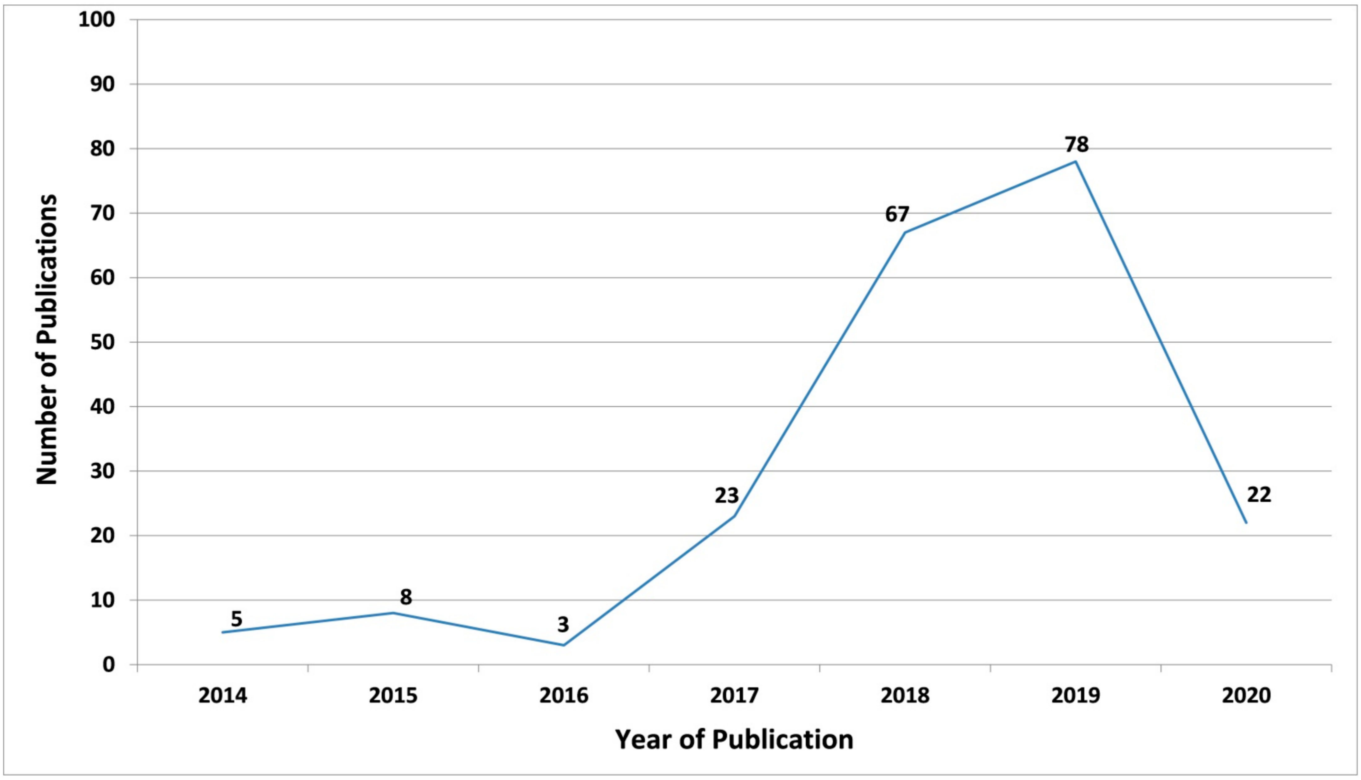

Figure 2. Number of publications per year (1 January 2014–31 March 2020).

Figure 3 illustrates the categorization of the 206 publications from the bibliographic databases of Scopus and Google Scholar into the six forenamed thematic categories. As displayed, "Additive Manufacturing Methods" has been studied by more than half of the papers in our final sample (N = 119, 57.8%) as opposed to "Additive Manufacturing Materials" (N = 26, 12.6%), which has been investigated to a less substantial degree. Regarding the CE-oriented sub-categories, it is worth noting that "Recycling" is far and away the most popular one, representing the research interest of exactly half of the papers in our sample (N = 103, 50%), which is greater than twice the amount of papers in the "Reuse" (N = 44, 21.4%) category and almost five times more papers (N = 22, 10.7%) compared to "Remanufacturing & Repair". It is worth mentioning that our systematic literature review, the results of which will be presented in Section 4, focuses on the three CE-oriented subcategories, namely "Recycling", "Reuse" and "Remanufacturing & Repair" and how they can be promoted by various "Additive Manufacturing Methods" and "Additive Manufacturing Materials".

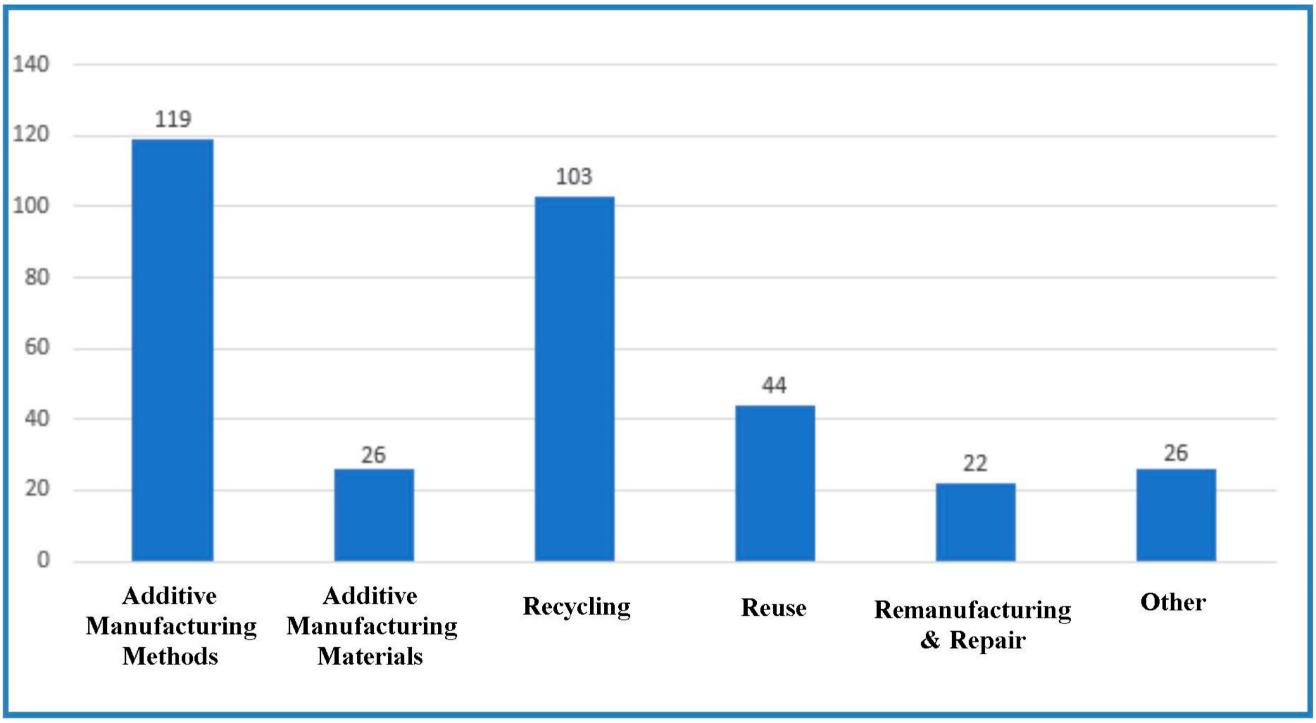

Figure 3. Classification of the 206 selected publications into six thematic categories.

3. Previous Review Efforts

Before presenting the results of our systematic literature review, a brief and coherent study on previous review efforts is undoubtedly necessary. This step was of paramount importance in this paper, in terms of assessing the topic and sub-topic selection in preceding literature reviews and identifying grey areas, which determined how to proceed in our review as well as highlighted future research directions.

3.1. The Review Collection Process

As illustrated by Figure 4, after imposing the same time frame and search field criteria as described in Section 2, but limiting document type to include "Review", the study sample from Scopus decreased to 19 results. Of these review results, only 15 were included in this analysis, with the remaining four being rejected. In particular, "Plastic Waste Management in Indonesia: Review" [14], was rejected due to the inability to access the full-text of the publication. Furthermore, "Research Progress in Recycling and Reuse of Carbon Fiber Reinforced Resin Composites" [15], was excluded, due to its irrelevance to our topic as well as being written in a language other than English. Finally, "Paper-based Chemical and Biological Sensors: Engineering aspects" [16] and "Recent Advances in Sulfonated Resin Catalysts for Efficient Biodiesel and Bio-derived Additives Production" [17] were also deemed unacceptable, since their main subject was not relevant to either AM or CE. Table 2 provides a comprehensive description of the main details of each review retrieved from the Scopus bibliographic database, with the last column indicating whether it is considered acceptable or not.

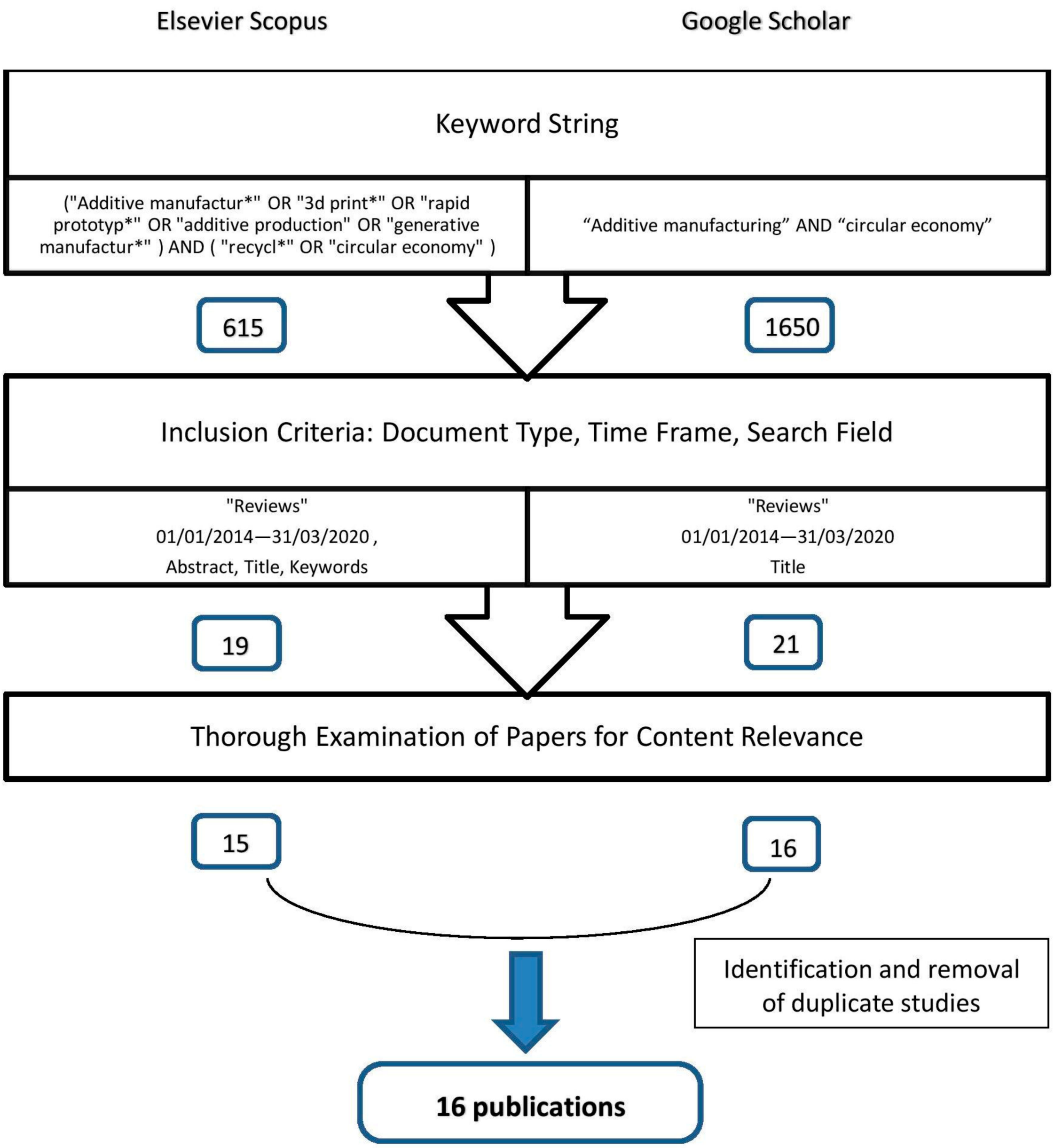

Figure 4. The Review Collection Process.

Table 2. A comprehensive description of the core theme of reviews from Scopus (1 January 2014–31 March 2020).

References	The Study Deals with ...	Acceptable? (Yes/No)
[14]	The identification of the most significant hurdles in recycling efforts in Indonesia.	N
[18]	The clarification of the interaction between laser and metal powder, with a strong focus on its side effects.	Y
[19]	Friction stir processing in the modification of the cast structure, superplastic deformation behavior, preparation of fine-grained Mg alloys and Mg-based surface composites, and AM.	Y

Table 2. *Cont.*

References	The Study Deals with . . .	Acceptable? (Yes/No)
[20]	The classification of laser-based AM technologies, operational principles of direct laser metal deposition, feedstock quality requirements, material laser interaction mechanism, and metallurgy of Ti-6AL-4V alloy.	Y
[21]	Processing techniques used in recycling of thermoplastics polymers with different types of reinforcements, especially for AM applications. It bridges the gaps for use of primary (1°), secondary (2°), tertiary (3°) and quaternary (4°) routes as an industrial processing standard with low cost AM technology.	Y
[22]	The principles and capabilities offered by the existing metal AM technology for object repair and restoration namely, direct energy deposition, powder bed fusion, and cold spray technology.	Y
[23]	3D metal AM from an interdisciplinary perspective, providing an overview on sustainability, basic principles, and a conceptual framework on environmental performance, implicit constraints regarding materials, recycling and use/reuse tools for extended life cycle.	Y
[24]	The Directed Energy Deposition (DED) process and its role in the repairing of metallic components.	Y
[15]	The recycling techniques and evolution of resin-based thermosetting and thermoplastic carbon fibers.	N
[25]	How rising technologies from Industry 4.0 can be integrated with CE practices to establish a business model that reuses and recycles wasted material such as scrap metal or e-waste.	Y
[26]	The main policies that have motivated the transition to a CE model and within this, to CO_2 recycling.	Y
[27]	The fundamental aspects of the production of polyurethane foams (PUFs), the new challenges that the PUFs industry is expected to confront regarding process methodologies in the near future are outlined and some alternatives.	Y
[28]	Recent trends, such as fast prototyping of reactors via 3D printing of flow channels, miniaturisation and use of multi-physics modelling.	Y
[29]	The sustainability of AM, the context of which is introduced, with a focus on energy and environmental impacts.	Y
[17]	Cation-exchange resins, micro and mesoporous acidic resins, supported acidic ionic liquids, ionomeric membranes and the use of alternative organic polymer-based acidic catalysts (hybrid systems).	N
[30]	The current progress of Metal AM feedstock and various powder characteristics related to the Selective Laser Melting process, with a focus on the influence of powder granulometry on feedstock and final part properties.	Y
[31]	Various recent sustainable manufacturing ideas applied in the prominent sectors with an aim to either recycle/reuse the discarded ones or to produce a fresh part in eco-friendly manners.	Y

Table 2. *Cont.*

References	The Study Deals with . . .	Acceptable? (Yes/No)
[16]	The design, chemistry and engineering aspects of the development of paper-based chemosensors and biosensors.	N
[32]	The advanced shape memory technology with a focus on polymeric materials.	Y

As for Google Scholar, after filtering the results to only include reviews, two new entries were found. However, the review entitled "Plastic Recycling in Additive Manufacturing: A systematic literature review and opportunities for the circular economy" [33] was rejected, since its date of publication (15 April 2020) is outside the predetermined study period. Similarly to before, Table 3 provides a comprehensive description of the main details of both reviews retrieved from Google Scholar.

Table 3. A comprehensive description of the core theme of reviews from Google Scholar (1 January 2014–31 March 2020).

Reference	The Study Deals with . . .	Acceptable? (Yes/No)
[33]	The current advances on thermoplastic recycling processes via AM technologies.	N
[34]	The guidelines and parameters that can guide the paths to the integration of AM with the concept of CE.	Y

3.2. *Review Classification*

The 16 review papers resulting from the aforementioned process were extensively studied and classified based on two coding criteria, research subjects and review types. The results of this classification are presented in this section.

3.2.1. Review Subject

The core theme of every single one of the 16 reviews was identified, facilitating the process of classification into five categories of interest (Table 4), which are described below: (1) "Additive Manufacturing Methods", which includes reviews specializing in specific AM methods; (2) "Sustainability", which refers to reviews concentrating on recycling, reuse, remanufacturing, repair and, in general, environmentally friendly production with minimization of resource and raw material consumption; (3) "Additive Manufacturing Materials", which includes reviews focusing on specific materials, their properties and how they are able to affect modern 3D printing technology; (4) "Digitization—Industry 4.0", which refers to reviews examining the modernization and digitization of conventional processes in the context of AM, with the use of Radio Frequency Identification (RFID), Internet of Things (IoT), Big Data Analytics, Cloud Computing, Artificial Intelligence (AI), etc.; (5) "Practical Applications", which includes case studies and experimental applications, providing quantitative results and practical conclusions. It is worth mentioning that studies can be classified into more than one category.

Nearly two thirds of the reviews in our sample (N = 10, 62.5%) fall into the "Sustainability" category, followed by "Additive Manufacturing Materials" (N = 6, 37.5%), "Additive Manufacturing Methods" (N = 4, 25%) and "Practical Applications" (N = 4, 25%). It is beyond a shadow of a doubt that "Digitization-Industry 4.0" (N = 3, 18.75%) is the most under-reviewed category, and thus additional research is needed on that category. However, reflecting on the fact that the advent of Industry 4.0 in manufacturing is relatively new, this conclusion is plausible.

Table 4. Review Classification based on five Thematic Categories.

References	Additive Manufacturing Methods	Sustainability	Additive Manufacturing Materials	Digitization-Industry 4.0	Practical Applications
[21]		X			X
[18]	X	X	X		
[20]	X		X		
[19]			X		
[23]		X	X	X	
[25]		X		X	
[22]		X			
[24]	X	X			
[34]		X			
[27]			X		
[26]		X			X
[29]		X		X	
[28]					X
[31]		X			
[30]	X	X	X		
[32]					X
# * of Publications	4	10	6	3	4
%	25%	62.5%	37.5%	18.75%	25%

* Number of Publications.

3.2.2. Review Type

According to the works presented in [35], a review study is a type of research which synthesizes past work with a view to accelerating the accumulation and assimilation of recent knowledge into the existing body of knowledge. A broad spectrum of review types, abiding by different criteria, have been recognized in the literature and in an attempt to provide a reference review typology; the authors in [36] identified fourteen discrete review types based on the Search–Appraisal–Synthesis–Analysis (SALSA) analytical framework. In this paper, we utilize their typology and identify four review types in which the reviews of our sample fall, i.e., Systematic, Qualitative, Quantitative and Mixed-methods types.

More specifically, a Systematic Review meticulously synthesizes empirical evidence stemming from an exhaustive search, while abiding by pre-determined guidelines and eligibility criteria (inclusion/exclusion criteria) so as to answer a specific research question [37]. The reviews examined in this typology are capable of being systematic, depending on their compliance or non-compliance with pre-specified requirements. A Qualitative Review integrates the findings of qualitative studies, namely exploratory research divulging insights into a problem and elaborating on concepts using non-numerical data. A Quantitative Review integrates the findings of quantitative studies, namely studies generating numerical data, with a view to disclosing patterns in research. Finally, a Mixed-methods Review combines both qualitative and quantitative components.

Table 5 presents the classification of the 16 reviews into the five above-described review type categories. "Qualitative" reviews were proven to be the most dominant type of review in our sample (N = 6, 37.5%), followed by "Quantitative" (N = 5, 31.25%) and "Mixed-methods" reviews (N = 2, 12.5%). Moreover, less than a fifth (N = 3, 18.75%) of the reviews fall into the "Systematic" category, a lack justifying the need for additional pertinent efforts. The limited number of systematic literature reviews combined with the fact that their objective was to assess the current literature under the lens of quite specific research questions, sparked our interest in pursuing a systematic literature review specifically dedicated to a broader evaluation of the developments in the field. Indeed, given that the main subjects addressed in these reviews are limited to the capabilities of metal AM for object repair and restoration in the context of CE [22], the exploration of Industry 4.0 technologies (including AM) as enablers of CE through the proposition of a circular business model [25] and the suggestion of guidelines and parameters enabling the integration of AM with the concept of CE [34], to our knowledge, a systematic literature review devoted to AM in the context of CE, as a whole, has not yet been attempted. This gap is addressed in the present systematic literature review, the results of which are presented as follows.

Table 5. Review Classification based on the typology proposed in [36].

References	Systematic	Qualitative	Quantitative	Mixed-Methods
[21]			X	
[18]		X		
[20]		X		
[19]			X	
[23]		X		
[25]	X			
[22]	X			
[24]		X		
[34]	X			
[27]				X
[26]				X
[29]		X		
[28]			X	
[31]		X		
[30]			X	
[32]			X	
Number of Publications	3	6	5	2
%	18.75%	37.5%	31.25%	12.5%

4. Recycling, Reuse, Remanufacturing and Repair with the Help of AM

While there is a variety of alternative approaches to dealing with end-of-life materials and products, only three of them could help reintroduce some of their remaining value into production systems: recycling, reuse and remanufacturing [38]. In this context, resources—after their useful life has been exceeded—are recovered and recycled, reused or remanufactured to create new products, thus abiding by CE principles towards the development of a regenerative economic system, contributing to diminishing the burden on the environment by making sure resources remain in use for as much time as possible. In this section, recycling, reuse and remanufacturing, as well as repair—which is intrinsically linked to remanufacturing-, are examined under the lens of the production process of AM, and pertinent literature efforts resulting from our systematic literature review are presented.

4.1. Recycling

As already mentioned, recycling takes place when a product can no longer serve any function and would otherwise be disposed of as waste [39]. How 3D printing can contribute to embracing the value of waste, after its collection and separation, is an issue that is of interest to researchers, since AM is capable of being used as a recycling process, exploiting materials made of recyclable components with both environmental and economic advantages [40]. Logistically speaking, the successful implementation of recycling systems is contingent upon the size and location of production facilities and new forms of manufacturing, such as AM, have the potential to decentralize them, consequently increasing overall flexibility, and reducing logistical costs and delivery times, while, at the same time, diminishing environmental impacts [41,42]. Decentralized distributed manufacturing techniques are becoming all the more common [43], providing excellent opportunities for the development of local closed-loop recycling systems [44]. In this subsection, two aspects of distributed manufacturing are investigated through the lens of AM: (1) Distributed recycling and (2) Closed-loop supply chains, followed by efforts pertinent to the (3) Recycling of different types of waste.

4.1.1. Distributed Recycling

An emerging technical area with great potential for the development of plastic waste recycling models is that concerning the concept of distributed recycling for AM in the context of CE [45]. Traditionally, recycling has been focused on large, centralized structures in order to take advantage of economies of scale. Nevertheless, this approach has several drawbacks pertaining to increased complexity resulting from the transportation of large but lightweight plastics [46,47]. AM makes it possible for discarded plastics, instead of being transported en masse to recycling centers or landfills, to be converted into feedstock for 3D printing [48]. The advantages are numerous and relevant to the reduction of greenhouse gas (GHG) emissions and the carbon footprint as well as energy savings of the order of one thousand million MJ per year [49–51]. In particular, compared to traditional plastic manufacturing methods, such as plastic injection molding, in 3D printing the filling density of a product can be controlled and, by reducing it to the minimum necessary for mechanical functionality, no substantial waste of material should be produced and energy consumption as well as GHG emissions should be reduced, all of which contribute to achieving environmental sustainability [47]. Moreover, distributed recycling is proven to be essential in areas where material supply is limited, yet waste production and demand for custom components are high [52]: circumstances justifying the model's growing adoption [49] and the reversing of the historical trend towards central recycling facilities [53,54].

The authors of [53] studied distributed recycling through a RecycleBots network, for the production of filament made of HDPE (high-density polyethylene). Their research aimed to determine whether this method is more environmentally advantageous compared to traditional HDPE recycling. The results demonstrated that the former method uses less embodied energy than the best-case scenario used for the latter method. Similarly, the authors of [47] combined the distributed recycling method using a vertical Recyclebot to make filament with distributed manufacturing using a delta RepRap to print useful products from post-consumer waste. It was concluded that traditional ABS (acrylonitrile butadiene styrene) production consumes at least twice as much energy as the proposed distributed approach.

The works presented in [55] focus on Gigabot X, an open source 3D printer able to recycle plastics on a large scale, with the help of which objects were printed and then tested for their mechanical properties. First, virgin PLA (polylactic acid) was analyzed, and then compared—in terms of tensile strength—to four kinds of recycled plastic, namely recycled PLA from previous prints (the most commonly used plastic in AM), recycled ABS (the second most commonly used plastic in AM), recycled PET (polyethylene terephthalate) (the most common plastic waste) and, last but not least, recycled PP (polypropylene) (the second most common plastic waste). The authors of [54] found out that recycled PC (polycarbonate) could be efficiently used as a raw material for AM directly with a Gigabot X, while it also appeared to be an effective material in a broad spectrum of uses, able to replace more expensive solutions for both consumers and the industry.

The authors of [42] examined a model in which 3D model files are sent digitally, for their production via 3D printers. In this model, the objects are manufactured and assembled in a decentralized network with high-performance printers and specialized personnel for the final assembly and finishing steps. The authors of [45] successfully investigated technical avenues for the distributed recycling of polymer composites by converting windshield wiper blades into useful, high-value biomedical products, such as fingertip grips for hand prosthetics. Last but not least, the authors in [56] addressed the market need for environmentally sustainable and ethically constructed products by developing an "ethical product standard" for 3D printing filament, based on existing fair trade standards, technical and life cycle analysis of recycled filament production and 3D printing manufacturing. Ultimately, the proposed "ethical product standard" identified six key pillars, namely minimum pricing, fair trade implementation as well as labor, environmental, safety, health and social standards, including the ones covering discrimination, harassment, freedom of association, collective bargaining and discipline.

Theoretically, the adoption of the distributed recycling model is possible. Decentralized recycling is capable of eliminating the barriers associated with conventional recycling, mainly due to cost-effective open source technology, shorter distances and decreased amounts of transportable plastic waste [42]. Nonetheless, it remains a thorny issue among experts. On the one hand, it is alleged that consumers will turn to the most convenient solution, namely the online purchase of AM products. On the other hand, others predict a significant market opportunity for "consumer production". In the final analysis, the future most likely lies in a mix of both perspectives, determined by a plethora of constraints, such as energy budgets, feedstock materials, design know-how and intricacy of assembly—limitations which are already present in the manufacturing status quo, but will take a different shape in the future [41].

4.1.2. Closed-Loop Supply Chain

Overall, two types of recycling networks coexist, reverse supply chain and closed-loop supply chain [57]. The first case refers to a network responsible for the recovery of disposed products followed by their recycling or reuse in other products. The second one refers to a network that integrates both the upstream and downstream supply chain, meaning that the forward value chain process, from the supplier to the customer, is followed by a reverse one, where the products are recovered for recycling or reuse [46].

Closed-loop production systems are increasingly considered to be a promising strategy to reduce the environmental impact of industrial activities. As a matter of fact, CE represents a system where resource flows are closed-loops [58], the optimization of which is one of the most efficient strategies for an environmentally sustainable production [38]. This is where the authors in [46] focused their research, by proposing a closed-loop recycling model, assisted by 3D printing technology. In this model, a particular type of plastic is collected locally from different waste sources and then transported for recycling, to be used for the production of plastic filament for AM. The proposed plan is an optimal closed-loop supply chain configuration, dictated by constraints, such as the capacity of each recycling point and guided towards the maximization of economic gains and minimization of environmental consequences. The authors of [59] investigated closed-loop manufacturing with ABS across multiple recycling phases using AM. Filament production parameters were examined using virgin, one-time recycled and two-times recycled ABS. The methodology described in this study may provide a practical solution for the management of recyclable ABS polymer waste, such as plastics from electronic waste or the interior of cars.

With a view to expanding the application of closed-loop production, more knowledge and skills are needed. To that end, the authors of [38] created a closed-loop process chain for continuous material utilization, which they integrated into the learning factory ("Die Lernfabrik") at the Technical University of Braunschweig in Germany, in order to provide engineers with the opportunity for practical experience in closed-loop production systems. The developed process chain is capable of producing work pieces for the production line as well as recycling them at the end of their useful life. A plethora of learning modules on direct digital manufacturing, AM and the environmental perspective of manufacturing were developed. The need for sufficient knowledge is also supported by the authors of [60], who claim that studies on the recycling of 3D printing materials are extremely limited. To address this knowledge gap, the main objective of their study was to investigate the potential use of closed-loop recycling of PLA in 3D printing, in terms of changes in properties and pertinent environmental impacts. In particular, PLA was extruded into a filament and fed into an FDM (Fused Deposition Modelling) 3D printer. The printed products were shredded, turned into filament and re-processed. The cycle was repeated until the material could not be further printed in 3D. During each cycle, a specific amount of sample was extracted for analysis, so as to detect possible changes in its properties. Virgin

PLA was then mixed with recycled PLA in different proportions, as a way to improve its properties and upgrade the quality of the final product.

To sum up, at the end of their life cycle, products are collected as waste and then separated to treat possible mixed or contaminated materials. The usable pieces are shredded and then turned into feedstock for 3D printing and ultimately new products, the creation of which thereby closes the material loop [38,46]. In this closed-loop paradigm, value is added to waste, as it can contribute to the generation of new products as well as the reduction of energy consumption and GHG emissions [46]. In short, closed-loop practices can be a viable approach to waste management and the adoption of CE [60].

4.1.3. Recycling of Different Types of Waste

Plastic

Plastics are indispensable, omnipresent, durable, versatile, corrosion-resistant materials, integrated into a wide range of applications with a view to accommodating our modern society's increasing needs. Our ever-growing population dictates the continuous evolution of the plastics industry [61] in order for it to ultimately flourish in today's constantly shifting competitive landscape [62]. Production of new plastics in 2015 surpassed 300 million tonnes [63], whereas from the 1950s to 2015 it aggregately exceeded 8.3 billion tonnes, half of which was manufactured after 2004 [64]. In addition to the traditional plastic waste streams, the increase in the use of 3D printers has led to the demand for more plastics and, therefore, the increase of plastic waste [65], the recycling of which is one of the most essential elements for the adoption of the CE [46], as it is a recoverable resource able to be used for the re-creation of products of commercial value [61]. Indeed, even 3D printers themselves produce waste, for example, through failed or test prints or broken parts and structures, such as supports and bases, which are discarded as waste after their use [66]. Still, 3D printing is capable of aiding and accelerating CE by providing a possibility of valorization of end-of-life plastics in a continuous sustainable loop. Several efforts have been found in the literature and presented below, focusing on the recycling of plastic waste with the help of AM.

The authors of [67] transferred disposable plastic bottles to a crusher where they were cut into small equal plastic parts, then melted and passed to an extruder, where filament was produced. The proposed model is a technologically viable and fully environmentally friendly solution, since defective products can be re-inserted into the crusher on the spot and reused. Similarly, the authors of [65] also studied a recycling model for producing filament for 3D printers made of ABS and PLA waste. The proposed system consists of separate machines for grinding the material, extruding it in the form of a filament and adapting it to the desired diameter. In terms of appearance and dimensional accuracy, the items did not differ significantly, however, the recycled product was discolored. In terms of mechanical performance, the maximum pre-fracture stress was reduced by approximately 11%, while an increase in its stiffness and fragility was also observed.

The authors of [68] examined the suitability—compared to the commonly used ABS—of recycled HDPE in the form of flakes and pellets to determine if it can be used as a feedstock for 3D printers. This research is a reference guide for future studies on the utilization of plastic waste in 3D printing, always aligned with CE principles. The findings of the experiment carried out by the authors in [49], on the mechanical properties of recyclable PLA for AM, concluded that recycling a filament once or twice did not significantly affect its mechanical properties and durability, as opposed to when undergoing further recycling cycles. In fact, recycling a filament three times led to increased standard deviation.

The authors of [69] developed feedstock filament wire made of recycled polymer waste as base matrix with SiC/Al_2O_3 reinforcement for sustainable development. After testing its tensile and mechanical properties, it was concluded that this technique would encourage researchers to use waste polymer in AM applications. The author of [51] compared the properties of parts 3D printed with virgin PLA to those printed with recycled PLA by testing their tensile yield strength, modulus of elasticity, shear yield strength and hardness. The results demonstrated that the parts 3D printed with recycled material exhibited mechanical properties similar to the parts 3D printed with virgin material, thus promoting the adoption of this method for reducing consumed resources, energy, costs and carbon dioxide emissions in 3D printing.

The authors of [44] used recycled plastic waste for 3D printing surface finishing post-processing, as a means to repair defective surfaces, weld broken parts and enhance the roughness and mechanical strength of objects in a sustainable way. Environmentally speaking, this process returned at least 9% of the generated waste as input to production. The authors of [70] conducted research on the synthesis of a new eco-polyol based on PLA waste to be utilized for the production of foams used in various applications, such as thermal insulation. The authors of [71] used recycled plastic bottles and containers as 3D printing filament to manufacture low-cost unmanned aerial vehicles (drones). The filament was made of at least 90% recycled material.

The authors of [48] proposed a methodology to evaluate the recyclability of thermoplastics used as feedstock for 3D printers, which then applied using recycled PLA for FFF (Fused Filament Fabrication). The results of the experiments demonstrated excellent prospects for the use of recycled material in open-source 3D printers. Still, it was confirmed that recycling deteriorates the mechanical properties and consequently the quality of the final product. The authors of [72] examined various types of virgin and recycled plastic (LDPE, HDPE, PET and PP) for the production of filament through a multi-criteria decision-making process. The authors concluded that recycled PET exhibits better properties and performance than virgin PET, hence laying a solid foundation for its adoption and use by AM as an alternative filament for 3D printing. Finally, the authors of [73] analyzed the obstacles that arise in the recycling of plastic with regard to its subsequent use in AM by conducting interviews with experts in the field. A total of 22 obstacles were identified, which were classified into five general categories: technical, economic, social, organizational and regulatory.

All in all, the plastics industry has demonstrated a wide spectrum of ways to exploit discarded plastic items in many applications and fields [74]. However, more attention should be paid to studying the variety of stages of the recycling process rather than just the collection of plastic waste [46]. The most common procedure to treat plastic waste for 3D printing is to crush it and cut it into small parts which are then extruded into a filament [75]. Another way to utilize plastic waste is to mix it with new material [59], even metal [76], which has been proven to greatly improve the final product's mechanical properties [59]. Unfortunately, every time a polymer is subjected to a thermal cycle in order to be recycled, its mechanical properties deteriorate [55]. For instance, the tensile strength of recycled materials is much lower than that of virgin materials [77]. This not only means that the produced objects will not exhibit the expected strength, but also that their mechanical properties will not be able to be recovered [78]. The deterioration of mechanical properties can be attributed to thermomechanical reactions during reprocessing, the natural aging of the material and the presence of additives [77]. In general, the same material can be subjected to up to five recycling cycles without the need for further addition of virgin material or other additives to ameliorate its mechanical properties [55].

Electronic Waste and Magnets

The rapid increase of e-waste also emerges as one of the most serious problems of the last decades [79,80], while their low recycling and reuse rates aggravate the situation even more [80]. Although e-waste recycling began in the 2000s and is strengthened with the product stewardship legislation targeting televisions and computers [41], e-waste recycling rates amount to only 15%, mostly due to its complex nature. In particular, e-waste consists of a plethora of materials, including metal, glass and plastic, the largest amount of which is made up by the latter, representing about 40–58%, by weight, of mobile phones and 70% of printers. In total, plastic makes up almost 20% of all electronic waste [80]. The authors of [80] studied the recycling and conversion into sustainable filament of plastic from electronic waste and in particular printers at the end of their life cycle. The effects of repeated recycling, up to four extrusion cycles, were studied. 3D printing using plastic electronic waste has proven to be more flexible compared to virgin plastic, rendering e-waste very suitable to be utilized in 3D printing [59].

The recycling of magnets containing expensive rare earth elements (REEs) has attracted the attention of researchers, owing to potential disruptions in the supply of REEs. The authors of [81] used Nd-Fe-B magnets to develop a magnet recycling process via cryomilling and subsequent remanufacturing of the bonded magnets. The recycled magnet demonstrated enhanced density and remanence compared to the starting bonded magnets. The authors of [82] investigated the preparation of filament for 3D printing of bonded magnets using recycled Sm-Co powder recovered from industrial grinding swarfs and blended into PLA. It was shown that magnetic properties did not deteriorate, but instead ameliorated, possibly as a consequence of reduced particle rotation when loading recycled Sm-Co powder into PLA, compared to the original powder.

Glass, Sand and Concrete

As far as the construction sector is concerned, cement is known to be associated with high carbon dioxide emissions; thus, efforts are being made to find renewable sustainable materials [83]. Glass is a 100% recyclable material, so it can be recovered from waste and recycled for other uses, for instance as a replacement for the necessary additives in concrete. In general, the construction sector is a viable option for utilizing recycled glass, since cement is the most widely consumed material after water [84].

3D printing has begun to draw the attention of the construction sector [85]. The authors of [84] explored the possibility of replacing the necessary additives in cement-based materials used in 3D printing with recycled glass, and investigated the potential effects on concrete both in its liquid and solid form. In the same vein, the authors of [86] carried out a case study in Singapore, where a large amount of sand remains unused as waste after construction or demolition. The authors of [87] developed a technique in which sand and mineral binders are used to 3D print monolithic concrete materials. This technique was then used to generate more complex building components, whose mechanical properties were compared to the corresponding conventionally constructed objects, showing promising results both in terms of performance and aesthetics. The authors of [88] utilized glass fibers from scrap turbine blades as a reinforcing additive in thermoplastic filament for 3D printing. Their research addressed the problem of increasing wind turbine waste levels, while at the same time focusing on improving the mechanical properties of 3D printed products.

Rubber Tires

Only approximately 10% of discarded rubber tires are used for the creation of new products, in spite of the fact that rubber powder is completely sustainable, as it is created mechanically without releasing harmful substances into the atmosphere. The authors of [89] focused on the use of elastomeric powder from end-of-life tire material in AM. Furthermore, 3D Printing with latex, as proved by the authors, does not affect the mechanical properties of final products. However, it was concluded that it alters their thickness. In the same context, the authors of [61] proved that it is possible to 3D print big parts, such as furniture, made from a blend of 60% of tire waste granulate and 40% of recycled PP. Furthermore, another solution to the recycling of discarded tires is the production of ground tire rubber for 3D printing, which can generate both environmental and economic advantages, since its use as filler in other materials is able to reduce manufacturing costs [40].

Taking everything into account, various research efforts have been conducted with respect to recycling supported by AM in the context of CE, in the form of distributed manufacturing, presenting a plethora of economic and environmental incentives. The adoption of a distributed recycling model—despite it being a subject of contention among experts—and closed-loop supply chain models have been proven to be radical approaches of distributed manufacturing, emerging as sustainable initiatives for future business success. However, the subject is still at its infancy, with the majority of publications taking part in our review focusing on plastic waste and just a slight number on electronics, magnets, glass, sand, concrete and rubber tires, arousing the need for experimentation with different types of wastes in various conditions and settings.

4.2. Reuse

4.2.1. Reuse after Recycling

An important issue which must be taken into account when it comes to designing products is their subsequent disposal, explored under the lens of recycling and reuse. In other words, material selection in product design should be guided by its added value as waste for its subsequent use as feedstock for the manufacture of new products [41]. The more AM becomes acknowledged, the more powder is needed as raw material, thus highlighting the need for its recycling and reuse [90]. In fact, the production of parts made of recycled metal powder using AM methods is an emerging process that growingly attracts scientific interest [91]. Approximately 80–90%, according to the authors of [92], or even up to 95–97%, according to the authors of [93], of used powder does not melt during 3D printing and can be reused, which shows enormous potential for resource efficiency [91,93–96], rendering material waste a sustainable resource, with added value for AM [95,97].

Although the recycling of metal powder for AM is of paramount significance to the reduction of costs, processing time, energy consumption and material waste [91], the main question lies in how it affects powder quality and consequently the properties of final products [78]. Ideally, unused powder could be recycled and reused countless times [73]. However, its morphology, mechanical performance and composition change with each cycle of recycling, and material quality deteriorates [91,98] due to increases in the molecular weight of the residue [73,92,98]. This is because the repeated oxidation of recycled powder changes particle size distribution and the powder becomes thinner. Therefore, the indicated number of recycles is limited [91] so as not to jeopardize the quality of final products and, therefore, the reliability of AM [90]. There is a broad spectrum of studies in the literature presenting a variety of recycling strategies, where the same powder is used repeatedly from 5 to over 30 times [91].

There are multiple ways to recycle waste powder and, hence, bring economic benefits, as it is a less costly process than the supply of virgin raw material [90]. Since low-quality powder might affect final products, techniques to maintain its quality throughout its life are required [73,91]. Waste powder can be refreshed with virgin unused powder [99] at a rate of at least 30–50% [73,92,100,101], and thus reused for a few more times for the manufacture of high quality products [73] before it becomes waste with no way of recovery [100]. In the literature, this process of recycling and reusing waste powder from AM processes to subsequent ones has been extensively studied, aiming to reduce the energy footprint and maximize economic performance, always guided towards the adoption of a CE model where waste is not discarded but utilized in new production processes [90].

Metal

The authors of [102] investigated the effects of reusing Ti-6Al-4V ELI powder before and during the printing process, and evaluated the impact of reuse times on the tensile properties of solid SLM (Selective Lase Melting) material. The authors concluded that powder flowability ameliorated as reuse times increased while, after 31 reuse cycles, it was observed that its tensile strength slightly increased. Ti-6Al-4V powder was also the focus of [20], in which the possibility of its reuse in aerospace applications was explored. The authors of [99] compared the characteristics of virgin and recycled powders followed by the corresponding items produced in industrial systems. The authors of [103], after 10 successful reuses of 17-4 PH stainless steel powder, observed no significant changes in the chemical composition and crystallographic phases between the virgin and recycled powder. These results can be generalized to cover all metal-based AM methods. The authors of [104] also examined 17-4PH powder employed in the SLM process—in terms of morphology, chemical composition and microstructure—in three different states: (1) virgin state, (2) after recycling 10 times and (3) after recycling 20 times. The purpose of this study was to detect changes in powder properties in order to determine the maximum number of reuse cycles for optimal performance. The results indicated major changes in the powder after 20 reuses that could detrimentally impact the mechanical properties of final products, leading the authors to recommend that reuse cycles should be conducted in a controlled manner.

The authors of [96] concentrated on 304L steel powder that was recycled and reused seven times in the L-PBF (Laser Powder Bed Fusion) process to examine the differences between virgin and heat-affected powder formed during processing. They proved that the powder changes morphologically, chemically and microstructurally with repeated reuse. The authors of [105] studied 316L steel powder, concluding that it can be reused for multiple builds with minimal differences in the mechanical properties of final products. Similarly, the authors of [94] carried out a thorough characterization on the surface and microstructure of both virgin and recycled stainless steel 316 L powders employed in the SLM process. The results divulged that changes are not notable, thus promoting the reusability of recycled powders for several cycles. The authors of [106] developed a simplified method for evaluating changes in the morphology, composition and flowability of powder used in the SLM process. They inferred—by comparing powders commonly used in AM—that, due to their low density, lightweight alloys are most affected by reuse. In particular, AlSi10Mg was proven to be the most sensitive to reuse, followed by Inconel 718. On the contrary, Ti6Al4V was the least affected by reuse. The authors of [78] also examined Ti6Al4V alloy samples produced by EBM (Electron Beam Melting), the recycling of which turned out to adversely influence the lifespan of the final product, compared to the same product made of virgin powder. The authors of [107] studied and compared two types of metal powder used in the PBF process, based on their rheological properties; recycled FS 316L and virgin MetcoAddTM 316L-A powder. They confirmed that mixing both powders results in a high-quality raw material for reuse. The authors of [108] examined the surface alterations in virgin and reused Alloy 718 powders during the EBM process. The authors of [109] developed an environmentally friendly and reusable metal ink for the 3D printing of very dense metallic structures. The metallic ink consists of steel micro powders, a biodegradable polymer called chitosan, acetic acid and deionized water. It can be used for the low-cost production of metallic structures and then reused.

Plastic

The authors of [110] focused on the recycling of Polyamide 12 (PA12) powder after SLS (Selective Laser Sintering) and its reuse as filament for FDM. The properties and performance of recycled PA12 are similar to those of virgin PA12, so it can be successfully used in the FDM method, bringing about a twofold advantage. Not only does it tackle the issue of SLS waste but it also—given its low cost—diminishes the cost of molten deposition molding, hence benefiting the 3D printing industry as a whole. Still, the authors of [111] proposed a more general methodology model for this process which is described as follows: To begin with, due to the thermomechanical cycles the powder has undergone, it has to be analyzed to find out its melting and crystallization points. With the aim of improving its mechanical properties, the use of ceramic or metal additives is necessitated, whereas, to enhance its plasticity, plasticizers or other additives should be employed. This mix of materials then needs to be tested to confirm or refute its ability to be used in the development of filament for FDM. In case that discrepancies in properties between recycled and virgin filament are recognized, the former must be modified accordingly with various additives in order for it to be usable. From an economic perspective, the use of recycled powder was proven to be more profitable.

The authors of [112] evaluated the possibility of reusing heat-exposed PET powder, proving that when exposed to print bed temperatures for approximately one hundred hours, it can be reused without refreshing it with virgin powder. On the contrary, PA12 powder, even when exposed for just one hour, showed a rapid increase in its molecular weight, which significantly affected its rheology and melt flow. Therefore, PA12 powder needs to be refreshed with virgin powder at a rate of 30–70%. The same results were found in [113], which demonstrated that recycled PET powder is fit to be used in FFF printing, as long as the material is thoroughly cleaned and dried. The authors of [101] examined nylon and indicated that it can be successfully reused without compromising the quality of final products.

Sand and Concrete

The authors of [87] explored innovative uses of recycled aggregates and their reuse in the construction sector and architecture. A strategy was proposed for the formation of a "waste map" in the area between Como and Milan, designed to optimize waste management locally through proper planning and thus contribute to reduction in energy consumption, resource use and GHG emissions in the long run. The work presented in [90] also focuses on the construction sector and, in particular, the possibilities of mixing used metal powder with cement to improve the quality of concrete constructions in addition to reaping the environmental benefits of reusing wasted powder. The authors of [85] considered the possibility of replacing sand in construction with recycled glass. Even though the results indicated that the mechanical strength of recycled glass concrete is inferior to the sand aggregates concrete, the flow properties of the former are superior to the latter, thus elucidating the need for creating equilibrium between the mechanical strength and flowability of the mix design.

In conclusion, the reuse of recycled powder can yield both economic and environmental benefits [93], and a plethora of studies have been devoted to emphasizing its potential for sustainable production supported by AM. Reducing the cost of filament through the reuse of used powder mixed with virgin powder, and the consequent reduction in the amount of virgin powder required [103], enhances the tendency of all the more industries towards the utilization of AM. Nevertheless, this approach has not yet been universally adopted, primarily owing to the potentially reduced quality resulting from such a raw material, as observed in Ti and Al alloys [93]. This hesitancy towards the reuse of recycled powder predominantly concerns industries that are completely intolerant of risk, such as aircraft and biomedical applications [94]. Continuous thermal changes, environmental conditions, laser-powder interactions, etc., are able to affect powder characteristics and lead to the production of objects with altered chemical composition and mechanical properties [18,101].

Thus, a deeper analysis of powder properties is required in order to be able to determine its quality before deciding whether to reject or reuse it, always aligned with the target of minimizing resource consumption. The addition of particles can be employed to enhance mechanical or other properties, such as thermal and electrical conductivity, stiffness or elasticity of a structure [89]. Another way to improve powder manufacturing is by ameliorating the gas atomization process or preventing out gassing of the melt pool [91]. However, it has been shown in the literature that the mechanical properties of final parts could be improved, decreased or unaffected by the reuse of feedstock material [18] and, regardless, material powder, even recycled, remains a high quality raw material compared to, for example, low quality plastic waste (bottles, bags, etc.).

4.2.2. Reuse without Recycling

The authors of [114] worked on the issue of direct material reuse without the need for recycling. In particular, their study investigated a combination of additive (EBM, SLM, Direct Metal Deposition—DMD) and subtractive (Computer Numerically Controlled—CNC machining) manufacturing, a strategy that leads to the creation of metal components directly from end-of-life parts. This strategy makes full use of resources, reduces waste production and energy consumption and, hence, helps alleviate environmental impacts. The authors of [115] developed a project called EDUCABOT3D in order to raise awareness in high school students about e-waste with the support of AM. A mobile robot chassis was modeled using two ways of control between sensors and actuators, one with a rapid prototyping board and another one assembled with components of obsolete electronic devices in a printed circuit board. The authors of [116] also conducted in-depth research on waste reuse without recycling. "Project RE_" explores AM as a "do-it-yourself" tool for the reuse of end-of-life products. For instance, used cans and jars were transformed into pencil holders or piggy banks through the addition of customized lids.

In summary, powder reuse—after or without recycling—appears as an extremely useful practice, promoting the sustainability, quality and cost-effectiveness of parts. However, powders of different materials can be affected in different ways depending on a plethora of factors. These factors include the number of recycles prior to reuse, the rate of refreshment with virgin powder, the AM process employed, material properties, experimental conditions, etc., giving the space to explore a multitude of scenarios, which is a necessary step towards the optimization of the process. Moreover, the limited number of publications on reuse without recycling reflects the need for additional research on the matter, given its potential to dispense businesses—whenever possible—from the cost of recycling as well as to provide resource efficiency.

4.3. Remanufacturing & Repair

4.3.1. Remanufacturing

As already stated, one of the main pillars of CE is the recapture of value of end-of-life products that would otherwise be lost. Remanufacturing is defined as "the rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts" [117]. In this process, an item is disassembled, cleaned, inspected, restored, reassembled and tested by skilled workers [22], and returns to an as-new condition [22,117]. Remanufacturing is undeniably more environmentally sound compared not only to conventional landfilling techniques [118], but also to recycling. Indeed, it is more efficient in that it retains durable cores in their next life cycles, thus diminishing the need to build new components each time [22].

The potential of remanufacturing to give new life to end-of-life products is a great driving force for AM [119], through which special geometries can be generated permitting part optimization and redesign [23]. Remanufacturing often also relies immensely on subtractive manufacturing. First, the part is machined to remove unwanted material and then new material is added on top to achieve the required geometry. Thus, the item is either upgraded with new functionalities or the broken part is repaired [118].

The authors of [118] focused on a hybrid subtractive–additive remanufacturing method, through which material can be removed from and added to a used part, in order to sustain or upgrade its functionality. The aim of their research is to obtain the optimal hybrid remanufacturing strategy, which is achieved through an innovative algorithm, examining a specific part bearing a loading, so as to help engineers calculate what features should be removed or added. The authors of [117] have paid great attention to the use of AM in remanufacturing and described the following key steps for this process: after a product is received, it is thoroughly cleaned to remove dust and impurities. It is then inspected to evaluate the internal and external conditions of its core and to decide whether it can be remanufactured or, in the case of defects, repaired through AM. The AM technology that should be employed is dependent upon the material, shape and volume of the core of the product. According to the works presented in [117,120], the most used AM methods for remanufacturing are DED and PBF, while the authors of [121] also add FDM. As for the type of the material, the authors of [117] deem metal, plastic and ceramic to be fit to be used in PBF, as opposed to DED in which only metal can be used.

The authors of [122] proposed an innovative recycling and remanufacturing process based on AM of carbon fiber reinforced thermoplastic composites, which creates filament with superior mechanical performance. This process has the potential to develop a “green” composite based on AM, so that there is no dependence on carbon fibers, while at the same time delivering enhanced mechanical properties and significant environmental and economic benefits. Important issues to consider are the material recovery rates and energy consumption levels of the recycling process. In this study, an overall material recovery rate of 75% was accomplished, where continuous carbon fiber was 100% recovered and converted into an impregnated filament without any damage to the properties of carbon fiber. The overall energy consumption for recycling and remanufacturing was higher compared to the conventional processes and could be further ameliorated by improving production efficiency.

To sum up, the most important aspects of AM in the context of CE are the efficiency in resource and energy consumption and product lifespan extension, criteria fully accommodated by remanufacturing [23]. On the contrary, recycling requires additional energy to be expended, not to mention the fact that the energy bound to the product is lost [114], while remanufacturing requires approximately 20–25% of the energy consumed for the initial production of an item. Thus, remanufacturing emerges as an ideal solution for managing components that have been used, failed or reached the end of their life [118].

4.3.2. Repair

The implementation of effective production techniques designed to extend a product’s lifespan through repair is a topic that has been of great concern to researchers [23,116], and although AM has been generally used for prototyping, its use for repair, especially through the 3D printing of spare parts, is increasing rapidly [123]. The key difference between repair and remanufacturing lies in the fact that in order to repair a part, the issue causing its failure would have to be recognized and then repaired, whereas in remanufacturing, that part would have to undergo diverse processes and end up indiscernible from a new one, meaning that it would essentially restart its lifecycle [124]. While conventional processes necessitate the manual reparation of a component and then it’s attachment to the broken part, AM can directly build-up in the position of the broken part layer by layer [125,126]. The ability to immediately repair an item instead of dumping it in a landfill actively combats waste generation and resource depletion [123], thus promoting CE principles.

Of the different AM techniques, only three are applied for repair, namely DED, FDM and PBF [22]. In [22], each of the three AM methods used for repair was meticulously analyzed. Laser Cladding (LC), which is commonly used in the application of DED, is able to repair damaged parts—even in the case of wide solid constructions—or cracks by applying material on the damaged surface. It is worth noting that geometrical complexity remains a major challenge in this process. FDM is used to create new parts and fit to replace damaged ones, considering that it might be more advantageous for a part to be self-produced by the user instead of ordered from the manufacturer, especially for parts no longer available for purchase. Last but not least, PBF—in contrast to the aforementioned two methods—requires the object surface to be flat and parallel to the platform previous to the repair process. The authors of [127] analyzed a polymerization strategy to develop 3D printing reprocessable thermosets allowing users to convert a printed 3D structure into a new shape, repair a broken part by simply 3D printing new material onto the damaged site and recycle unwanted printed parts so that the material can be reused. With conventional thermosetting 3D printing materials, when a part is broken, it is not able to be repaired since its chemically crosslinked networks are permanently damaged. However, with this approach, printed parts are repairable through thermally activated self-healing.

The authors of [128] compared the environmental ramifications of conventional and LBM-based manufacturing through a case study for the repair of a gas turbine burner. Contrary to the conventional repair process, only a low percentage of material needs to be removed and turned into scrap through the AM repair process, thus preventing additional material waste. The work presented in [44] deals with 3D printing surface finishing post-processing with the use of recycled plastic waste. In this study, the proposed process was performed on four types of surface defects, i.e., (1) warping holes, (2) skip layers or intermittent deposition, (3) stair effect gaps and (4) excessive air gap, using plastic paste made of recycled FDM waste. This method makes it possible to substantially reduce the use of support materials, hence directly promoting waste recycling and indirectly reducing waste generation. The authors of [129] described a project in which secondary raw materials are reused for the repair of vending machines for beverage containers (internal aluminum structures and 3D printed plastic parts).

As a final note, a key parameter in complying with CE criteria is optimizing part design and guiding it towards easy maintenance, repair and restoration, i.e., ease of assembly and disassembly, consideration of the degree to which the component can be repaired by the user himself/herself, etc. [41]. A way to facilitate this orientation process is by making a technological leap through the creation of digital databases where spare part designs are stored and utilized at all times for various functions of the supply chain [23]. Digital storages of spare part designs allow direct exchange of information for their production and custom repair, thereby enabling the production of spare parts on-demand, fast repair and the reduction of required storage capacity for inventory to a minimum [116].

In summation, the superiority of remanufacturing—in terms of energy expenditure and material utilization—against conventional landfilling and recycling processes renders it a prominent practice for the treatment of end-of-life products. At the same time, it triggers the need for more research on the issue, with an emphasis on the application of information and technology as well as innovations, not only allowing the optimization of the products' upgrade, restoration and repair, but also assisting the operation of the entire supply chain.

5. Conclusions

The research presented in this paper aims to contribute to the structure of the scientific field residing in the intersection of AM and CE by determining the status of its current state-of-the-art, proposing an initial typology of existing research efforts, identifying research gaps and highlighting areas with a significant potential for added-value future research and applications. In this direction, a classification of 206 publications from the bibliographic databases of Scopus and Google Scholar was conducted, into six thematic categories. The main subject directions identified in our sample concentrate on "Additive Manufacturing Methods", "Additive Manufacturing Materials", "Recycling", "Reuse" and "Remanufacturing & Repair". The most popular ones gravitate towards "Additive Manufacturing Methods" and "Recycling", each representing the topics of at least half of the papers in our sample. On the contrary, "Additive Manufacturing Materials", "Reuse" and "Remanufacturing & Repair" account for an eighth, fifth and tenth of the selected publications, respectively: a lack underlining the need for more emphasis on these subjects in the future, especially remanufacturing, which, as described in the literature review, is environmentally friendlier than recycling and, therefore, has strong potential benefits for sustainable manufacturing. Attention should also be paid to reusing, especially without recycling, given the limited efforts carried out on the matter. In terms of AM materials, plastic, metal, e-waste, magnets, glass, sand, concrete and rubber tires—in descending order from the most to the least studied—were identified in the literature.

Before conducting our systematic literature review, the authors needed to assess relevant antecedent reviews, for the purpose of which a second data collection process ensued. The selected reviews were categorized based on their subject and type according to the typology proposed by the authors of [36]. The subject categories identified in our review sample were the following: "Sustainability", "Additive Manufacturing Materials", "Additive Manufacturing Methods", "Practical Applications" and "Digitization-Industry 4.0". The vast majority of the reviews focus on recycling, reuse, remanufacturing and repair; in other words, they are related to sustainability issues, whereas AM materials, methods and practical applications have been investigated to a lesser extent. The application of modern digitized technologies and the study of their capabilities have been the least reviewed research directions. This lack is justifiable due to the recent advent of Industry 4.0, but necessitates further research in the future, since the digitalization of AM via the integration of "smart" technological innovations and production systems is expected to play an essential role in revolutionizing the industry by reducing overall costs and increasing quality and efficiency. The primary review types identified in our sample turned out to be four, i.e., systematic, quantitative, qualitative and mixed-methods reviews. Qualitative reviews have been the most common ones, as opposed to systematic reviews, the lack of which, although addressed by the present paper, is fairly alarming, alerting to the need for more pertinent efforts in the years to come.

Furthermore, in this systematic literature review, three key controversial research topics were identified for future development of the field. First, the extent to which distributed recycling will be adopted, as stated in our review, remains an equivocal issue among experts [41]. Therefore, future research should focus on the examination of various scenarios in which both domestic and globalized manufacturing are implemented to different extents, based on the respective needs and circumstances, with a view to achieving "the best of both worlds". Second, again, with regard to recycling, additional emphasis should be paid to the effects of thermal cycles on product mechanical properties during the various recycling stages. Last but not least, our final remark concerns the limited reuse of recycled powder, despite the reduced filament costs entailed [103], due to its potentially reduced quality. This illustrates the need for a more thorough analysis of powder properties, which will allow the assessment of its quality before deciding whether to reject or reuse it. At the same time, a multitude of other factors, including the number of recycles prior to reuse, the rate of refreshment with virgin powder, the type of AM process, experimental conditions, etc., should also be studied more extensively, a necessary step towards the performance improvement of the process. Finally, it must be noted that this study, despite its value, is not devoid of limitations. For instance, a plethora of papers were rejected due to non-abidance by the inclusion criteria, which were subjectively selected by the authors, as described in the methodology section. Nonetheless, the full texts of the final sample of 206 papers were thoroughly studied by all authors individually, who then discussed ambiguities until agreement was reached and papers were cautiously classified into categories before being analysed.

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