sustainability

Review

Waste Valorization through Additive Manufacturing in an Industrial Symbiosis Setting

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Abstract: Given the current environmental concerns related to manufacturing, the introduction to the industrial symbiosis concept brought purpose to waste, instead of disposing it in landfills or eliminating it through incineration. The waste generated by industrial processes, or end-of-life products, is redirected to be used as a "new" input in another process by one or more organizations, which is a mutual benefit or a "symbiosis". Despite its relevancy, the industrial symbiosis concept is marginally explored in the context of additive manufacturing; this emerging technology has disruptive potential regarding the use of different materials as secondary raw materials. This paper presents a systematic literature review regarding industrial symbiosis and additive manufacturing. The main objective is to identify how wastes can be used as input materials to additive manufacturing processes and what exchanges of resources occur in an industrial symbiosis setting. A final sample of 32 documents was reached and analyzed. Five examples of using waste streams in additive manufacturing processes to produce goods were highlighted and explored.

Keywords: circular economy; industrial symbiosis; additive manufacturing; literature review; 4R; waste; 3D printing

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1. Introduction

New trends and patterns are emerging through technological, economic, and social progress. As a result, new consumption habits are putting growing pressures on resource consumption and environmental protection. There is a need for new or modified processes to avoid or to reduce environmental harm and to promote business sustainability [1]. The circular economy allows for the regeneration of material flows to be exploited and for a balanced growth between economic development and the sustainable use of resources [2]. The 4R framework is presented as one of the core principles of the circular economy that have been used by practitioners and academics [3]. This framework [3] considers the following principles: (i) reduce: including discussions on rethinking, refusing, minimization, redesigning, reduction, prevention of resource use, and preserving natural capital; (ii) reuse: including discussions on reusing (waste is excluded), cycling, repairing, closing the loop, and refurbishing of resources; (iii) recycling: including discussions about recycling, closing the loop, remanufacturing, and reuse of wastes; (iv) recover: including discussions about the incineration of materials with energy recovery.

Efforts have been made by researchers and policymakers to find new strategies and conceptions that could contribute to manage waste more effectively and efficiently and to promote materials recycling and reuse [4]. The industrial symbiosis concept includes a diversity of practices that link different industrial systems. In order for the 4R framework to be effectively implemented, there is a need for exchanging resources among different entities. These exchanges are promoted through the development and implementation of industrial symbiosis networks.

Recently, additive manufacturing (AM), a hyper-flexible technology, has become a source of product and process innovation, enabling customized and personalized products (for example, for aircraft parts, dental restorations, medical implants, automobiles, and even for fashion products). It provides a new set of opportunities for exploring and developing a new logic for creating and capture value from such products and processes [5].

AM can be seen as an important technological enabler that is necessary for the implementation of a circular economy—it is decentralized and distributed; it replaces wasteful steps of traditional manufacturing; it provides flexibility in the range of products to be manufactured; and it saves materials, time, and logistics by being able to make objects in shape. Several projects are already in progress, such as RecWood3D [6], which is assessing the viability of a business model on the basis of the circular economy, using plastic waste and wood waste to develop new products with higher added value, such as filaments for 3D printing, meeting the requirements of the users. OWA 3D is a startup that produces filament from recycled materials as well [7]. Thus, there is already an increasingly developing market.

Therefore, this research intends to explore the process of developing industrial symbiosis networks in the AM industry within the context of the circular economy. Consequently, to do so, this paper conducted a systematic literature review on the industrial symbiosis and AM with the objectives of identifying what resource exchange can occur and how wastes can be used as input materials within AM processes in an industrial symbiosis setting. On the basis of the results, the aim was to identify possible research paths to further develop the topic and find new avenues for future potential industrial symbiosis networks involving AM as part of circular economy.

The paper is structured as follows. After this introductory section, Section 2 presents a brief background around the industrial symbiosis setting and the AM industry. In Section 3, the methodology that was considered to realize this research is presented. Section 4 presents the descriptive results of the systematic literature review. A critical analysis is made in Section 5. Conclusions about the results obtained are made in Section 6.

2. Background

2.1. AM Industry within a Circular Economy Context

AM can be defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [8]. The AM technology allows us to produce complex shapes from different types of materials [9]. According to the American Standard Testing and Materials—ASTM International, the AM technology is based upon seven principles [10] (that are described in Table 1) and could be deployed in with several main technologies, materials, and with different applications [11]. The most common materials used in AM are thermoplastics, ceramic pastes, metal, and ceramic powder and metal [11].

The AM as a disruptive technology can provide many significant advantages over traditional processes, such as the design being no longer limited by traditional machining constraints, eliminates the need for specific tool requirements and allowing the production of small quantities of a customized product [8]. This technology allows for the decrease of material's usage and can handle lightweight products [8]. While increasing processes' efficiency, AM technology can replace classical production technologies [12]. In the design phase of a product, AM allows customers to participate in it, and this may result in high levels of customer satisfaction [13].

Hence, AM is a highly flexible process that enables a company to be highly responsive to market needs at a minimal cost. Due to these benefits, large companies with broad product and manufacturing sectors are quickly developing and adopting AM to select components for expanding markets and developing new products.

Table 1. Additive manufacturing (AM) principles and technologies. Adapted from [10].

AM Principles	Example of AM Technology	Basic Principles
Powder bed fusion	Direct metal laser sintering Selective laser sintering Melting	Fusion of a specific coordinate in a small region of the powder bed using focused thermal energy.
Direct energy deposition	Laser engineered net shaping Plasma arc melting Laser cladding	Deposition of powder materials that coincides with focused thermal energy to melt it.
Binder jetting	3D inkjet technology	Liquid printing binder deployed onto specific coordinate, layer by layer of material powder that sticks at the particle.
Sheet lamination	Laminated object manufacturing Ultrasound consolidation Ultrasound	Attachment of sheets of materials.
Vat photo polymerization	Stereo lithography Digital light processing	Focused light-curing towards liquid polymer in a vat.
Material extrusion	Fused deposition modelling Fused filament fabrication Fused granular fabrication Fused particle fabrication 3D inkjet technology	Precipitation of building materials droplets through a heated nozzle.
Cold spray	Multi-metal deposition	Injected powder at high velocity to build material, caused by adhesion.

Adopting AM technologies may stimulate the rise of some trade-offs with the environmental performance of a company, such as [14]

- Energy use: at a process or machine level, most AM processes use more energy than traditional processes. However, AM allows us to produce complex parts on a single step. AM makes it easier to use renewable energies and enables distributed manufacturing.
- Waste: it is expected that AM uses less material and produces less waste. However, little information is available about the quantity and origin of the waste that is generated during AM processes.
- Safety: even though the societal and economic vantages of AM are still minimally explored [15], this technology has the potential to reduce hazards. However, the effect on workers' safety and health is still under discussion, namely, in what is a concern to the utilization of powder [16].

Currently, some of the AM applications enable and promote more circular production systems through the use of reclaimed and recycled materials as inputs for AM processes, which facilitates the implementation of circular concepts [17]. Therefore, the AM technology may also allow for incorporation of production wastes from other industries as secondary raw materials for AM processes. However, the industrial symbiosis concept is still marginally explored in the context of the AM.

The alignment between the circular economy and the AM must take into consideration some aspects that may contribute to the optimization of some circular systems' phases (for example, for reuse, rework, maintenance, and recycling of products), namely [18],

- Flexible manufacturing strategies: AM production systems are based on strategies that may support the minimization of transportation needs and can reduce the number of logistics activities.
- Maintenance interventions and hard repair: the spare parts can be manufactured by AM processes only if the necessity of using them arises. This can lead to savings in storage and space costs related to spare parts.
- Material savings: due to the absence of tooling, AM enables material savings. Using the almost exact amount of material needed to manufacture the product, AM allows reducing waste generation and the use of raw materials.

- Design-based economy: AM characteristics may decrease the barriers related to the product's and manufacturing process knowledge since parts can be manufactured directly from 3D CAD files without requiring manufacturing expertise.
- Extended product life span: due to the specific technical improvements given by the AM technology and also due to easier access to parts' repair interventions instead of manufacturing new parts, the product's life span may increase.

Currently, there are already some studies that explore the potential of AM in the development of the circular economy concept. AM enables circular design strategies such as repair and upgrades that extend a product's lifespan, without these being considered in the original product design. This is due to AM characteristics such as adaptability and digital production. Digital product files can be adapted to the change of needs or contexts or to enable repair [19].

2.2. The Industrial Symbiosis Setting and Resource Exchange

The use of the circular economy model would guarantee well-established competition in economic systems that would bring benefits at micro- and macroeconomic levels, with the stimulation of the growth of new business models and, consequently, job creation [20]. It is also highlighted that in order to have the implementation of the circular economy, efforts are needed at three levels: from the micro (which corresponds to a single entity), to the meso (that corresponds to associations of entities), to the macro (which corresponds to region, city, and country) levels [20]. Moreover, it can be applied to three main areas: waste management, production, and consumption. However, in industrial production, the implementation of the circular economy is related with the "industrial ecology" concept. Instead of the traditional industry, the industrial ecology relies on the "eco-efficiency" and the "industrial symbiosis" concepts [20].

It is underlined that the industrial symbiosis can be seen as a cooperation model for the optimization of the resource flows—it aims to obtain more collective industrial gains rather than individual ones [21]. The industrial symbiosis concept allows us to link industrial processes in a local or regional industrial system [21]. This happens because an exchange of by-products and utility share occurs, including the reuse and commercialization of "waste" which can be used as secondary raw material [22].

The article [23] highlights the fact that industrial symbiosis spins around the efficient use of resources through their reuse or share. However, there is a need to understand the different types of resources that can be exchanged within the industrial symbiosis scope.

In an industrial symbiosis setting, the resources can be categorized as wastes, energy, by-products, materials, services, structures, sub-products, and raw materials [23]. It is necessary to have in mind some of the definitions of the Waste Framework Directive (WFD) [24], namely, that a product is defined as "*all material that is deliberately created in a production process*", and a production residue is defined as "a *material that is not deliberately produced in a production process but may or may not be a waste*". WFD also defines waste as "*any substance or object which the holder discards or intends or is required to discard*". However, WFD set out four conditions that a production residue must have in order to be considered a by-product: (i) further use of the substance or object must be certain; (ii) the substance of object is produced as an integral part of a production process; (iii) further use is lawful, i.e., the substance or object will not lead to overall adverse human health or environmental impacts; and (iv) the substance or object can be used directly without further processing other than normal industrial practice. It is also important to highlight that there are end-of-life criteria specified for when certain wastes cease to be waste and obtain a status of product (or a secondary raw material) [25].

Even though energetic and material resources are the most frequent forms, sometimes equipment and services are also included in an industrial symbiosis setting. The work [26] refers to three types of actions that may occur between stakeholders in an industrial symbiosis relationship: (i) sharing of infrastructures, (ii) sharing common service needs, and (iii) by-product and waste exchange market—one or more industries use materials from another as secondary raw material.

Different types of stakeholders can have intervention in the industrial symbiosis network [27]—companies from different industrial sectors, service companies, governmental/municipals offices, local entities, non-governmental organizations, suppliers, consumers, and research centers, among others. These interventions can be understood as an exchange of resources in a value network constituted by the different entities or stakeholders.

Having knowledge of the existing cases in the literature waste valorization through additive manufacturing in an industrial symbiosis setting can foster new synergies through relationship mimicking, that is, knowledge of success cases can lead to similar organizations applying the same concept, albeit with different details. Therefore, identifying how wastes can be used as input materials to additive manufacturing processes and what exchanges of resources occur in an industrial symbiosis setting within a circular economy context. This issue is of great importance, especially since the stakeholders involved in the symbiosis are compelled to forge a trustful bond, as the operation of stakeholders that receive waste build upon, in part, on the flows of the issuing companies/entities and their supply with satisfying standards of quantity and quality.

3. Materials and Methods

A systematic literature review overcomes the perceived weaknesses of a narrative review [28]. A systematic review of the literature typically has different stages of planning, conducting and reporting, and dissemination. Each of these stages may include several steps of the review process that are part of a system or method that is designed specifically to address the question the review is setting out to answer. In this research, research design from [28–31] was followed (Figure 1), which comprises five phases: problem formulation, literature search, evaluation of research, research analysis and interpretation, and reporting results.

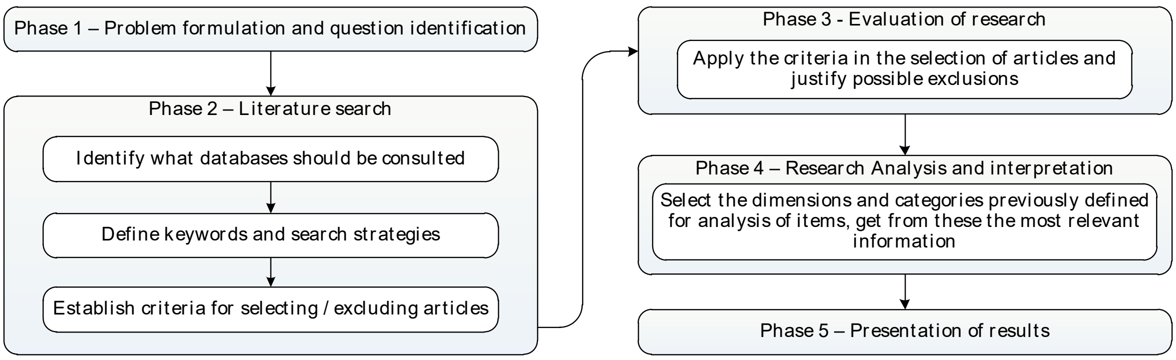

Figure 1. Literature review approach.

3.1. Problem Formulation

In Section 1, the theorical background of the AM industry and the industrial symbiosis concept was presented. Considering the lack of knowledge about the industrial symbiosis in the AM industry, this study aimed to structure the existing knowledge in the literature about waste valorization and exchange of resources within the AM context.

3.2. Literature Search

In the second phase, the bibliographic databases, keywords, and the search strategy were identified [31]. The use of various sources of information from unpublished studies, conference proceedings, and the internet is recommended by some authors, e.g., Tranfield et al. [28]. However, following the guidelines of [29], in this research, only peer-reviewed publications were considered, as a way of controlling the sample quality. Two databases with the highest coverage for the researched topic were considered: "Web of Science" and "Scopus".

The keywords composing the search stream were designed deliberately broad to ensure that articles related to AM and industrial symbiosis were located. Therefore, in a first step, the keywords "industrial symbiosis" and "additive manufacturing" were used. Given the fact that the industrial symbiosis concept is in its very beginning of implementation in the AM industry, no results were found in any of the databases. From this procedure, different combinations of the following keywords were tested: "industrial symbiosis", "3D printing", "additive manufacturing", and "symbiosis network". To obtain the broadest sample of documents for analysis, we widened the keyword "industrial symbiosis" and used the keyword "circular economy", which led us to a few studies already conducted within this subject.

The search strategy was to consider documents published until July 2020 and was performed in the field "topic" (which includes title, abstract, keywords, and keywords plus) for the database "Web of Science" and by article title, abstract, and keywords for the SCOPUS's database.

3.3. Evaluation of Research

Five research streams were used in both databases: (i) "industrial symbiosis" AND "additive manufacturing", (ii) "industrial symbiosis" AND "3D printing", (iii) "symbiosis network" AND "3D printing", (iv) "symbiosis network" AND "additive manufacturing", and (v) "circular economy" AND "additive manufacturing". Only one research stream found results: "circular economy" AND "additive manufacturing". More specifically, 28 results were found for the "Web of Science" database and 35 results from the "SCOPUS" database. The results from the different databases were compared and the duplicated documents were eliminated. A total of 41 documents were found.

Given the multifaceted nature of the circular economy concept within the AM industry, title and abstracts and subsequently full contents of the documents were reviewed for selection. According to [31], this phase should be conducted by more than one researcher. Subsequently, three researchers with knowledge on the circular economy and AM were involved in this phase.

To ensure that only relevant documents were considered, we established several inclusion/exclusion criteria: only documents in English were analyzed; all documents for which the publication type was defined as books were excluded; and, lastly, documents that did not refer to any of the 4Rs from the 4R framework [3] (reduce, reuse, recycle, recover) were eliminated.

The resulting documents were read in full to evaluate their focus on possible industrial symbiosis relationships and relevance to the problem formulation.

From this process, we reached a final sample of 32 documents. As shown in Figure 2, it is possible to conclude about the emerging importance of the topic that was supported by the increasing number of publications per year. Most of the documents analyzed corresponded to articles published in international journals, which corresponded to 72% of the total documents in the sample, and the remaining ones, at 28%, were conference articles.

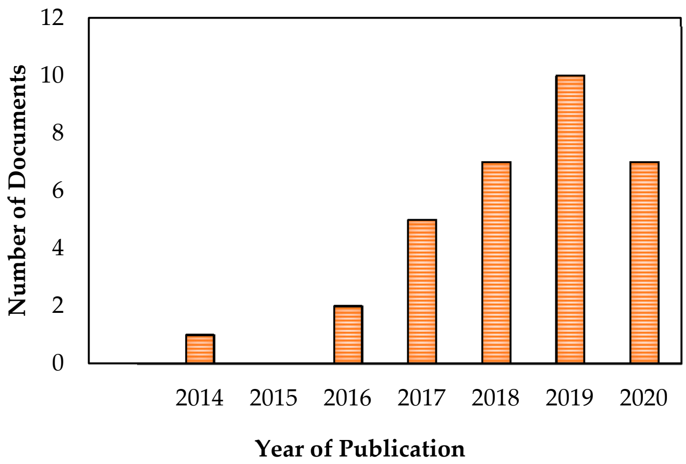

Figure 2. Number of documents per year.

3.4. Research Analysis and Interpretation

This phase aimed to summarize the information extracted from the sample. In order to analyze the collected information, we needed to create analytical categories that facilitate the ranking and the synthesis of each document [32]. In this study, a set of seven categories, and several subcategories, were used to analyze the documents in the sample, as presented in Table 2.

Table 2. Categories and subcategories considered for sample anaysis.

Category	Subcategories
Document identification	Authors—list of authors Publication date—year of publication Publication type—international journal or conference name Language—English or other
Domain	Research field—may include among other subcategories such as "Engineering", "Materials Science", "Science and Technology", "Environmental Sciences"
Research methods	Analytical—conceptual (e.g., conceptual models or future research/scenarios) Empirical—case studies, content analysis, statistical sampling (e.g., expert panels or surveys), mixed methods, experimental design (experimental empirical design) Others
Circular economy principles—4Rs [(a)]	Reduce, Reuse, Recycle, Recover
Industrial symbiosis characteristics [(b)]	Exchange of resources—it takes the value "yes" if there is an exchange of some type of resources, or the value "no" Type of resource—it includes waste, sub-product, by-product, raw material, product, energy, residue, material, services, structures, secondary raw material
Type of technology [(c)]	AM technology—for example direct metal laser sintering, selective laser, sintering/melting, laser engineered net shaping, plasma arc melting, 3D inkjet technology, among the ones cited in Table 1
Type of material [(d)]	Materials input for AM processes—containing the type of the material used in as input for the AM process as it is described in the document

Notes—[(a)] [3]; [(b)] [23]; [(c)] [10]; [(d)] [11].

4. Results

In this section, which corresponds to the fifth phase of the research methodology, the presentation of the results are given. The goal was to analyze in detail the sample contents and provide inputs to the problem formulation. A bibliometric analysis was performed, and it is firstly presented in this section.

4.1. Bibliometric Analysis

For this study, a bibliometric analysis of the documents in the sample was performed. By adopting bibliometrics, researchers are able to develop new knowledge through the analysis of a research field on the basis of a meticulous approach [33]. To study the scientific activity in a research field, bibliometrics applies statistical methods [34].

Bibliometrics combines two key procedures: science mapping and performance analysis. The former is based on first- and second-generation relational indicators that give a spatial representation of how the various scientific elements are related to each other [34]. According to [33], the science mapping main objective is to show the dynamic and structural organization of knowledge in the research field. On the other hand, performance analysis is based on activity indicators that provide data on the impact and volume of research through the use of a broad range of techniques, such as citation analysis or word frequency analysis [33].

For this study, we used co-occurrence of keywords as an indicator for the analysis to identify the main topics and trends investigated thus far. This indicator uses the keywords provided by each author in order to investigate the conceptual structure of the field [34]. According to [34], the analysis of keyword co-occurrence is built upon the principle that a research field can be identified by the specific associations that are established between its keywords. Since the co-occurrence of keywords does not need an intrinsic bias towards older studies, this indicator allows important recent works to arise.

The software program VOSViewer was used to calculate the indicator. In VOSViewer, co-occurrence network maps are generated that include keyword co-occurrence and key terms, citations network, density diagrams, and sources, etc. [35]. The generated graphs correspond to a network of elements through circles, whose size differs according to the importance of each element, while the network connections represent the closeness of links between those elements. The circles' spatial position and the different colors are used to cluster the items [33].

Analysis of Keywords in the Sample

The keyword analysis was performed with the main goal to evaluate the specifics of the discussion on how the circular economy concept is explored within the AM industry.

For the purposes of this study, we used the Keywords Plus function in order to harmonize the keywords used by authors in their publications. The performed analysis revealed that 1129 keywords were utilized in title, abstract, and keyword field of the 32 selected studies. However, only 50 of these terms appeared at least 5 times. The five keywords with the highest link strength were "additive manufacturing" (appeared 45 times), "circular economy" (42), "process "(34), "technology" (28), and "product" (28). The generated keywords co-occurrence network map is illustrated in Figure 3. It should be noted that "additive manufacturing", "circular economy", "process ", "technology", and "product" are the keywords with more importance, and therefore with bigger size.

As seen in Figure 3, the color of each node represents a different cluster, while the size represents the frequency [35]. According to this analysis, the keywords can be divided and classified into three clusters:

- Green cluster: composed of documents that analyze how the circular economy concept is explored and promoted within the AM context, mostly through repairing and restoration activities and through the product and process innovation and development.
- Red cluster: includes studies that relate technology innovation with recycling activities and waste management and also includes documents that focus on business models for firms that are willing to adopt new technologies focusing on circular economy applications.
- Blue cluster: characterized by the presence of articles focusing on sustainability and specific AM technologies, namely, AM technologies using powder.

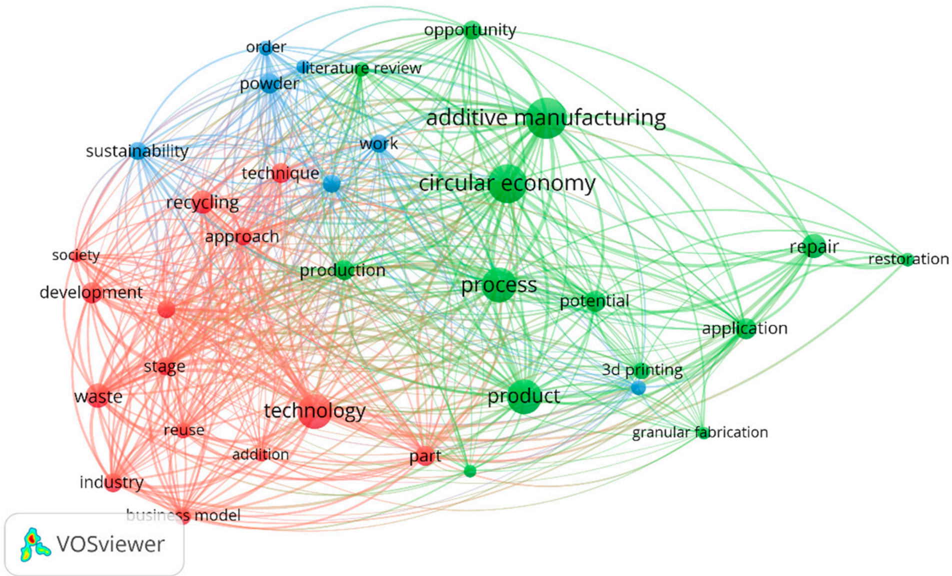

Figure 3. Network diagram of the co-occurrence of keywords.

The density analysis is represented in Figure 4. As can be seen in this diagram, it reveals that a large number of documents in the sample were focused on circular economy applications within the AM context. In this sense, the analysis confirmed that the AM technology has the potential to promote the circular economy concept, mainly through process and product innovation and development.

Figure 4. Density diagram of the co-occurrence of keywords.

After the bibliometric analysis, the detailed analysis of the documents was performed according to the defined categories, and is presented in Table 3.

Table 3. Characteristics of the selected papers in the sample.

Paper ID	Year	Pub. Type	Journal/Conference	Domain	Research Methods	Circular Economy Principles 4Rs	Potential Industrial Symbiosis Characteristics		Technology	Material Used
							Exchange of Resources	Type of Resource		
[36]	2020	Int. Journal	*Sustainable Materials and Technologies*	Materials Science; Engineering	E	Recycle	No	N/A	N/A	Plastic waste [(a)]
[37]	2020	Conf.	*Australasian Corrosion Association's Annual Conf.*	Materials Science; Physics	E	Reuse, recycle	No	N/A	N/A	N/A
[38]	2020	Int. Journal	*J. Cleaner Production*	Science and Technology—Environmental Sciences and Ecology	A	Recycle	No	N/A	Selective laser sintering/fused deposition modeling	Plastic waste [(b)]
[39]	2020	Int. Journal	*J. Cleaner Production*	Science and Technology Engineering; Environmental Sciences and Ecology	E	Recycle	No	N/A	N/A	N/A
[40]	2020	Int. Journal	*Resources, Conservation & Recyling*	Engineering; Environmental Sciences and Ecology	E	Recylce	No	N/A	Fused filament fabication/fused particle fabrication	Thermoplastic composite [(c)]
[41]	2020	Int. Journal	*Metals*	Materials Science; Metallurgy and Metallurgical Engineering	E	Reuse, recycle	No	N/A	N/A	Metal powders
[42]	2020	Int. Journal	*Resources, Conservation & Recyling*	Engineering; Environmental Sciences and Ecology	E	Recycle	No	N/A	N/A	N/A

Table 3. *Cont.*

Paper ID	Year	Pub. Type	Journal/Conference	Domain	Research Methods	Circular Economy Principles 4Rs	Potential Industrial Symbiosis Characteristics		Technology	Material Used
							Exchange of Resources	Type of Resource		
[43]	2019	Conf.	*Procedia Manufacturing*	Engineering	A	Recycle	No	N/A	Laser cuting	Metal waste
[44]	2019	Conf.	*WoodEMA Annual International Scientific Conf.*	Sciences and Technology; Mechanics and Tecnology; Engineering	E	Recycle	No	N/A	Fused deposition modeling	Wood plastic composites (d)
[45]	2019	Int. Journal	*Technologies*	Engineering	E	Recycle	No	N/A	Fused particle fabrication/fused granular fabrication	Post-consumer waste, 3D printed products, and 3D printer wastes
[10]	2019	Int. Journal	*Processes*	Engineering	E	Reuse, recycle	No	N/A	Direct energy deposition/powder bed fusion/cold spray technology	N/A
[46]	2019	Int. Journal	*Sustainability*	Science and Technology; Environmental Sciences and Ecology	E	Reduce, reuse	No	N/A	Selective laser sintering	N/A
[47]	2019	Int. Journal	*Applied Sciences—Basel*	Chemistry; Engineering; Materials Science; Physics	E	Reuse	No	N/A	Direced energy deposition	N/A

Table 3. *Cont.*

Paper ID	Year	Pub. Type	Journal/Conference	Domain	Research Methods	Circular Economy Principles 4Rs	Potential Industrial Symbiosis Characteristics		Technology	Material Used
							Exchange of Resources	Type of Resource		
[19]	2019	Int. Journal	*J. Cleaner Production*	Science and Tecnology; Engineering; Environmental Sciences and Ecology	E	Reduce	No	N/A	N/A	N/A
[48]	2019	Int. Journal	*Materials*	Materials Science	E	Recycle	Yes	Waste	Fused particle fabrication/fused granular fabrication	Plastic waste (e)
[49]	2019	Int. Journal	*Additive Manufacturing*	Engineering; Materials Science	E	Recycle	Yes	Waste	Fused particle fabrication/fused granular fabrication	Plastic waste (f)
[50]	2019	Int. Journal	*J. Manufacturing Technology Management*	Business and Economics; Engineering	E	Reuse, recycle	No	N/A	Selective laser sintering	N/A
[51]	2018	Int. Journal	*Inventions*	Materials Science; Engineering	E	Recycle	No	N/A	Fused granular fabrication/fused particle fabrication	Plastic waste (g)
[52]	2018	Int. Journal	*Materials*	Materials Science	E	Recycle	Yes	Waste	Fused particle fabrication/fused granular fabrication	Plastic waste (h)
[53]	2018	Int. Journal	*Materials Today Communications*	Materials Science	E	Reuse	Yes	Materials and waste	Binder jetting	Locally sourced materials (i)

Table 3. *Cont.*

Paper ID	Year	Pub. Type	Journal/Conference	Domain	Research Methods	Circular Economy Principles 4Rs	Potential Industrial Symbiosis Characteristics		Technology	Material Used
							Exchange of Resources	Type of Resource		
[54]	2018	Int. Journal	*California Management Review*	Business and Economics	O	Reduce, reuse, recycle, recover	No	N/A	N/A	N/A
[55]	2018	Int. Journal	*ACS Omega*	Chemistry	E	Reduce	No	N/A	Stereolithography apparatus	Biobased acrylate resins
[56]	2018	Int. Journal	*Construction and Building Materials*	Construction and Building Technology; Engineering; Materials Science	O	Recycle	No	N/A	N/A	N/A
[57]	2018	Conf.	*Cirp Life Cycle Engineering Conf.*	Science and Tecnology; Engineering	O	Recycle	No	N/A	N/A	N/A
[58]	2017	Conf.	*International Powder Metallurgy Congress and Exhibition*	Engineering	E	Recycle	Yes	Waste	Selective laser melting	Scrap feedstock
[59]	2017	Conf.	*IFIP Advances in Information and Communication Technology*	Decision Sciences	A	Reduce, reuse, recycle	No	N/A	N/A	N/A
[17]	2017	Int. Journal	*Technological Forecasting and Social Change*	Business and Economics, Public Administration	O	Reduce, reuse recycle, recover	No	N/A	N/A	N/A
[60]	2017	Conf.	*Sustainable Design and Manufacturing*	Engineering	O	Recycle	No	N/A	Direct energy de-position/powder bed fusion	N/A

Table 3. *Cont.*

Paper ID	Year	Pub. Type	Journal/Conference	Domain	Research Methods	Circular Economy Principles 4Rs	Potential Industrial Symbiosis Characteristics		Technology	Material Used
							Exchange of Resources	Type of Resource		
[61]	2017	Conf.	*Product Lifetimes and The Environment (Plate)*	Business and Economics; Science and Technology	E	Reduce, reuse, recycle	No	N/A	N/A	N/A
[18]	2016	Conf.	*Smart Innovation, Systems and Technologies*	Decision Sciences	E	Reuse, recycle	No	N/A	N/A	N/A
[62]	2016	Int. Journal	*Laser Assisted Net Shape Engineering 9 International Conf.*	Engineering; Optics; Physics	E	Reduce, reuse, recycle	No	N/A	Direct energy deposition/powder bed fusion	N/A
[4]	2014	Int. Journal	*Resources*	Environmental Science	A	Reuse	No	N/A	N/A	N/A

Notes: (a) stam sand and acrylonitrile styrene acrylate; (b) acrylonitrile butadiene styrene (ABS) and polyamide 12 (PA 12); (c) windshield wiper blade; (d) polylactic acid and commercial wood; (e) polycarbonate; (f) acrylonitrile butadiene styrene and polypropylene; (g) polylactic acid and acrylonitrile butadiene styrene; (h) polylactic acid, acrylonitrile butadiene styrene, polyethylene terephthalate, and polypropylene; (i) mussel shell waste; A—analytical; E—empirical; O—others; N/A—not applicable.

In a total sample of 32 documents, all of them focused on at least one of the 4Rs in the framework that is the core of the circular economy; moreover, it is possible to notice that the "R" corresponding to "recycle" was the most common (26 documents). This derives from the fact that most of these documents highlight the remanufacturing activity, which is part of the industrial symbiosis concept and can be promoted through the AM. From the 32 documents, most of them (23 documents) used empirical research methods, through the use of case studies or mixed methods. Only four documents used analytical research methods, developing conceptual models, or future research scenarios, and five documents were classified in the research category "others".

Even though the application of the industrial symbiosis concept within the AM industry is in its early beginnings, the systematic literature review provides evidence of the development of the multidisciplinary approach crossing the domains of Engineering, Materials Science, Business and Economics, Decision Sciences, Physics, Chemistry, and Environmental Sciences and Ecology.

In the sample under study, only five documents explored the possibility of having industrial symbiosis networks within the AM industry, through the exchange of resources, namely, wastes and other materials. In this study, the researchers distinguished between two types of wastes: the ones that serve as input for AM processes (external) and the others that are generated among the AM processes (internal). From the five documents explored, there is need to highlight that problems concerning variability of wastes' composition are not addressed. For wastes that often contain valuable properties in such concentrations, their recovery might be economically viable. Therefore, these raw materials are called secondary raw materials [63]. Only five documents focused on wastes' exchange as secondary raw materials using as input for different AM technologies: (i) three of them are related to material extrusion, namely, fused based fabrication, fused granular fabrication, and fused particle fabrication; (ii) one document describes an application related to powder bed fusion, in particular, selective laser melting technology; (iii) and the other document left is related to binder jetting.

In terms of waste exchange, three documents describe the use of plastic wastes as material input for the AM processes, one document refers to scrap feedstock as the waste that was used, and one document mentions the use of locally produced waste as inputs for the AM processes. The main findings of current applications of wastes as secondary raw materials in AM processes are described in the following way:

- In [49], the authors explored the possibility of using industrial 3D printers capable of fused particle fabrication/fused granular fabrication printing directly from waste plastic streams (external wastes) through the intervention of Green Fab Labs that could act as recycling centers for converting plastic waste into valuable products for their communities. As an example, the authors studied the Gigabot X printer, which is an open-source industrial 3D printer. Acrylonitrile butadiene stryrene (ABS) and polypropylene (PP) were the plastic waste streams that were used for printing three consumer-grade products: a skateboard, kayak paddles, and snowshoes. The results of this study showed that AM technology is capable of producing large high-value sports products with plastic waste streams.
- In [53], the authors developed an approach that aims to support the search and use of local materials (external wastes) as material input for AM and also materials that are recyclable to serve multiple lifecycles. The authors explored the possibility of adapting mussel shell waste into AM material. Mussel shells can be considered waste that is not suitable for composting, and printing mussel shell waste results in a ceramic-like material; therefore, a flowerpot was considered a suitable initial product application to demonstrate the current applicability.
- In [48], the authors explored the potential of using recycled polymers (external wastes) in 3D printing, namely, in fused particle fabrication or fused granular fabrication. The authors analyzed one of the possibilities to overcome the artificial cost barrier to distribute AM through the upcycled of plastic waste, namely, polycarbonate (PC)

plastic regrind, into 3D printing filament with an open-source waste plastic extruder (designated by Recyclebot). The study extended the potential to high-performance polymers and analyzed the material properties of the 3D-printed products. Three case study applications were explored: (i) using PC waste to successfully manufacture it into a mold that can be used for rapid molding of a lower melting thermoplastic point; (ii) using a home floor steamer whose outer plastic had become brittle and disintegrated but for which a replacement was designed to be optimized for ease in 3D printing, allowing a new steamer head to be printed from PC waste that performed the same function; and (iii) an open-source car window ice scraper with interchangeable blades was printed and tested—the handle was printed via polylactic acid (PLA) and the blade was printed in recycled PC. This study showed that recycled PC particles may be a useful and inexpensive material to be considered for use in AM on particle material extrusion 3D printers—external.

- In [52], the open source Gigabot X printer was used to develop a method in order to optimize fused particle fabrication or fused granular fabrication for recycled materials. The authors analyzed and compared virgin PLA pellets with recycled polymers that included the two most popular printing materials and the two most common plastic wastes. The results showed that the Gigabot X and similar printers may use a wide range of recycled polymer materials with no significant post processing.
- In [58], the authors applied the circular economy concept into AM through the recovery of metallic scrap generated in the AM process (internal wastes) to the feedstock material for selective laser melting. Powder from 100% scrap feedstock was prepared following two routes: (i) gas atomization of solid scrap without extra alloying and (ii) mechanical milling of agglomerated residue powder. The properties of the powder were tested and analyzed to determine the mechanical properties and were compared to commercial reference powder. The study showed that recycled powder properties entirely comparable to the reference can be reached.

Since there are already some applications of waste material input for AM processes, there is evidence that symbiosis networks could be developed in this environment, stimulated by the exchange of resources between entities.

In order to develop and implement an industrial symbiosis network, there is a need to consider not only the resources that will be exchanged but also to identify the possible entities that would be involved or intend to participate in the network. For the five documents analyzed in detail above, we identified the possible entities that would be involved in a symbiosis network. These entities correspond to the direct partners that exchange resources directly in the symbiosis network. The indirect partners that have a more indirect collaboration however necessary to support the resource exchanges were not identified. Moreover, only physical resources (materials or services) were identified, namely,

- In [49], the origin of the wastes used in the 3D printer (ABS and PP) came from two different entities: Northwest Polymers and McDunnough, Inc., respectively. There is an intermediary entity that allows the incorporation of these wastes in a 3D printer and converts them into consumer-grade products. This intermediary entity is the Green Fab Lab, which acts like a recycling center. The products resulting from printing the plastic waste corresponded to sports mobility products that would be sell to the final consumers. The industrial symbiosis network that could be developed for this process was created, considering only the three direct partners that exchange physical materials between them. As an example of how the initial configuration of the symbiosis network would be, we present the network in Figure 5.
- In [53], the authors highlight that approximately 50 million kilograms of mussels are produced in the Netherlands. The shells of the mussels are waste, and their origin came from the entity that represents the mussels' breeders. These wastes can be used as material input by entities that use a binder jetting additive manufacturing process. These entities would be responsible for the necessary treatment of the wastes before incorporating them in AM processes. By the end the process, and since the mussel

shell print mainly consists of calcium carbonate, ceramic-like materials can be printed (in [53], for example, a flowerpot was produced).

- In [52], the source of the recycled polymers that were used in the 3D printer came from different entities: Nature Works LLC, McDonnough Plastics, Northwest Polymers, and CiorC. These polymers can be used as material input by other entities that work or own an open source Gigabot X printer, which is a large scale recycled plastic 3D printer. From this process, a large variety of polymers can be printed at a lower print time when compared to the traditional fused filament fabrication process. These polymers can then be used internally or can be sold to other entities.
- In [48], the entity responsible for providing the recycled PC regrind as the waste to be incorporated was the McDonnough Plastics. As identically described in the previous process entities that work or own a Gigabot X printer can use these polymers to produce filament, which can also be used internally or can be sell to other entities.
- In [58], the focus was on the recovery of process side-streams back to feedstock material. In fact, there is not an industrial symbiosis network inherent to this process. However, if other entities that use selective laser melting as AM processes would have interest in it, the entity responsible for incorporating the process side-streams into feedstock material could sell the service to these other entities or even use the process side-stream from other entities, creating an industrial symbiosis network.

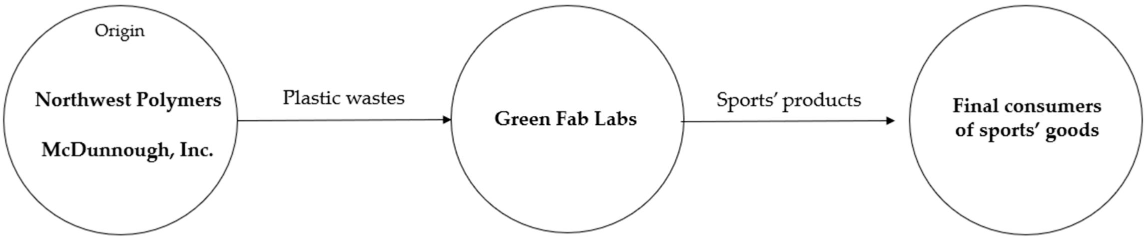

Figure 5. Possible industrial symbiosis network formed from plastic wastes used to produce sports goods.

5. Critical Analysis

This study has provided a germane discussion of the relevant literature, considering in particular the current environmental concerns related to waste management in the manufacturing industry. Currently, there are no comparisons available to other published literature—this study confirms what many academics in the research community may suspect but are not able to confirm, which is the fact that the published literature that combines industrial symbiosis with AM lacks depth, breadth, and scope. Therefore, there is a gap in the literature that can be explored, with this research making a compelling argument and underscoring the need of academics to further explore this research area.

This research aims to clarify and aid policymakers in both the public and private sector who develop waste policy and subsequent initiatives to reduce waste. From an academic perspective, this study aims to create dialogue and focus the debate to create a shift in policy direction, government regulations, and funding for waste recovery initiatives.

The topic of AM relies on a technical system, while industrial symbiosis engages at an organization level, and the correlation between them could be seen as unclear at first. However, as it can be seen in Table 3 that several forms of waste can be used as input materials for the AM processes, with many exchanges of resources that can occur in an industrial symbiosis setting being identified. By analyzing Table 3 from the few available studies, plastic waste seemed to be the material that is often a point of interest in these studies. A few studies identified possible avenues for having industrial symbiosis networks within the AM industry through the exchange of waste and other materials. This could be more profitable and achieve a real positive impact on our planet in addition to having a radical change in the business model of manufacturing engineering.

Some additive manufacturing technologies, such as selective laser sintering or multi jet fusion, succeed in recycling an important part of the material that has been used during the printing process [64]. Having new industrial symbiosis networks that involve the AM industry creates new possibilities in a way that there is a real advantage of a high percentage of the used material, generating less waste and having a lower environmental impact.

However, the study has several limitations. Some keys to industrial symbiosis are the collaboration and the synergistic possibilities offered by aspects that include geographic proximity [65], stakeholder engagement, logistical aspect [66], economic considerations, and the state of technology [67]. Thus, an analysis of the theoretical framework of industrial symbiosis and the elements found in the literature on the AM technology need to be generated in more depth. Since the number of studies are scarce, this topic needs to be further researched. Moreover, the discussion of the results does not take into consideration larger waste streams, including consumers' waste, which can limit a broader view of the field. Another limitation is related to the employed methodology for searching and finding publications. Limiting the search to papers written only in English could have resulted in several relevant publications for this study perhaps being circumvented. Another limitation is related to the delimitation of the search for scientific original articles, book chapters, and conference articles, obtained through publishers with international scientific indexing. This leaves out many studies that are not published in this way, thus omitting types of publications, such as reports or public documents, which certainly would comprehend more cases of industrial symbiosis with the AM. Therefore, a more inclusive research could be made by using surveys or engaging with industrial symbiosis facilitators that have the capability to provide a few additional case studies.

6. Conclusions

Using a systematic literature review, we examined the state of the art of the current circular economy relationships within the AM industry. The objective was to provide a useful synthesis of possible resource exchanges, namely, that which is related to waste and other materials in the AM processes. From a total sample of 32 papers, only 6 mentioned the exchange of materials. From these, five highlighted the potential use of wastes as secondary raw materials with different applications in various industries, namely, (i) to produce sports goods with plastic waste streams; (ii) to use mussel shells waste to produce a ceramic-like material, namely a flowerpot; (iii) to use recycled plastic regrind to produce a mold for rapid molding or to produce a new home floor steamer whose outer plastic had become disintegrated or to produce the bland and handle of an open-source car window ice scraper; (iv) to use scrap feedstock to produce powder to be used in AM processes; and (v) use of recycled materials in specific AM processes.

The current study shows that industrial symbiosis in AM research it is still in its infancy. In order to broader the sample, there is need to extend the keywords used in the database, extend the databases used, and review the inclusion/exclusion criteria.

From this study, it is possible to conclude that there is still a small quantity of research papers that combine circular economy with AM, highlighting the need to explore this research area. On the basis of the tendencies addressed in this study, and in order to ensure continuity, we recommend several future research scenarios. Mapping the industrial symbiosis development and the possible typologies of the networks is one future research scenario that could further the research of industrial symbiosis in AM. Addressing potential business models for industrial symbiosis in AM is another field that has not been explored yet. Moreover, this can generate innovation and new knowledge, including the knowledge management that has not been addressed in the literature, opening the potential for new studies and developments. Finally, the impact that industrial symbiosis in AM can have on the UN Sustainable Development Goals has not been researched, and thus it could be a potential topic of future studies.

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