



HAL
open science

Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy

Fabio A Cruz Sanchez, Hakim Boudaoud, Mauricio Camargo, Joshua Pearce

► To cite this version:

Fabio A Cruz Sanchez, Hakim Boudaoud, Mauricio Camargo, Joshua Pearce. Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy. *Journal of Cleaner Production*, 2020, 264, pp.121602. 10.1016/j.jclepro.2020.121602 . hal-02560191

HAL Id: hal-02560191

<https://hal.science/hal-02560191>

Submitted on 1 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Words 11350

Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy

Fabio A. Cruz Sanchez^{a,*}, Hakim Boudaoud^a, Mauricio Camargo^a, Joshua M. Pearce^b

^aUniversité de Lorraine, Équipe de Recherche sur les Processus Innovatifs, ERPI, F-54000 Nancy, France.

^bDepartment of Materials Science & Engineering, Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI 49931- 1295, USA

Abstract

The rapid technical evolution of additive manufacturing (AM) enables a new path to a circular economy using distributed recycling and production. This concept of Distributed Recycling via Additive Manufacturing (DRAM) is related to the use of recycled materials by means of mechanical recycling process in the 3D printing process chain. This paper aims to examine the current advances on thermoplastic recycling processes via additive manufacturing technologies. After proposing a closed recycling global chain for DRAM, a systematic literature review including 92 papers from 2009 to 2019 was performed using the scopus, web of science and springer databases. This work examines main topics from six stages (recovery, preparation, compounding, feedstock, printing, quality) of the proposed DRAM chain. The results suggested that few works have been done for the recovery and preparation stages, while a great progress has already been done for the other stages in order to validate the technical feasibility, environmental impact, and economic viability. Potential research paths in the pre-treatment of recycled material at local level and printing chain phases were identified in order to connect the development of DRAM with the circular economy ambition at micro, meso and macro level. The development of each stage proposed using the open source approach is a relevant path to scale DRAM to reach the full technical potential as a centerpiece of the circular economy.

Keywords: distributed recycling, plastic recycling, additive manufacturing, 3D printing, circular economy

1. Introduction

Plastic materials offer a variety of chemical and mechanical properties to be useful for a wide array of applications. Unfortunately, the plastic waste pollution poses a major threat because of the issue of non-degradability affecting the ecological environments (Hopewell et al., 2009; Ryberg et al., 2019; Thompson et al., 2009). Indeed, recycling rates remain small (approx. 14%) in the plastic packaging field on a global scale (Hahladakis and Iacovidou, 2018). Even in Europe, which tends to lead on environmental stewardship, the recycling rate is about 32.5 wt% (Plastics, 2019). However, these values take into account the amount of plastic waste collected, rather than the total amount in circulation (Kranzinger et al., 2018). To tackle this accumulation of waste problem, the european strategy for plastics in the circular economy (CE) is gaining attention in the policy and business debate surrounding sustainable development of industrial production (European Commission, 2018; Geissdoerfer et al., 2017). CE tackles a central societal issue concerning the current principle “take, make, dispose” (linear economy) and its negative effects caused by the depletion of natural resources, waste generation, biodiversity loss, pollution (water, air, soil) and non-sustainable economics (Buren et al., 2016). The validation (technical, economic, legislative) of waste plastic as a secondary raw material in industrial processes is considered now a core target to integrate CE into the plastic value chain (Simon, 2019). Strategies of open and closed-loop recycling as well as upcycling and downcycling functionality approaches can offer paths to validate the secondary raw materials (Zhuo and Levendis, 2014).

On the other hand, additive manufacturing (AM) -also known as 3D printing- and its direct (or distributed) manufacturing capabilities is becoming a key industrial process that could play a relevant role in the transition from a linear to circular economy. AM technologies are expected to transform the production process (Chen et al., 2017; Jiang et al., 2017;

*Corresponding Author

Email address: cruzsanc1@univ-lorraine.fr (Fabio A. Cruz Sanchez)

Rahman et al., 2018) thanks to their ability to transform a numerical model into a deposition of material (points, lines or areas) to create a 3D part (Bourell et al., 2017). The expiration of the first patents has contributed to an increased interest, creating consumer value and potential for disruption (Beltagui et al., 2020; West and Kuk, 2016). In economic terms, the global additive manufacturing market is expected to reach USD 23.33 billion by 2026 (Data, 2019). However, determining when and how to take advantage of the benefits is a challenge for traditional means of production. From a societal viewpoint, Jiang et al. (2017) reported that the product development could change from traditional stage-gate models to iterative, agile processes changing the scenario by 2030. A large number of products can already be manufactured with AM, which affects the geographical spread and density of global value chains (Laplume et al., 2016). It is expected that the reach of AM printable products will be much greater in the future, as the production of multi-material and built-in functionalities (e.g. electronics) will be possible to a large extent. In addition, the production of spare parts can be carried out on-site, modifying the role of suppliers in the production lines (Zanoni et al., 2019). Matt et al. (2015) explored the stages of distributed model factories and decentralized production types ranging from distributed capabilities to cloud production. Thus, the need of transport will be much more carefully because of the fact that AM will enable decentralization of production to localities near customers or in the most extreme distributed scenario at the customer's premises (Bonnín Roca et al., 2019; Petersen and Pearce, 2017; Wittbrodt et al., 2013). Moreover, AM technology makes it possible to reduce market entry barriers, reduce capital requirements and achieve an efficient minimum scale of production to promote distributed, flexible forms of production (Despeisse et al., 2017). This enables an alternative option from an economy-of-scale to an economy-of-scope, where the products are highly personalized satisfying niche communities or even individuals (Hienerth et al., 2014; Petrick and Simpson, 2013). For these reasons, the AM technology could be a driver for a shift in manufacturing from globally distributed production to local facilities. Significant efforts are being made by industry and the scientific community to move AM techniques from rapid prototyping and tooling stages towards direct digital manufacturing (DDM) (Gibson et al., 2010; Holmström et al., 2016), with the concomitant environmental and social benefits. Nevertheless, Niaki et al. (2019) demonstrated that environmental and social benefits are not the key preferential factors in the adoption of AM technologies in different industrial sectors. Only the economic factor remains relevant in the AM implementation, considering time- and cost-saving as the most important reasons.

The opportunities of AM on CE are only beginning to be explored. It is necessary to understand what are the contributions and barriers for the integration of AM development with CE requirements. More specifically, to understand the opportunity that AM brings to plastic waste issues (Garmulewicz et al., 2018). As traditional centralized plastic recycling processes have proven to be inefficient (Kranzinger et al., 2018), the sustainability dimension of AM needs to be performed at early phases as the diffusion of this technology will continue to grow in the years to come. The implementation of AM into circular economy purposes enable the possibility to use local materials supply chains (Despeisse et al., 2017) promoting in-situ recycling (Ford and Despeisse, 2016) with highly distributed sources of consumer waste could lead to a reduction in transportation (Kreiger et al., 2013) and the environmental impact of intensive resource exploitation. Hence, AM can be seen as a recycling tool to reuse a thermoplastic waste material, and then influencing the structure of material supply to improve resource consumption efficiency. Indeed, using open source technology is an important driver to boost the local recycling process (Buitenhuis et al., 2010; Santander et al., 2020).

Nevertheless, at this stage a better understanding of the global recycling chain value is needed for additive manufacturing. Different issues such as the technical and logistical feasibility of distributed recycling via additive manufacturing (DRAM) needs to be globally clarified (Hart et al., 2018). Moreover, the different stages required to transform the plastic wastes into secondary raw materials for AM are required to be highlighted. Therefore, this work presents a systematic literature review study based on the specific research question: *What are the advances and barriers on thermoplastic recycling processes via additive manufacturing technologies?* In this paper, firstly, a closed recycling global chain specific for AM process is proposed. And secondly, the advances at each stage of this recycling chain are mapped in the scientific literature in order to have an overview of the opportunities and challenges to overcome. Many authors have pointed out the practices of the R framework as core principles of CE (Miliotis, 2018; Morseletto, 2020; Rosa et al., 2019). In this way, AM could be a driving technology enabling the implementation of local niches of the R framework at a local scale.

This paper begins in Section 2 by providing a background on the plastic issues and an overview of the related environmental aspects on additive manufacturing context. Section 3 presents the overall methodology used in the literature review including a global framework and the steps followed in order to identify relevant documents considered in this review. Then, Section 4 presents the results considering each phase in the recycling chain value. Then Section 5 presents the discussion of the result focalised in three elements: Section 5.1 is focalised on the pre-treatment of the recycled material at local level, Section 5.2 is related on the printing process chain and use of the recycled parts and in Section 5.3 is about on the open source as driver of the DRAM approach. Finally, conclusions and perspectives are presented in Section 6.

2. Theoretical background

2.1. Plastic Issues

The European Commission identified plastic materials as a priority area, with the aim of making all plastic packaging recyclable by 2030 (European Commission, 2015; European Commission, 2018). Different challenges have been identified as political (e.g. China's decision to restrict imports of certain types of plastic waste (Brooks et al., 2018)), economical (e.g. weak or non-existent markets for recycled plastics (Milios, 2018)), social (e.g. cultural mind-sets and attitudes towards resources recovered from wastes (Blomsma, 2018)), technical (e.g. design for recycling (Horvath et al., 2018)), and legal aspects (e.g. standardization, recycling symbols (Hennlock et al., 2015; Milios et al., 2018)). Therefore, the creation of a context that improves the economics and quality of plastic recycling are essential issues to solve in order to create value from these secondary resources. Specifically, the quality assessment of materials, components and products upstream and downstream of the point where they are disposed of as wastes are more important aspects to be determined (Iacovidou et al., 2019)..

Regarding industrial ecology of polymers, primary, secondary, tertiary and quaternary recycling are the four main approaches for recycling plastic solid wastes (Al-Salem et al., 2009; Clift, 1997; Hopewell et al., 2009; N. Singh et al., 2017). The primary and secondary recycling is performed as a mechanical recycling process. Mechanical recycling includes the physical treatment to reprocess plastic waste into new products where it entails technologies for sorting/separation, decontamination, size reduction, remelting and production (Al-Salem et al., 2009; Fisher, 2004; Hopewell et al., 2009; Perugini et al., 2005; N. Singh et al., 2017). Several studies showed the relevance of mechanical for single plastic/bioplastic waste streams in terms of environmental impacts (Arena et al., 2003; Perugini et al., 2005) and energy (Lazarevic et al., 2010; Piemonte, 2011). Moreover, it is a key enabler to circular economy for closing the loop on polymer wastes (Ragaert et al., 2017). However, mechanical recycling meets several obstacles as management and collection are complex and technical considerations of the plastic degradation (Al-Salem et al., 2009; Hopewell et al., 2009). The incompatibility between most polymers makes the sorting process essential for satisfactory properties (Signoret et al., 2019). The separation of laminated flexible structures (e.g., food packaging) for recycling is not economically viable, which explains that the packaging applications, the largest contributor to the production of plastic waste, are sent to landfills (Craighill and Powell, 1996; Curtzwiler et al., 2019). From a logistical point of view, the recycling process is less economically viable given the low weight/volume ratio and the complex heterogeneity of mixed waste which implies an investment in transport, storage and sorting facilities. Additionally, the price of recycled plastic is a function of the prevailing oil price (Hopewell et al., 2009). Therefore, chemical recycling is a preferable option for complex and contaminated wastes (Ragaert et al., 2017).

From a technical perspective, the final quality is the main issue for mechanically recycled products. Figure 1 presents a technical characterization framework with three major elements for a holistic quality assessment of recycled material (Badia and Ribes-Greus, 2016; Karlsson, 2004; Vilaplana and Karlsson, 2008).

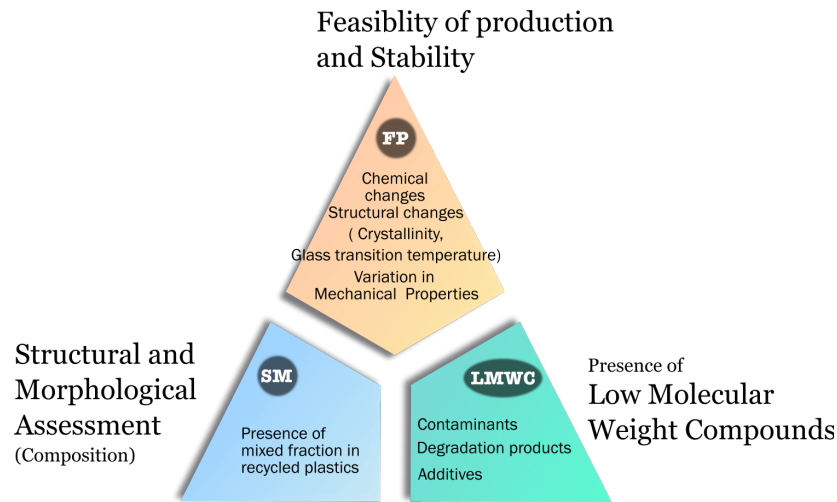


Fig 1. Technical framework for quality assessment of recycled plastics. Adapted from (Karlsson, 2004; Vilaplana and Karlsson, 2008)

They can be defined as follows:

Structural and morphological (SM): determines the chemical nature of recycled polymer constituents

Feasibility of production and stability (FP): it refers to macroscopic properties such as thermal, mechanical and rheological of the recyclates.

Low molecular weight compounds (LMWC): it concerns the analysis of degradation products (additives, impurities, contaminants) in the polymer structure.

For each element, Badia and Ribes-Greus (2016) proposed a multi-scale characterization framework including experimental and analytic techniques. This framework enables to map the quality from the micro- to macro properties of the recycled material.

2.2. Polymers under the Additive Manufacturing context

Additive manufacturing is defined as a process of joining materials to manufacture objects from 3D models, where the manufacturing process is made layer by layer (ASTM, 2015). According to the ISO standard, the seven main process categories are: (1) binder jetting, (2) direct energy deposition, (3) material extrusion, (4) material jetting, (5) powder bed fusion, (6) sheet lamination, and (7) vat photo-polymerization. From the polymer perspective, Figure 2 presents the overview of the classification of the AM technologies that use polymer materials and the physical principle exploited in the process.

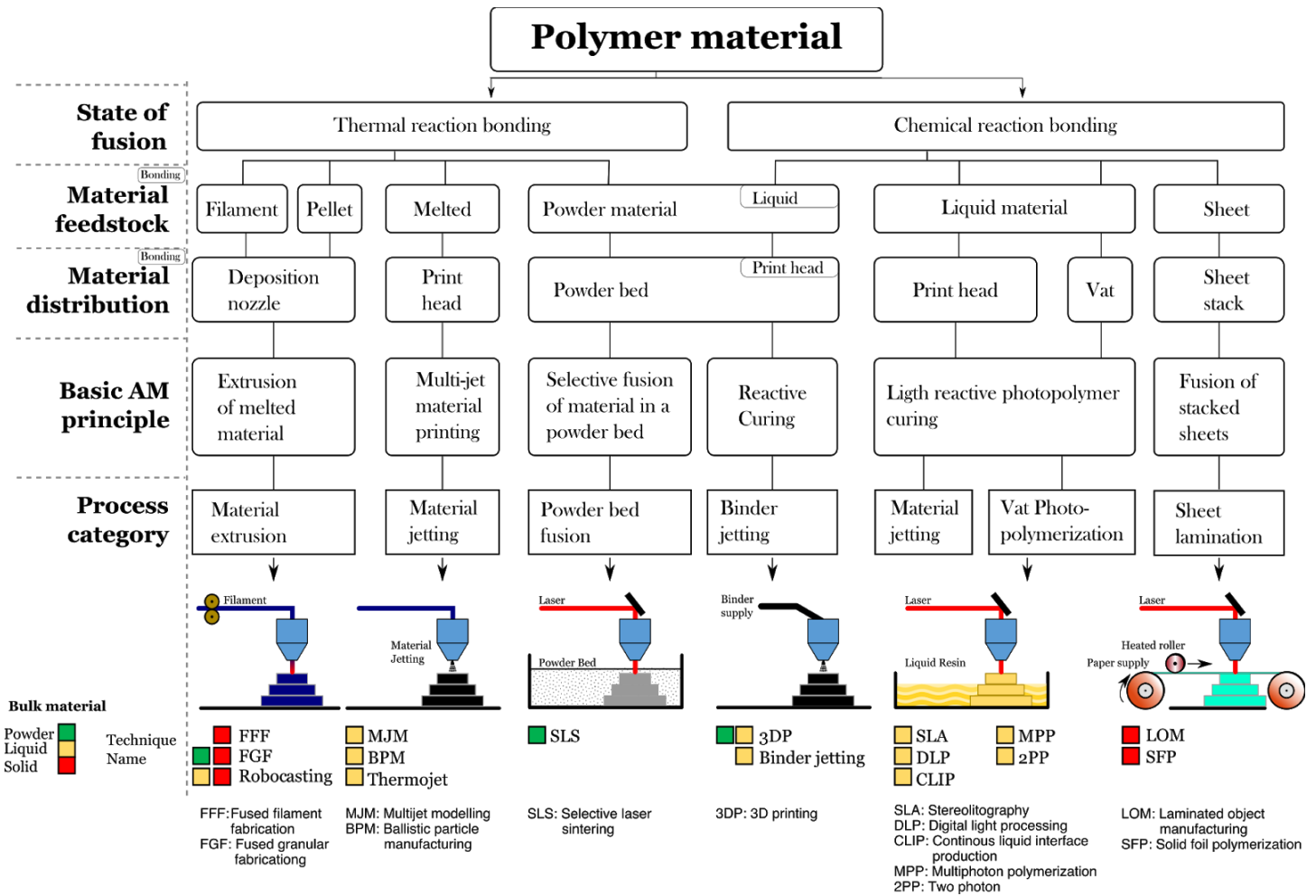


Fig. 2 Overview of single-step AM processes that uses polymer materials. Adapted from (González-Henríquez et al., 2019; Singh et al., 2017)

Polymer materials are a key area in the field of AM and are by far the most used material type (Bourell et al., 2017; Ligon et al., 2017). They include thermoplastics, thermosets, elastomers, hydrogels, functional polymers, polymer blends, composites, and biological systems. Recent works presented a completed review on polymer materials in AM (Ligon et al., 2017), including a focus on 4D printing (González-Henríquez et al., 2019) and elastomers (Herzberger et al., 2019). The additive principle applies to all AM technologies, however, in function of the building principle of each technique, there are different physical aspects in order to join the material. This implies that different functional material requirements and parameters need to be considered in order to guarantee a holistic technical comprehension of the material/process/properties relationship. Most of the thermoplastic (amorphous) materials are processed by material extrusion which is the most extended AM technology (González-Henríquez et al., 2019). Material extrusion systems deposit molten and semi-molten polymers using a movable nozzle or orifice serving as printing head. Fused filament fabrication (FFF) and its proprietary cousin fused deposition modeling (FDM) are the most popular techniques in material extrusion systems. In these techniques, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are among the most used materials (Carneiro et al., 2015). However, general polymers that can be melted at an adequate temperature without degradation are usually useful candidates for material extrusion systems (González-Henríquez et al., 2019).

Technical requirements of material extrusion processes include interfacial adhesion and undisturbed polymer entanglement to manufacture nonporous objects with mechanical properties similar to products made by conventional

techniques (Turner and Gold, 2015). In this case, rheology, thermal and mechanical properties need to be characterized to validate the use of a particular material. In the scientific literature, there have been many advances to characterize the geometric characteristics (Cruz Sanchez et al., 2014; Hebda et al., 2019), mechanical properties such as tensile (Dizon et al., 2018; Jasiuk et al., 2018; Tanikella et al., 2017), fatigue (Safai et al., 2019; Yadollahi and Shamsaei, 2017), flexion (Phan et al., 2019) and thermal properties (Turner et al., 2014). Moreover, multiple applications have successfully used polymer materials including dental (Stansbury and Idacavage, 2016), tissue engineering (Bose et al., 2013), drug delivery (Goyanes et al., 2014), medical (Culmone et al., 2019), humanitarian (Savonen et al., 2018).

Nevertheless, from a technological perspective, different challenges have been identified for the development of polymers' AM in order to improve their competitiveness (Ligon et al., 2017). This competitiveness is related to the functionality of the printed object, evolving from rapid prototypes or tooling to the user-final product. Thus, mechanical properties are one important factor. Efforts have been made to reduce the anisotropy of the printed parts (Torrado et al., 2015). Often, products produced by AM have inferior mechanical properties compared to other manufacturing techniques in many cases, particularly in the direction of build (Ko et al., 2019). Also, manufacturing speeds are inferior to those of traditional processing like injection molding. On the other hand, the current development of 4D printing is an important way to develop smart polymeric materials. Shape memory polymers, hydrogels or active polymer based composites are currently explored in multiple studies in order to evolve the static 3D printed part to change their shape given a specific trigger or environment (González-Henríquez et al., 2019). Objects with complex shapes, compositions (e.g. multi-material), gradients (e.g. multi-color) and multi-functional (e.g. hard-soft) in a single step is an important challenge, which is becoming more common in advanced AM systems.

2.3. AM and Environmental Issues

Considering the different specificity of AM processes, a broad field of opportunities emerges to develop more sustainable means of production at different levels of the chain values (Ford and Despeisse, 2016; Khorram Niaki et al., 2019). This shift goes from design and manufacturing optimization (part / assembly) until the synthesis of advanced materials into the final product (Chen et al., 2015; Drizo and Pegna, 2006; Freitas et al., 2016). There are possible impacts in the upstream phase (e.g. supply chains) as well as the downstream phase (e.g. reparability, recycling and end of life) (Drizo and Pegna, 2006; Morrow et al., 2007; Subramanian Senthilkannan Muthu, 2016). Ford and Despeisse (2016) proposed a framework identifying sustainability benefits of AM, differentiating four main stages: (1) Design, (2) Production, (3) Consumer/Prosumer, and (4) End of Life as illustrated in Figure 3:

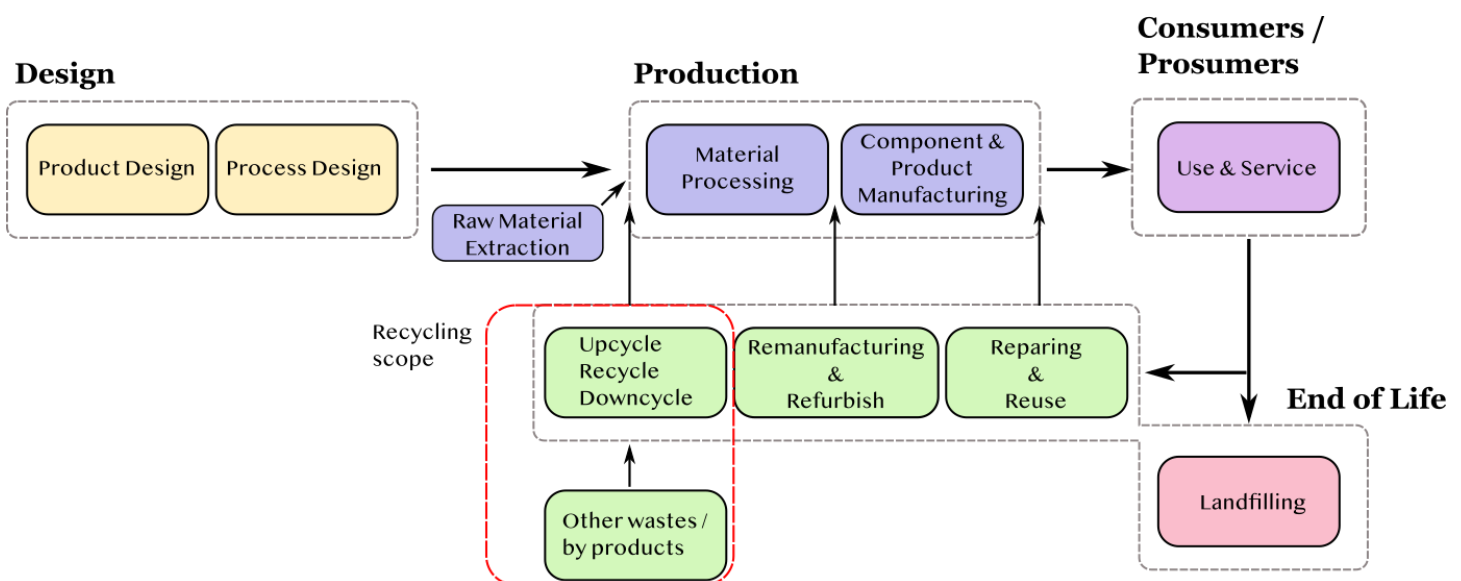


Figure 3: Life cycle perspective for identifying sustainability benefits. Adapted from (Ford and Despeisse, 2016)

Considering environmental aspects, the clear advantage of AM at the design stage (Figure 3) is the opportunity to produce more complex and optimized components reducing assembly operations. Higher flexibility compared to traditional manufacturing reduces the product development time and cost, while improving human interaction and consequently, improving the product development cycle (Guo and Leu, 2013; Vaezi et al., 2013; Wong and Hernandez, 2012). Nonetheless, operational requirements and constraint processes limit the absolute geometric freedom (Mellor et al., 2014; Peng et al., 2018).

In the production phase (Figure 3), Peng et al. (2018) underlines three main aspects: (1) resource consumption, (2) waste management, and (3) pollution control. In resource consumption, several studies have measured the energy consumed by AM equipment and auxiliary subsystems (Baumers et al., 2011; Mognol et al., 2006), material consumption (Bourhis et al., 2013) and comparison between traditional and additive processes (Morrow et al., 2007; Yoon et al., 2014). Considering the waste management, certainly the principle layer-by-layer improves the material yields (ratio of final product weight / input material weight). However, examples of waste include powdery materials that are no longer usable, waste generated by unexpected defects and/or supporting structures created in the printing process. Singh et al., (2017a) reported a complete review on zero waste manufacturing in which additive manufacturing represents an opportunity to implement this roadmap. This opportunity could be realized through the development of direct digital manufacturing (Chen et al., 2015). Finally, considering the pollution control, AM uses fewer auxiliary harmful chemicals than conventional manufacturing (e.g. forging lubricants, cutting fluids or casting release compounds). Emission rates for FFF are relatively low, it does not lead to a traceable pollution in a well-ventilated room (Steinle, 2016). However, precautions should be taken when operating many printers and styrene- and nylon-based filaments without the aid of filtration systems and in poorly ventilated spaces (Azimi et al., 2016; Kim et al., 2015; Stephens et al., 2013).

In the consumers phase, the adoption and diffusion of additive manufacturing (Niaki et al., 2019; Rylands et al., 2016) by different communities from the user-driven innovation paradigm (Hienerth et al., 2014; Hippel, 2005), have resulted in growing interest for the personal fabrication (Mota, 2011), do-it-yourself (DIY) (Fox, 2014) and peer-to-peer (Kostakis and Papachristou, 2014) practices at open spaces such as fablabs, hacker/maker spaces and innovation laboratories (Osorio et al., 2020). Different authors have stated that the capacities of digital manufacturing (Kostakis et al., 2018; Nilsiam and Pearce, 2017) are undergoing a democratization process (i.e. widespread use of the technology). Which on the consumer side, allows private and industrial users to design and produce their own goods (Rayna and Striukova, 2016), enhancing the concept of 'prosumer' (Birtchnell and Urry, 2013; Toffler, 1980). In the prosumer context, four drivers were identified to promote environmental sustainability in personal fabrication : (1) product longevity, (2) co-design, (3) local production and (4) technology affordance (Kohtala, 2015; Kohtala and Hyysalo, 2015). A strategy of cleaner prosumption takes into account the 'what, how, and why' of the produced element. Nevertheless, it is found that the lack of knowledge about AM impacts on the social and environmental aspect is an issue for AM adoption (Matos and Jacinto, 2019). AM practitioners might not be aware of the environmental dimensions when choosing a AM technology (Niaki et al., 2019).

The end-of-life stage (Figure 3) attempts to close the loop that can be achieved at different levels in AM. Repair and maintenance ability that AM could contribute to in order to extend the product life span as a key feature. This cost-effective approach has been usefully exploited for metal parts giving great potential in the repair of damaged components (Yin et al., 2018). Likewise, reverse engineering is an approach to foster repairing and refurbishing while reducing the cost and risk of developing new products (Paulic et al., 2014; Zhang and Yu, 2016). Although it should be pointed out as more businesses adopt an open source business model, reverse engineering processes will become unnecessary (Pearce, 2017a). Finally, concerning the recycling process, several initiatives have been reported in open source communities in order to create low cost extruders to produce plastic filament for FFF 3D printers (Baechler et al., 2013; Filabot, 2012; Lyman, 2016; Woern et al., 2018b). Companies start to sell recycled filaments and some organizations and entrepreneurial initiatives (Bank, 2020; Hakkens, 2016; LF2L, 2020; Plast'if, 2020; PPP, 2020; Qactus, 2020) are appearing to recycle waste plastic towards products with a higher added value.

Zander (2019) explored the current use of recycled filaments in material extrusion and biodegradability of 3D printing filaments as replacement of oil based feedstock. However, there remains a need for understanding the continuum stages that should be studied in order to create a closed-loop recycling chain for additive manufacturing. The study of the global recycling chain enables a holistic analysis in order to determine the stages that need to be solved in order to scale-up the use of recycled materials. Based on that, the next section presents a systematic literature review about the recycling via additive manufacturing. The context of this literature review is to clarify the recycling scope from Figure 3 (in red line).

3. Methodology

Considering the mentioned challenges of plastic waste and regarding the recycling scope in Figure 3, the Figure 4 shows the proposed closed-loop framework in order to identify the scientific literature at each phase based on the literature on polymer recycling (Chong et al., 2015). This will allow us to identify advances in the global value chain that enables DRAM.

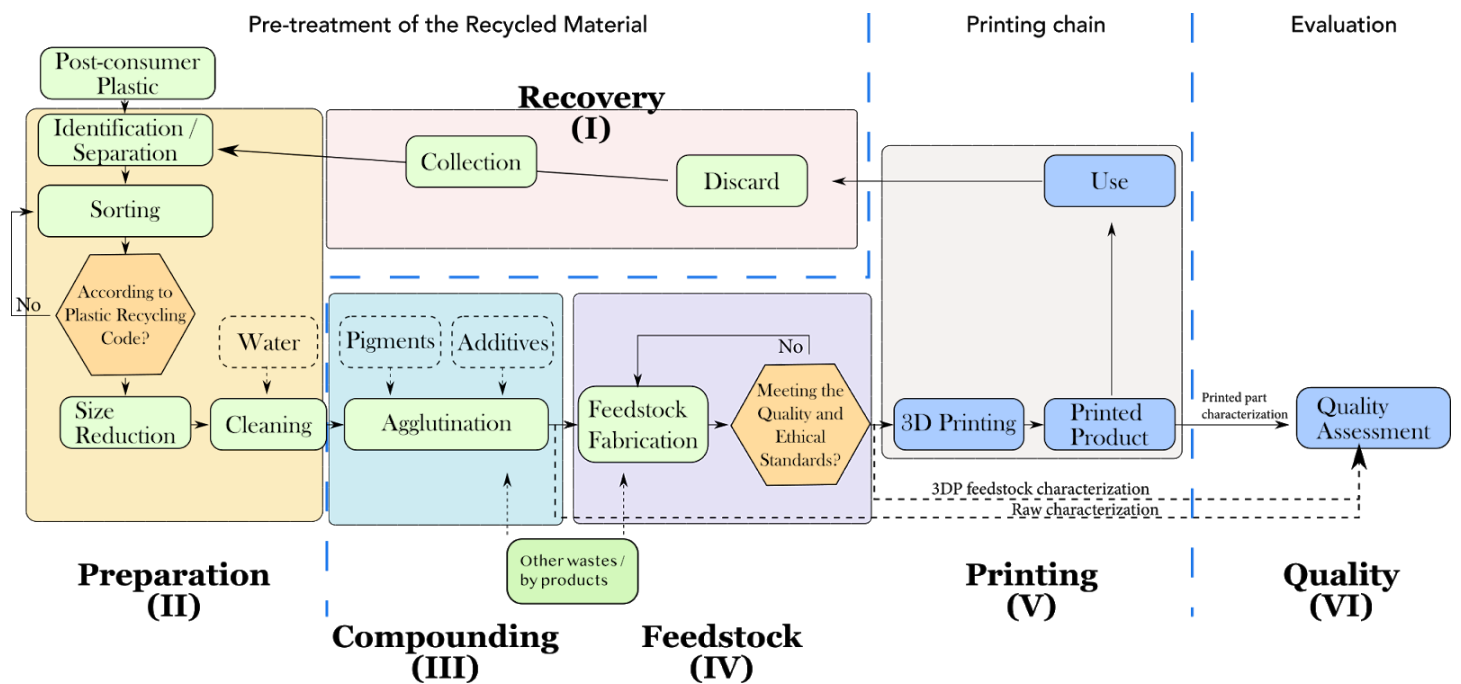


Figure 4: Closed-loop recycling framework for distributed recycling via additive manufacturing (DRAM) process.

The *Recovery (I)* phase concerns the logistic operations to consider in order to collect the plastic wastes to be reused in DRAM. The *Preparation (II)* phase corresponds to the actions and strategies to identify, separate, sort, size, reduce and clean waste plastic to guarantee adequate quality for DRAM. The *Compounding (III)* phase refers to the development of mono- and composite-materials. The *Feedstock (IV)* phase identifies the actions to fabricate the material usable for the printing process, either filament for FFF or the particle size for fused granular fabrication (FGF). *Printing (V)* stage identifies applications and process improvements for the recycled printed part. Finally, the *Quality (VI)* phase identifies the multi-level technical characterization performed to the recycled material.

A systematic review protocol is used to carry out the selection of the studies based on the guidelines of Siddaway et al. (2019). This approach minimizes the risk of publication bias and enables researchers to perform future reviews to identify new research paths (Budgen and Brereton, 2006). The review protocol is composed of the following steps:

1. **Search strategy:** It defines the type of studies, keywords, search equations and the databases to be considered in the review.
2. **Study selection criteria:** It describes the inclusion and exclusion principles that are useful to subset the retrieved documents.
3. **Study selection procedure:** It describes how the selection criteria is performed. The steps and the features to analyze in order to accept or reject a particular study are defined.
4. **Data extraction strategy:** Defines the information that is extracted from the studies.
5. **Study quality assessment:** Evaluates the pertinence of a study regarding the research question. Quality checklists are used to guide the evaluation of the study.

Table 1: Systematic review protocol for the literature.

| Stage | Principle | Description |
|---------------------------|------------------|---|
| Search Strategy | Type of studies | Journal papers and conference proceedings. |
| | Keywords | <ul style="list-style-type: none"> • "3D Printing", "additive manufacturing" • Recycling • "Plastic", "Polymer", "Thermoplastic" |
| | Search equation | (3D printing OR additive manufacturing) AND Recycl* AND ("Plastic" OR "Polymer" OR "Thermoplastic") |
| | Period of time | 2009 - June 2019 |
| | Databases | Scopus, Springer, Web of Science |
| Study selection | Criteria | <ol style="list-style-type: none"> 1) Articles related to the use of recycled thermoplastic for AM technology 2) Studies should be focused on engineering, material or process design. |
| | Procedure | <ol style="list-style-type: none"> 1) Title, abstract and keywords are screened 2) Introduction section and conclusions were read 3) Full article was reviewed 4) Selection is made on the quality assessment |
| Data extraction | Closing the loop | <ul style="list-style-type: none"> • Source of the plastic waste • Parameter used as quality indicator before printing • Application intended for the recycled printed part |
| | Technical test | <ul style="list-style-type: none"> • Characterization test for raw, or 3D feed stock or recycled printed part |
| Quality assessment | QA 1 | Is the study related to the phases I, II, III, IV or VI? |
| | QA 2 | Is a recycling methodology presented in the experiment? |
| | QA 3 | Does the study present implications of plastic recycling on AM technology? |

The procedure to select the articles is illustrated in Figure 5. The search is limited to peer-reviewed journal articles and proceeding conferences published in English. At the beginning, a total of 1143 studies were identified using the respective search engine of each scientific database. The repeated studies were deleted and a total of 1068 studies were screened in order to select those related to our objective. Title, abstract and keywords were analyzed resulting in 715 papers (67 % of total) being rejected by applying the inclusion criteria. So, 353 full articles were obtained for a deeper reading including the introduction and conclusion to verify the relevance to our scope based on study selection criteria. Finally, 92 articles were selected for this research. The presentation of the results is made in the next sections.

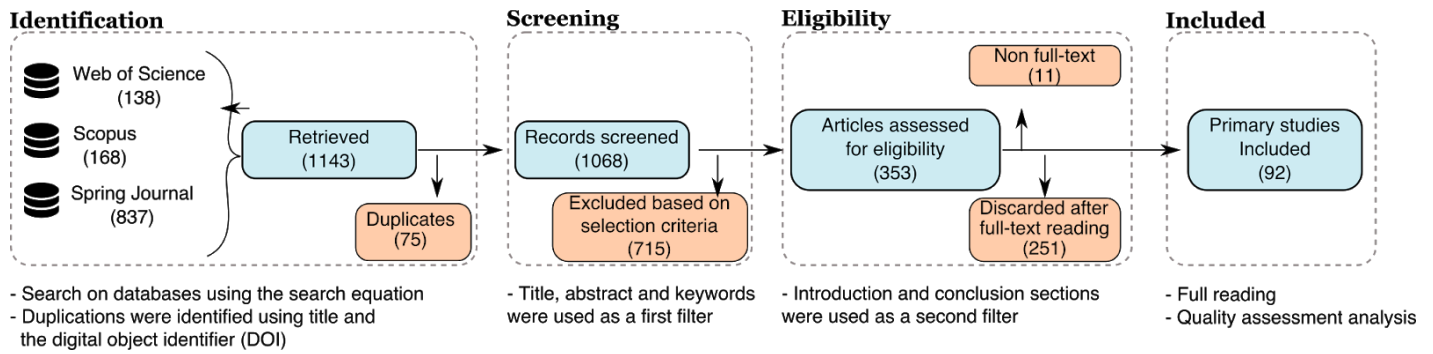


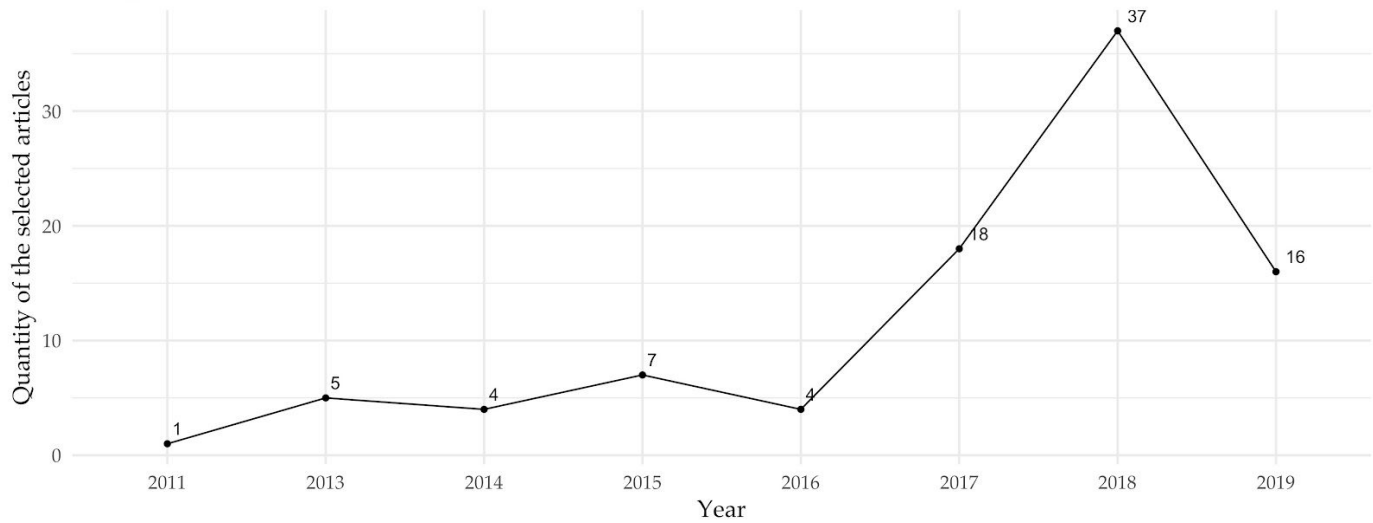
Figure 5: Systematic literature review methodology. Adapted from the PRISMA principles (Moher et al, 2009, Siddaway et al., 2019)

4. Results

The table A1 presents the detailed description of the set of 92 studies considered in this review according to the protocol described above.

Figure 6a presents the temporal distribution of the documents. It should be noted the literature review for this study occurred at the end of June 2019, which explains the drop off in the last year shown in Figure 6. However, a growing interest since 2016 in the subject is observed with an increase of published documents. A total of 64 journals were identified. Figure 6b illustrates the ranking of journals with at least 2 documents considered in this review. Each study was positioned in at least one phase of the proposed framework, having as criteria the quality assessment from the review protocol. The data extraction was performed for the closing the loop purposes and the technical quality assessment presented in section 2.1. In addition, each study was mapped in terms of the sustainable dimension (technical, economic, environmental or social).

A Temporal distribution of the studies



B Journals with at least two documents

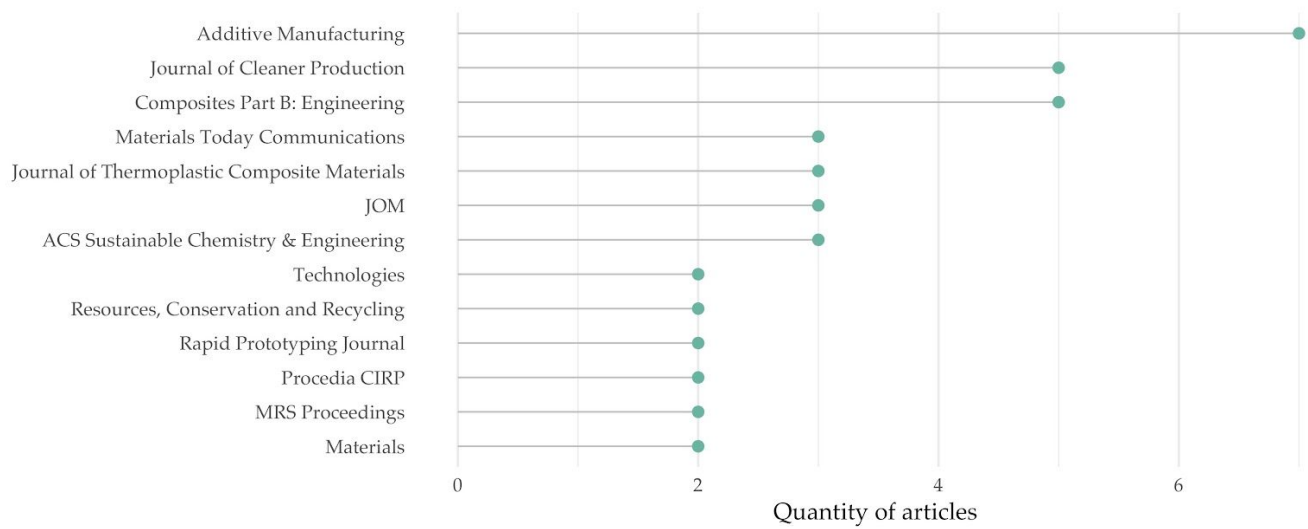


Figure 6: Temporal distribution. Note: data only to June 2019

On the other hand, Figure 7 summarizes the distribution of analyzed publications according to the recycling phase considered and their scope. It appears from the figure that most of the studies deal with technical aspects in the development and characterization of materials for DRAM (Compounding (III) phase). On the opposite side, the Recovery (I) and Preparation (II) phases are the least studied. Moreover, the technical aspect is the most studied in the literature. Nevertheless, social aspects have been only partially treated.

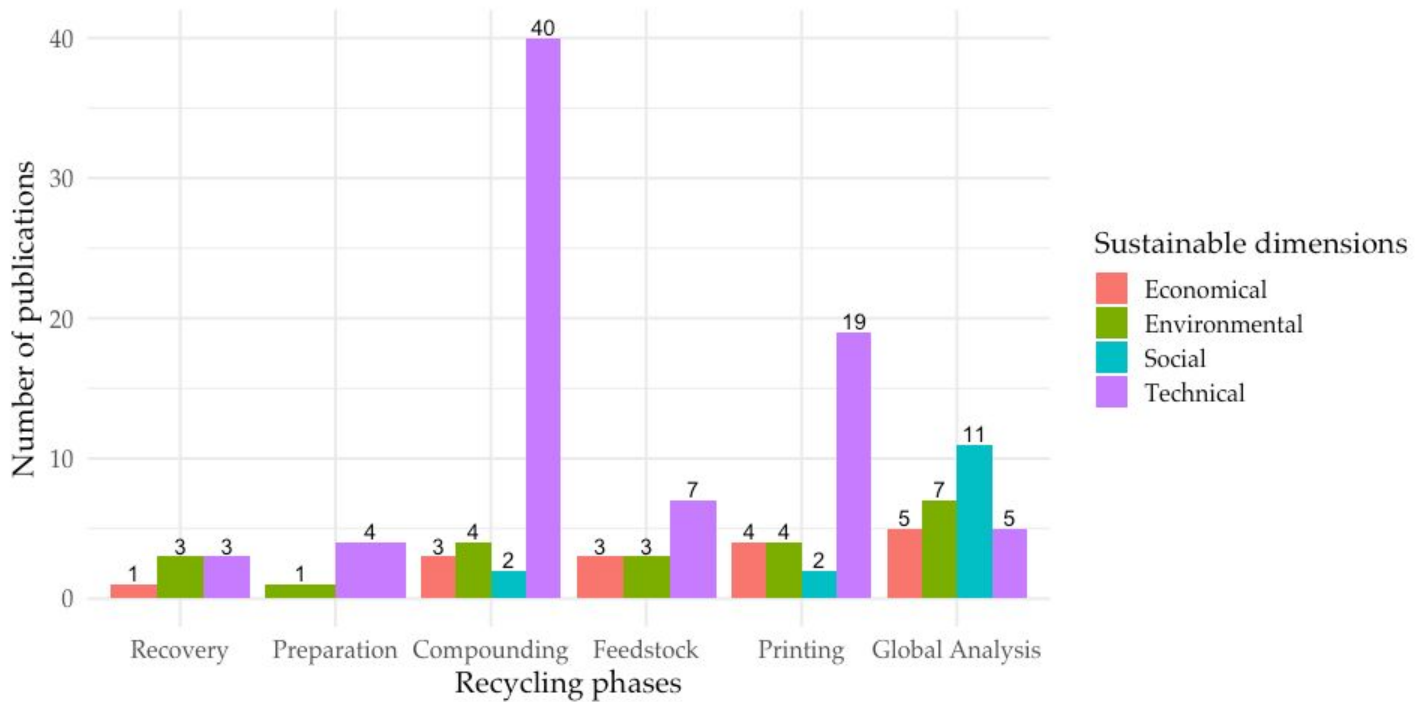


Figure 7: Global results of the literature review.

To better understand the advances, the results are presented in three main elements. First, section 4 presents the technical studies that are identified in the different stages considering the proposed framework (Figure 4).

Then, section 5 proposes a discussion of challenges to overcome about DRAM on the circular economy purposes.

4.1. Recycling Phase I: Recovery

The focus of the recovery stage is on the collecting and logistics operations to collect the plastic wastes. One main point to highlight is that the discard stage was not sufficiently addressed in the literature. The use of a recycled material was given as an asset and not as an object of research discussion. On the other hand, one hypothesis at this stage is that distributed recycling can promote shorter and simpler supply chains where the reduction of the transportation impact is a main feature (Despeisse et al., 2017; Garmulewicz et al., 2018). Using life cycle assessment tools, it was evidenced the environmental gains of the use of distributed approach (Kreiger et al., 2013; Wittbrodt et al., 2013). Moreover, recent research on the design of a closed-loop approach (Zhao et al., 2018), including the definition of supply chain network for plastic recycling based on AM technologies was identified (Pavlo et al., 2018). Nevertheless, more research is needed to evaluate and measure the global impact of the supply chain to collect waste materials in terms of social and political dimensions. In this stage it is fundamental to create logistical indicators in order to clarify the actors and to define under which conditions a closed-loop model could be applicable at a local level.

4.2. Recycling Phase II: Preparation

The preparation phase deals with processes to adequate waste materials in order to be usable recycled feedstock including identification, sorting and size reduction processes. Concerning the identification, Hunt et al. (2015) proposed a recycling code framework taking as example the resin identification developed in China. One key element of this proposal is the code expansion ability as more complex 3-D printing materials are introduced, which enables more flexibility regarding the current identification of plastic codes (1 to 7). An open source script was developed in order to be

included in the printed part for recycling purposes. The widespread adoption of plastic identification during the printing process could foster environmental consciousness about the recycling option. Further work is necessary to integrate such a concept into the wide array of open source slicing and CAD software.

Regarding the sorting process, it is found that this stage was the least considered in our set of studies because the studies reported the use of a material identified from a specific waste (i.e PLA from fablabs) or it is put as initial insight in the methodology without more details on how the material was sorted or cleaned. Concerning the size reduction, there have been different attempts to design and build prototypes for shredding recycled material (Lee et al., 2019; Reddy and Raju, 2018; Romero-Alva et al., 2018). It is reported from manual operations (e.g. hardware scissors - Granulometry: > 5mm) (Chong et al., 2017), use of industrial rotor beater mill (Granulometry: 0.2-5mm) (Jaksic, 2016) and cryogenic grinding process (Granulometry: 450-750 μ mm) (Boparai et al., 2016; Singh et al., 2016). Regarding the cleaning process, the use of using mild soap and water to remove particles from plastic wastes containers was stated (Woern et al., 2018b; Zander et al., 2018). However, a definition of a 'cleaned material' was not found in the reviewed studies.

4.3. Recycling Phase III: Compounding

Compounding phase step is related to the development of mono- and composite-materials for DRAM purposes. Concerning mono recycled materials, different studies have been made to show the technical feasibility to recycle mono-plastics. They include, polyethylene terephthalate (PET) (Zander et al., 2018), high-density polyethylene (HDPE) (Baechler et al., 2013; Kreiger and Pearce, 2013), linear low density polyethylene (LLDPE) and low density polyethylene (LDPE) (Hart et al., 2018; Kumar et al., 2019), polypropylene (PP) (Pepi et al., 2018; Stoof and Pickering, 2018; Zander et al., 2019), polystyrene (PS), polylactic acid (PLA) (Anderson, 2017; Cruz et al., 2015; Cruz Sanchez et al., 2017), acrylonitrile butadiene styrene (ABS) (Cunico et al., 2019; Czyżewski et al., 2018; Lanzotti et al., 2019; Mohammed et al., 2019, 2018a, 2018b, 2017; R. Singh et al., 2019d), polycarbonate (PC) (Reich et al., 2019), thermoplastic elastomer (TPE) (Woern and Pearce, 2017) and biomass-derived poly(ethylene-2,5-furandicarboxylate) (PEF) (Kucherov et al., 2017).

One of the main conclusions of these studies is the positive technical feasibility to use recycled mono-materials for printing purposes through a variety of pathways (Dertinger et al., 2020). However, not all thermoplastics are in the same maturity level for DRAM purposes. For instance, recycled HDPE has been proved from a technical (Kumar et al., 2019; Singh et al., 2018) and life cycle analysis perspective (Kreiger and Pearce, 2013). For PLA material, tensile (Cruz Sanchez et al., 2017) and flexural (Lanzotti et al., 2019) properties have been studied. Using recycled PET, Zander et al., (2018) argued that the printing process was challenging in part due to its high fusion temperature, crystallinity, water absorption to weak interfacial welding between layers. The presence of low compounds and contaminants in the recycled PET structure potentially leads to an accelerated degradation (Zander et al., 2019). On the other hand, recycled ABS, PLA, HDPE are well consolidated as materials for DRAM. Efforts need to be made in order to improve the printability of PP, and PET due to bed adhesion, deformation and weak interfacial welding between printed layers. The printability is a function of the cooling process and the diffusion of polymer chains between layers, and thus, failures in the printing process commonly occurs at these interfaces (Turner et al., 2014). Concerning the recycling for conventional thermosets for AM is limited. However, new development materials on reprocessable thermosets (3DPRTs) is a major research axis to explore (Cicala et al., 2018; Zhang et al., 2018).

On the other hand, there have been several literature reviews about the technical aspect of composite materials in the AM context (Brenken et al., 2018; Hofstätter et al., 2017; Mohan et al., 2017; S. Singh et al., 2017b). Special attention has been paid on the production of polymer/composite feed stock filament as it is economical, environmentally friendly and adaptable to flexible filament materials (S. Singh et al., 2017b). Details about mechanical properties of composite materials for printing using virgin materials are well documented elsewhere (Brenken et al., 2018; Mohan et al., 2017). However, in our case, the main goal is to present studies related to composite that uses recycled materials in their approach. It is noticed that the studies consider strategies to include recycled material in terms of composites plastic/plastic, plastic/metal, plastic/ceramics and plastic/fibers.

Blending virgin/recycled material at various ratios via extrusion process can be a cost-effective way to increase re-use of recycled materials. Advances in this regard were found using PP/PET/PS (Zander et al., 2019), ABS/PLA/HIP (R. Singh et al., 2019a), PP/Tires Wastes (Domingues et al., 2017). Additionally, R. Singh et al., (2019a) investigated a multi-material printing to superpose recycled layers using a multi-nozzle in order to evaluate structural applications. This approach might be useful for the creation of meta-materials contained using local deposition of specific layers (soft, hard and mix) in the printed object for custom functional prototypes. These approaches to print locally recycled materials within the printed part can enable experimental studies to determine optimal quantities of mixed material (virgin + recycled) in different locations of the printed part. This technical aspect can contribute to the establishment of quality standards for AM composite materials containing recycled plastic.

Metal composites using recycled polymer were explored using iron powder (Kumar et al., 2019; Xu et al., 2018), tungsten carbide (Kumar and Czekanski, 2018), iron/silicon/chromium/aluminum (Pan et al., 2018). For instance, Pan et al. (2018) evaluated the effects of adding Fe, Si, Cr, Al nano-crystalline powders into the recycled PP/HDPE for filament extrusion. Physical and mechanical analysis tests revealed that recycled PE/PP filaments with 1% Fe–Si–Cr or Fe–Si–Al resulted in improved thermal stability, yield strength and elastic modulus compared with the original recycled filaments, thanks to the enhancement of inter-facial adhesion between the nano-metal powders and the polymer reducing crack formation. Xu et al. (2018) developed a reusable metallic ink from biodegradable polymer and highly alloyed steel. The obtained results envision applications where the porosity and comparable electrical and mechanical performances that are required using a cost-effective alternative. The development of plastic / metal composite material would be for DRAM applications that use built-in functionalities such as electrical conductivity. The use of iron powder in the recycled polymer matrix could lead to non-destructive testing applications in civil engineering (Kumar et al., 2019).

Plastic / ceramic composites have been explored for rapid tooling applications (N. Singh et al., 2018a) using polymer waste as matrix material and SiC/Al₂O₃ from the filament development to the use on investment casting (Singh et al., 2016). Recycled nylon (Boparai et al., 2016; Singh et al., 2016), HDPE (A. K. Singh et al., 2018; N. Singh et al., 2019, 2018a), LDPE (N. Singh et al., 2018b), ABS (R. Singh et al., 2019c) and syntactic foams (A. K. Singh et al., 2018) have been successfully tested. Rheological and thermal behaviour (Boparai et al., 2016) confirmed the suitability of plastic / ceramic filaments. The melt flow index (MFI) value has been highlighted as a quality indicator for the composite material, prioritizing obtaining a value equivalent to commercial filaments to avoid changes in the default printing process. The results of this recycling route are encouraging to further develop applications with much more added value in DRAM.

Finally, the creation of composite feedstock for AM using natural recycled fibers is a means to improve material properties, but also, to add value to waste organic materials. The inclusion of reinforcing fibres offers the potential to reduce shrinkage, better mechanical properties, add value to the recycled polymer and recycled fibers. Fibers such as harakeke, hemp and recycled gypsum (Stoof and Pickering, 2018), biochar (Idrees et al., 2018), banana (R. Singh et al., 2019b), wood residues (Horta et al., 2018; Pringle et al., 2017) and macadamia nutshells (Girdis et al., 2017) were converted into a viable composite filament filament for 3D printing applications. Nevertheless, a maximum fiber content needs to be considered in the process. Above from there, filaments and printing defects appear affecting the mechanical and geometrical stability (Stoof and Pickering, 2018). This recycling route for different types of agricultural wastes reinforced with the recycled polymers could improve sustainability options for both materials (R. Singh et al., 2019b).

Other types of fibers include the use of glass (Rahimizadeh et al., 2019; Veer et al., 2017), and recycling of continuous carbon fiber reinforced thermoplastic composites (CFRTPCs) (Tian et al., 2017). Recycling of printed CFRTPCs is an axis of development given the superior mechanical properties of these compounds to create lightweight structures. This approach represents a cleaner production model for future compounds. However, recycling efficiency is an opportunity

to improve in order to meet the requirements of industrial production. In the same way, the work developed by (Rahimizadeh et al., 2019) proved the feasibility of using recycled glass fibers from wind turbine blades with comparable mechanical properties to virgin filament.

4.4. Recycling Phase IV: Feedstock

The main goal of this phase is to obtain an adequate recycled material in order to be used in the printing. The open source hardware approach (free, self-replicating, modular) of this design is noteworthy, as it reduces costs, facilitates manufacturing and assembly, while ensuring the reproducibility of the process. For instance, Woern et al. (2018b) provided the designs for a waste plastic extruder (recyclebot) capable of making commercial-quality 3-D printing filament. The filament fabrication conditions reported were 0.4kg/h using 0.24 kWh/kg with a diameter precision $\pm 4.6\%$. In this line, Zhong et al. (2017) evaluated the recyclebot extruder prototype in terms of the energy payback time using the embodied energy of the PLA and ABS materials. The use of the recycler to create a printing filament from post-consumer plastics has proven to be an effective way to save energy. Indeed, the coupling of solar energy and waste recycling is an important opportunity for rural and humanitarian applications as noted by (King et al., 2014; Mohammed et al., 2018a).

Similarly, Woern and Pearce (2018) presented an open-source 3-D printable pelletizer chopper system for providing compounding for filament making or feed stocks for direct particle printing purposes.

An interesting approach is the identification of specific plastic waste in order to validate secondary raw materials. For instance, using packaging waste (meals-ready-to-eat) from the military sector, Hart et al. (2018) recycled proved the chemical resistance, minimal permeability, and flexibility, and toughness for non-load bearing applications where barrier properties are required. Supply material is difficult to obtain in army operations because of its remote location, reducing the supply dependence will not only increase the operational readiness and self-sufficiency but will also improve the security of combatants (Pepi et al., 2018). Therefore, local recycling is a structural advantage in this type of context. Other specific recycling source were PET bottles (Idrees et al., 2018; Mosaddek et al., 2018), e-waste (Czyżewski et al., 2018; Gaikwad et al., 2018; Zhong and Pearce, 2018), tire rubber (Alkadi et al., 2019; Domingues et al., 2017). Indeed, Zhong and Pearce (2018) showed that e-waste plastic from computer labs could be directly recycled into products with AM for cost savings over 300X compared to equivalent commercial products.

An interesting approach is the use of leftover material in selective laser sintering (SLS) to be used in FFF (Kumar and Czekanski, 2018, 2017; Mägi et al., 2016, 2015). In SLS, powders that have not been sintered in the printing process become unusable (after a certain number of reuse cycles) and eventually become waste. Since high energy consumption is required for the production of powders, the generation of these wastes has an impact on the global sustainability of the process. The production of filaments from SLS waste to be used in the FFF technique was successfully demonstrated and mechanical properties and economic advantages are reported in (Kumar and Czekanski, 2018, 2017). If these two processes are connected, they could contribute to overall environmental sustainability by tightening the loop in the material life cycle. Other types of synergies among industrial processes can be possible identifying mono-material specific waste niches to be reused in distributed recycling. However, it is necessary to define the requirements of the plastic waste. This concept is normally referred to as industrial ecology (Clift and Druckman, 2016). Significantly more work is needed to map the lessons of industrial ecology to the distributed manufacturing and recycling proposition described here.

4.5. Recycling Phase V: Printing

The fused filament fabrication is well established in the additive manufacturing context. Nonetheless, the technical development of fused granular fabrication (FGF) could be an important path to prove the recyclability of plastic wastes (Canessa et al., 2017; Reich et al., 2019; Woern et al., 2018a). FGF is able to print from pellet material eliminating the need to manufacture filament. These FGF systems have successfully recycled a number of virgin polymers as well as

post consumer waste in a “green fablab” context (Byard et al., 2019). For instance, Woern et al. (2018a) tested the open source Gigabot X to evaluate virgin PLA and four recycled PLA, ABS, PET and PP particles. Experimental work was made to optimize the print speed and extrusion conditions in order to find optimal printing set-ups for each polymer. Printing time was reduced (6.5x to 13x) with respect to conventional printers depending on the material, with no significant reduction in the mechanical properties. Indeed, using plastic / plastic composite of recyclable polypropylene (PP) blended with tire wastes was proved by Domingues et al. (2017) using a robotized equipment. These examples open extraordinary new possibilities to enhance the DRAM. This approach takes away the filament fabrication, which is a time-, cost-consuming process. An important research path is to evaluate the printability for a wide range of recycled polymers with minimal post-processing via FGF. Exploring new recycled polymers from specific niches could lead to new recycling loops.

Other types of direct extrusion include a piston-drive head (Volpato et al., 2015) and screw-based (Canessa et al., 2017) extrusion approaches. However, more research is needed to evaluate degradation profiles, the stability of the cross-sectional area affecting the dimensional and surface finish, the influence of granulometry in the printing process. Determination of optimal configuration parameters for specific materials and a real estimation of their performance in terms of relative flow rate, printing speed, and global energy consumption are required (Canessa et al., 2017). The direct extrusion systems could facilitate the use of recycled materials in DRAM, and the research needed to make these systems widespread has just begun.

4.6. Recycling Phase VI: Quality

In the transition from waste-to-product, it distinguished the material quality evaluation in three distinct moments: (1) raw material, (2) 3DP feed stock, and (3) printed part. Figure 8 shows the percentage of the registered studies that declare a technical characterization of plastic waste based on the type of test (y-axis) and the moment that is performed (x-axis).

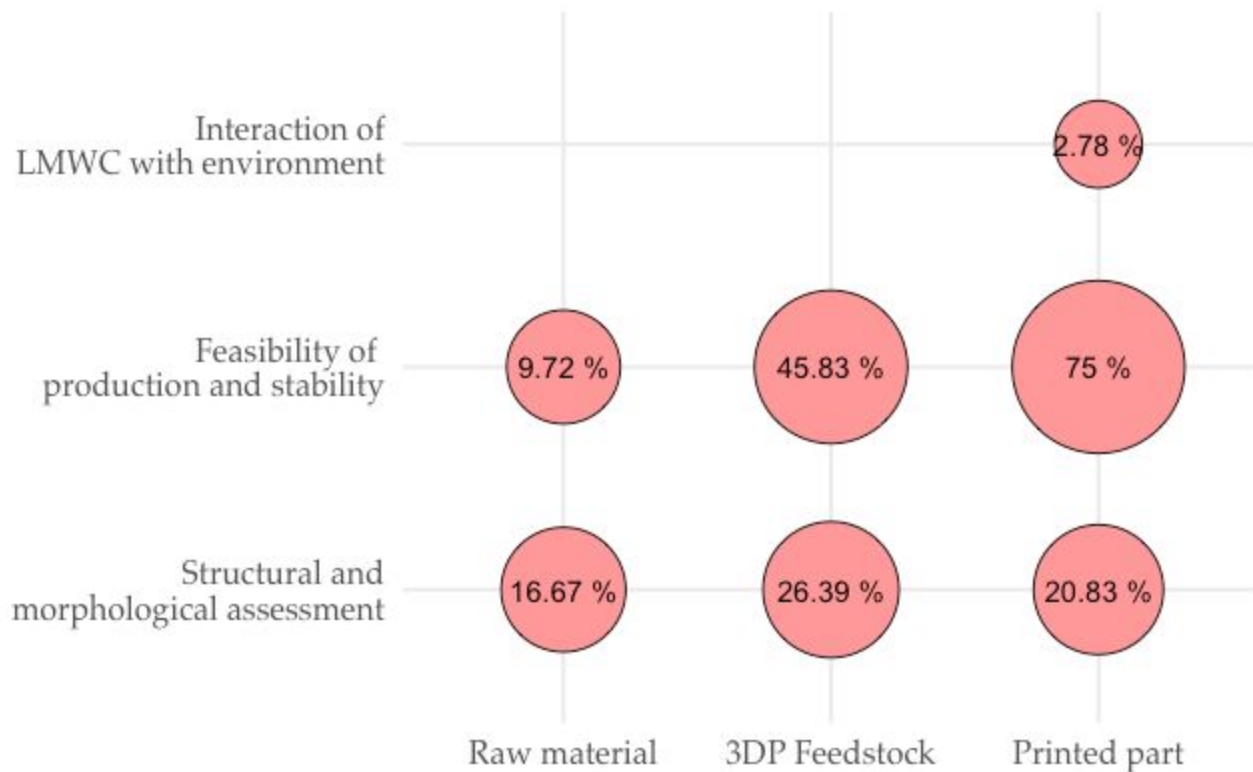


Figure 8: Percentage of technical characterization by type and moment, reported in the retrieved studies

Among the technical studies, 75% reported a characterization test to the recycled final part, about 46% for the 3DP feed stock filament, yet only 9% tested the raw recycle waste. The technical assessment of raw material properties allows users to estimate the quality of the initial recycled material. Key properties such as flowability and thermal characteristics. For instance, Kumar and Czekanski (2017) evaluated the melt flow index (MFI) of three different proportions of recycled HDPE reinforced with SiC/Al₂O₃ with the aim to have comparable rheological behavior as a commercial filament.

Concerning the 3DP feed stock, it refers to the evaluation of the filament properties in the case of fused filament fabrication. For FFF technique, diameter and linear density of the filament are considered as the most important quality parameters. Mechanical properties such as tensile modulus and elastic modulus of the filament are evaluated as they are important for estimating the degradation caused by the extrusion process. In the case of composite filaments, morphological analyses are performed to validate the distribution of the matrix and filler within the filament structure (Pan et al., 2018). For FGF, size particle distribution is generally explored as a quality input.

Finally, the last case is the evaluation of the properties of the printed object. Printability is one of the first tests performed on waste material, which refers to the capacity of the material to be extruded preserving the dimensional geometry after extrusion and having a minimum of strength. Mechanical properties were the most used test for the validation of the recycled material for DRAM counting tensile (Cruz Sanchez et al., 2017), flexural (Lanzotti et al., 2019), fatigue (Letcher and Waytashek, 2014). Different printing issues can be found such as warping, deformation or buckling. Also, specific elements such as barrier properties of the printed model (Hart et al., 2018).

Moreover, the creation and validation of methodologies that improve DRAM could help support the ambition of zero-waste. Concerning the FFF technique, different methodologies have been found in the literature (Chong et al., 2015; Cruz Sanchez et al., 2017; Cunico et al., 2019; Feeley et al., 2014; Gaikwad et al., 2018; Singh et al., 2016; Tian et al., 2017). In terms of technical recyclability, Cruz Sanchez et al. (2017) reported a general methodology to evaluate the degradation curves of thermoplastics using PLA as a case study. For composite materials, Singh et al. (2016) presented

a methodology to reuse nylon-6 waste for the casting process. From a modeling perspective, Clemon and Zohdi (2018) proposed a mathematical framework that identifies the distribution of stress contributions from the micro- and macro-scale based on mixed recycled content for the printing process. The development of methodological approaches allows researchers to reduce the development time and cost of mixed material optimizing experimental sets. In summary, the Table 2 summarizes the advances in the plastic recycling in the context of additive manufacturing

Table 2: Advances in Distributed Recycling for additive manufacturing

| Phases | Subcategory | Research | Focus | Reference |
|------------------|---|--|--|--|
| I | Collection | Supply chain | Closed loop, mathematical optimization | (Pavlo et al., 2018) |
| II | Identification | Recycling codes | Recycling codes, distributed manufacturing | (Hunt et al., 2015) |
| | Size reduction | Shredding equipment, pelletizer | Size distribution | (Reddy and Raju, 2018; Romero-Alva et al., 2018; Woern and Pearce, 2018) |
| III | Mono-Plastics | ABS | Tensile properties | (Czyżewski et al., 2018; Gaikwad et al., 2018) |
| | | PLA | Tensile properties | (Anderson, 2017; Cruz et al., 2015; Cruz Sanchez et al., 2017) |
| | | HDPE | Tensile, thermal, filament extrusion | (Baechler et al., 2013; Chong et al., 2017; Kreiger et al., 2013) |
| | | PET | Tensile, DMA, DSC | (Zander et al., 2018) |
| | | TPE | Thermoplastic elastomer, thermoplastic polyurethane | (Woern and Pearce, 2017) |
| | | PEF | Green polymer | (Kucherov et al., 2017) |
| | | Epoxy | 3DPRT, epoxy, tesind infusion | (Cicala et al., 2018; Zhang et al., 2018) |
| | Composites | Plastic / Plastic | Multi Material printing | (Alkadi et al., 2019; Dunnigan et al., 2018; He et al., 2020; Hu et al., 2017; R. Singh et al., 2019a; Zander et al., 2019) |
| | | Plastic / Metals | LDPE, HDPE, PA2200, Fe powder, tungsten carbide, metallic ink | (Kumar and Czekanski, 2018; Kumar et al., 2019; Pan et al., 2018; Xu et al., 2018) |
| | | Plastic / Ceramics | HDPE, nylon, bakelite, SiC/Al2O3, syntactic foams, aluminum matrix composite, thermal properties | (Boparai et al., 2016; A. K. Singh et al., 2018; N. Singh et al., 2019, 2018a, 2018b; R. Singh et al., 2019c; Singh et al., 2016) |
| Plastic / Fibers | Carbon fiber reinforced thermoplastic composites (CFRTPCs), fiberglass, Biochar, Liquid Crystal Polymer (LCP), banana fiber, natural fibres, Macadamia nutshell | (Gantenbein et al., 2018; Girdis et al., 2017; Idrees et al., 2018; Rahimizadeh et al., 2019; R. Singh et al., 2019b; Stoof and Pickering, 2018; Tian et al., 2017; Veer et al., 2017) | | |
| IV | Extrusion | Open hardware | recyclebot, energy payback time, pelletizer | (Baechler et al., 2013; Woern and Pearce, 2018; Woern et al., 2018b; Zhong et al., 2017) |
| | Secondary raw materials | Powder bed fusion to FFF | SLS, FDM, polyamide composite | (Kumar and Czekanski, 2018, 2017; Mägi et al., 2016, 2015) |
| | | Niche recycling | packaging, fiber recovery, wind turbine blades, mussel shell, military meal-ready-to-eat | (Rahimizadeh et al., 2019; Sauerwein and Doubrovski, 2018; Zander et al., 2018; Czyżewski et al., 2018; Gaikwad et al., 2018; Hart et al., 2018) |
| V | Fused granular fabrication (FGF) | Material properties | gigabot X, moineau pump, PC, ABS, PLA, PET, PP | (Canessa et al., 2017; Reich et al., 2019; Whyman et al., 2018; Woern et al., 2018a) |

| | | | | |
|----|---------------------|------------------------------|--|---|
| VI | Printed part | Large scale | HDPE, wood fibers, composites, tires wastes, economical life cycle | (Byard et al., 2019; Domingues et al., 2017; Horta et al., 2018; Keating and Oxman, 2013; Volpato et al., 2015) |
| | | Quality improvement | mechanical properties, surface finishing, melt flow index | (Cunico et al., 2019; Lanzotti et al., 2019; Sa'ude et al., 2015) |
| | | Modelling | phase averages, integrity, composite strength | (Clemon and Zohdi, 2018) |
| | Driven applications | Case studies | energy storage devices, dry cells, Humanitarian aid, eco-printing, solar, Space, In-space manufacturing (ISM), Drones, Educational, wood furniture waste-based | (Fateri et al., 2018; Jaksic, 2016; Mohammed et al., 2018a, 2018b; Mosaddek et al., 2018; Pringle et al., 2017; R. Singh et al., 2019d; Zhong and Pearce, 2018) |
| | Environmental | Life cycles assessment tools | LCA, distributed recycling & | (Gaikwad et al., 2018; Kreiger et al., 2013, 2014; Kreiger and Pearce, 2013; Zhao et al., 2018) |
| | | Recycling methodologies | cradle to cradle, thermo-mechanical recycling | (Chong et al., 2015; Cruz Sanchez et al., 2017) |
| | Economical | Life-cycle economic | costs, ROI | (Byard et al., 2019; Petersen et al., 2017; Wittbrodt et al., 2013) |
| | | Entrepreneurial | Business Model, circular economy, industry 4.0, service design | (Nascimento et al., 2019; Petruzzi et al., 2017; Wittbrodt et al., 2013) |
| | Social | Barriers and opportunities | disruptive technology , technological innovation | (Garmulewicz et al., 2018; Peeters et al., 2019) |
| | | Material | intellectual property, open source materials | (Pearce, 2015; Ramakrishna et al., 2019) |
| | | Faire trade | ethical product, fair trade standards & | (Feeley et al., 2014) |
| | | Recycling demonstrators | Solar Energy, green manufacturing, educational, mini-factory | (Heyer et al., 2014; King et al., 2014; Lee et al., 2019; Mohammed, Wilson, Gomez-Kervin, et al., 2018; Muschard and Seliger, 2015; Radharamanan, 2011) |

5. Discussion of the results

The purpose of this research is to make a systematic review of the literature on thermoplastic recycling within the context of additive manufacturing. Figures 6 and 7 summarize the obtained results, from these it appears clearly that:

- There is a growing interest for DRAM initiatives, as 92 papers were registered in the last decade coming from a diverse variety of research teams (Figure 6).
- Although significant advances have been achieved on the Compounding and Printing stages, in order to develop DRAM initiatives, more efforts should be devoted by the research community to the Recovery and Preparation stages.
- Technical aspects are the most addressed, as 71 papers out of 92 treat the technical dimension. At the same time, Environmental (22), Economical (16) and social (13), are sustainability dimensions that are still to be further developed.
- In order to achieve this, there is a need for a holistic view and multiple competencies and points of view are needed. 28 papers were registered having a global vision of the DRAM initiative.

In that follows, the current advances in the field for each stage within the recycling process from Figure 4 and the deep analysis of the papers reported in appendix A. To make easy this analysis will be divided into three main aspects: 1) preparation of the recycled material at local level, (2) the printing process chain and use, and finally (3) the opportunities of open source to foster distributed recycling in the circular economy context.

5.1. Pre-treatment of the recycled material at local level

The distributed recycling via additive manufacturing activity could emerge mainly as local user-driven initiatives (Feeley et al., 2014) and the recycling network is not necessarily as a formal structured industrial supply chain sector (Santander et al., 2020). Therefore, the recovery stage and the definition of pre-treatment conditions (discarding, identification, separation, sorting, cleaning, size reduction and drying) remains an important point to improve the readiness and effectiveness of the technical conditions required at a local level. The adequation process is more efficient when

processed in small volumes from sectors which produce homogeneous waste streams (Karlsson, 2004), reducing the costs associated with sorting and cleaning (Hopewell et al., 2009) given the complexities when the waste is mixed with other materials (Signoret et al., 2019). Nascimento et al. (2019) stated that the technologies of the industry 4.0 can help to identify and collect waste in the frame of a circular smart production system model. Indeed, the role materials informatics can play an important role in order to achieve high-speed and robust acquisition, management, multi-factor analyses, and dissemination of diverse recycled materials data (Ramakrishna et al., 2019), and to assist in the development and protection from ‘intellectual property tragedy’ of the public domain materials for low-cost open source 3D printers (Pearce, 2015). In the reviewed literature, several studies choose a particular waste source or type of plastic waste in the recyclability analysis. The remaining question is how to evaluate a particular waste source or niche, defining qualitative indicators (Horta Arduin et al., 2020) that allows practitioners to choose materials that can be printable. A systematic analysis to qualify possible mono-stream waste sources is unclear from the evidence of the reviewed studies. For example, in the case of recycling of waste electrical and electronic equipment, the “Internet + WEEE collection” platforms are strategies to collect that are receiving attention from business ecosystems (Jian et al., 2019; Sun et al., 2020). Also, data-driven frameworks (Jiang et al., 2020) with internet of things and data mining technologies could be explorative approaches to implement for distributed recycling. There are research opportunities to develop optical sensors at both industrial and small-scales to improve the sorting of wastes (Signoret et al., 2019). The development of ex-ante methodologies and tools of analysis to clarify the potential of the landfill reduction is a research path to further improve the distributed recycling process.

The other critical point concerns the sorting and cleaning process to promote distributed recycling. From the selected literature, it is not clear how the cleaning process should be made at local level and under which conditions is technical and economically feasible. The appropriate decontamination is important because of the toxic pollutants present in the plastic wastes (Picuno et al., 2020; Verma et al., 2016). The decontamination step needs to be framed in terms of occupational safety, health risks and testing protocols that could reduce harmful fumes in the feedstock fabrication (filament or pellets) testing procedures is required in distributed recycling (Feeley et al., 2014). Also, the development of small sorting technologies (Rani et al., 2019) are needed to be integrated in the recycling chain for DRAM. If the recycling process is developed as community-based initiatives (Diehl et al., 2018; Mohammed et al., 2018a), the technological development should be focused on the characterisation of separated and commingled plastic fractions using quick, reliable and relatively cheap methods (Karlsson, 2004).

On the other hand, the use of life cycle assessment tools demonstrated the environmental advantage of distributed recycling network to process post-consumer goods into 3D printing feedstock because of lower embodied energy than both virgin and conventionally recycled materials (Baechler et al., 2013; Kreiger et al., 2013, 2014; Kreiger and Pearce, 2013; Pavlo et al., 2018). It was argued that the trend reversal from large-scale and centralized approaches towards local manufacturing and recycling was economically advantageous (Gwamuri et al., 2014). Nevertheless, more work is needed in the definition of the local scale (e.g. house, building, neighborhood), the structural facilities required (Pavlo et al., 2018), and the stakeholders to involve clarifying the conditions to implement recycling networks. For instance, innovation spaces such as fablabs were identified as possible actors to participate as recycling hubs for a community (Byard et al., 2019; Peeters et al., 2019). However, due to the economical and quality issues in the preparation phase, it remains uncertain the economical advantages (Peeters et al., 2019). The modeling of closed-loop approaches might also contribute to identify the required infrastructural and organizacionales elements to viabilize a sustainable recycling operation (Santander et al., 2020).

5.2. Printing process chain and use of the recycled parts

The technical validation of the use of recycled material in the printing process chain has been the main research focus from the reviewed papers. The thermo-mechanical simulation to create recycled filament (virgin or composite) is until now the common place that studies have characterized the recyclability process. Both mono- and composite-materials prove the advances in this area. A technical path to complete the recycling evaluation is to detail at molecular level the

degradative mechanisms through the thermo-oxidation recycling process (Tröger et al., 2008). Modelling the oxidative degradation under different environmental conditions enables determinate polymer thermal aging, the sensitivity to the attacking environment and consequently the lifetime of the recycled printed object (Karlsson, 2004; Vilaplana and Karlsson, 2008).

However, the question that remains unclear is about the willingness by users to use recycled 3D objects and eventually to become 'prosumers' in the recycling process (Kreiger et al., 2014). Educational courses on distributed recycling are perceived as a means to encourage students to think about the access to the digital manufacturing capabilities and their sustainability-related issues (Jaksic, 2016; Schelly and Pearce, 2019). Moreover, the examples of consumer objects as furniture (Pringle et al., 2017), drones (Mosaddek et al., 2018), or local manufacturing and recycling demonstrators (Heyer et al., 2014; Muschard and Seliger, 2015) could improve the lack of awareness of the value of recycled materials (Garmulewicz et al., 2018). There are economic advantages of using recycled printed products. For instance, Petersen et al. (2017) proved that the cost to fabricate a Lego block could be reduced from 6 cents/block to about 0.5 cents per block. In the toy market, the reduction for final users can range between 75%-90% under the condition that open source design files remain available. For larger products, the use of FGF proved large high-value sporting goods products (e.g. snowshoes) only in the extreme case of producing only 1 per week was not economic. The ROI for all other capacity factors ranged from 10 to 240% without including labor (Byard et al., 2019).

The drivers for adoption of recycled printed products relies on the domain of technology and cost of usage, including the decrease in the cost of open source 3D printers and its feedstock along with the increase in the number and quality of free designs (Rayna and Striukova, 2016). Nevertheless, beyond the pure technical aspects of the 3D printing domain, the deepest barrier for the use of recycled products relies on societal consumption (linear economy) and the high quality demand from consumers (Peeters et al., 2019). From a systemic perspective, the plastic waste issue is beyond the consumer side and the responsibility needs to include the extraction and production stakeholders (Conlon, 2020). Thus, one key element to redefine the definition of waste in a global sense (Ewijk and Stegemann, 2020). The legal framework is a missing aspect that was not found in the reviewed literature. Therefore research on the creation of minimal standards that need to be met to validate a recycled product.

5.3. Open source as a driver to foster distributed recycling for circular economy purposes

Open source is one factor that has contributed to foster the adoption of additive manufacturing for a larger public than industrial and research laboratories (Beltagui et al., 2019, 2020; Raasch et al., 2009). In that sense, it is suggested that the open source could be a driver to foster also for the recycling process, reducing the costs to create technology for the pre-treatment stage, which at the end will be a driver for the circular economy. The development of open hardware scientific equipment is getting attention thanks to the high profit/cost ratio guaranteeing a technical performance equal or superior to traditionally manufactured equipment (Pearce, 2017b). The integration of open source hardware development within traditional education systems opens up possibilities in both pedagogical and research aspects (Irwin et al., 2014). The development of digital manufacturing capabilities, electronics and free software, creates a whole ecosystem that allows designers to move from conceptual prototypes to functional prototypes at a reduced cost (Pearce, 2014).

There have been several studies in the scientific literature about the definition (Korhonen et al., 2018a, 2018b), key elements (Ghisellini et al., 2016) and the scope (Geissdoerfer et al., 2017) of the circular economy concept in the scientific and business literature. Cramer (2018) identified that four conditions need to be met in order to use high grade recycling in the circular economy framework: 1) an adequate collection system and logistics; 2) guaranteed volumes of supply; 3) market demand for recycled materials; and 4) quality guarantee of recycled materials. Based on the definition of the circular economy concept proposed by (Kirchherr et al., 2017), the potential research opportunities for DRAM driving the circular economy at the:

Micro level:

- Development of low-cost, free and open source, digitally manufactured (ideally from recycled waste) tools to enable distributed DRAM including: scientific tools to enable grading and typing recycled waste plastic, tools for separating materials, shredding them, and improvements on the existing tools to either produce waste plastic filament or directly 3D print waste plastic.
- Development of novel waste based composites that involve material characterization, as well as life cycle economic and environmental assessments of DRAM.
- Develop applications of these new DRAM waste material composites and markets for these applications.

Meso level:

- Finalize complete closed loop DRAM case studies based on material and location to demonstrate technical, ecological and economic feasibility.
- Develop business models that can fabricate and sell these DRAM tools, their kits or components as well as services around calibrating, using and maintaining them.
- Develop paths to enable existing recycling organizations and businesses to convert to these new DRAM-focused business models.

Macro level:

- Develop policies to provide incentives for the open source development (Heikkinen et al., 2020) for these paths for DRAM .
- Development of educational materials, curricula, public service announcements, and school programs to implement DRAM in public and private schools, community centers, maker/hackerspaces and fablabs, and religious communities.
- Develop means to disrupt fossil-fuel based plastic markets by offsetting materials with DRAM based products.

6. Conclusions and perspectives

In this article, a systematic literature review was performed in order to map the advances in the plastic recycling for additive manufacturing. A framework using 6 main stages (recovery, preparation, compounding, feedstock, printing, quality) was proposed in order to identify the global value chain of the distributed recycling via additive manufacturing approach.

Based on the results, it is concluded that the recovery and preparation stages are less studied. Research efforts need to be taken in the pre-treatment of the recycled material, including efficient models to collect waste material, technology and methodologies to develop quality indicators of the waste material. Then, based on these indicators, strategies of local cleaning and sorting process could be potential opportunities to promote. Thus, a systematic definition of the process to perform for cleaning, sorting and size reduction including quality indicators for each of them is a major research path. In addition, it is important to identify sectors which produce homogeneous waste streams and that are feasible to collect are important with the purpose to connect particular niche waste with potential applications with add value thanks to the 3D printing advantages.

On the other hand, it was observed that a big amount of work has already been done in the scientific community in order to validate the technical feasibility at compounding, feedstock and printing stages for numerous mono and composites-materials based on recycled assets. This is explained by the fact that the structural and feasibility of production assessment levels are well documented in the literature. Nevertheless, to maximise the potential of distributing recycling, attention should be focused on the willingness to use recycled 3D objects. Several driven applications of waste material were found including furniture, toys. The validation of DRAM needs to continue to show the usefulness of

recycled printed parts. However, the research on the creation of minimal standards and legal framework are major elements to validate.

Finally, we have proposed different future research paths at the micro, meso and macro level to better understand the connections between circular economy and distributing recycling to reach the full potential. The establishment of such links can aid in the development of technical, social and economical aspects fostering waste management policies to improve the closed and open loop recycling. Moreover, it is relevant to the development of each stage proposed in this review in order to scale the acceptability of DRAM to reach the full technical potential as a masterpiece of the circular economy. Research focused on the recyclability of conventional thermoset plastics is a future perspective in order to increase the scope of the DRAM approach for CE.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869952 and by the french PIA project « Lorraine Université d'Excellence », reference ANR-15-IDEX-04-LUE »

References

- Alkadi, F., Lee, J., Yeo, J.-S., Hwang, S.-H., Choi, J.-W., 2019. 3D Printing of Ground Tire Rubber Composites. *Int. J. Precis. Eng. Manuf. Technol.* 6, 211–222. <https://doi.org/10.1007/s40684-019-00023-6>
- Al-Salem, S., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Manag.* 29, 2625–2643. <https://doi.org/10.1016/j.wasman.2009.06.004>
- Anderson, I., 2017. Mechanical Properties of Specimens 3D Printed with Virgin and Recycled Polylactic Acid. *3D Print. Addit. Manuf.* 4, 110–115. <https://doi.org/10.1089/3dp.2016.0054>
- Arena, U., Mastellone, M.L., Perugini, F., 2003. Life Cycle assessment of a plastic packaging recycling system. *Int. J. Life Cycle Assess.* 8, 92–98. <https://doi.org/10.1007/BF02978432>
- ASTM 52900, 2015. Standard Terminology for Additive Manufacturing – General Principles – Terminology. *ASTM Int.* i, 1–9. <https://doi.org/10.1520/F2792-12A.2>
- Azimi, P., Zhao, D., Pouzet, C., Crain, N.E., Stephens, B., 2016. Emissions of Ultrafine Particles and Volatile Organic Compounds from Commercially Available Desktop Three-Dimensional Printers with Multiple Filaments. *Environ. Sci. Technol.* 50, 1260–1268. <https://doi.org/10.1021/acs.est.5b04983>
- Badia, J., Ribes-Greus, A., 2016. Mechanical recycling of polylactide, upgrading trends and combination of valorization techniques. *Eur. Polym. J.* 84, 22–39. <https://doi.org/10.1016/j.eurpolymj.2016.09.005>
- Baechler, C., DeVuono, M., Pearce, J.M., 2013. Distributed recycling of waste polymer into RepRap feedstock. *Rapid Prototyp. J.* 19, 118–125. <https://doi.org/10.1108/13552541311302978>
- Bank, P., 2020. The Plastic Bank. <https://plasticbank.com/who-we-are/> (accessed 13 March 2020).

- Baumers, M., Tuck, C., Bourell, D.L., Sreenivasan, R., Hague, R., 2011. Sustainability of additive manufacturing: measuring the energy consumption of the laser sintering process. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* 225, 2228–2239. <https://doi.org/10.1177/0954405411406044>
- Beltagui, A., Kunz, N., Gold, S., 2019. The role of 3D printing and open design on adoption of socially sustainable supply chain innovation. *Int. J. Prod. Econ.* 1–16. <https://doi.org/10.1016/j.ijpe.2019.07.035>
- Beltagui, A., Rosli, A., Candi, M., 2020. Exaptation in a digital innovation ecosystem: The disruptive impacts of 3D printing. *Res. Policy* 49, 103833. <https://doi.org/10.1016/j.respol.2019.103833>
- Birtchnell, T., Urry, J., 2013. 3D, SF and the future. *Futures* 50, 25–34. <https://doi.org/10.1016/j.futures.2013.03.005>
- Blomsma, F., 2018. Collective ‘action recipes’ in a circular economy – On waste and resource management frameworks and their role in collective change. *J. Clean. Prod.* 199, 969–982. <https://doi.org/10.1016/j.jclepro.2018.07.145>
- Bonnín Roca, J., Vaishnav, P., Laureijs, R.E., Mendonça, J., Fuchs, E.R., 2019. Technology cost drivers for a potential transition to decentralized manufacturing. *Addit. Manuf.* 28, 136–151. <https://doi.org/10.1016/j.addma.2019.04.010>
- Boparai, K., Singh, R., Fabbrocino, F., Fraternali, F., 2016. Thermal characterization of recycled polymer for additive manufacturing applications. *Compos. Part B Eng.* 106, 42–47. <https://doi.org/10.1016/j.compositesb.2016.09.009>
- Bose, S., Vahabzadeh, S., Bandyopadhyay, A., 2013. Bone tissue engineering using 3D printing. *Mater. Today* 16, 496–504. <https://doi.org/10.1016/j.mattod.2013.11.017>
- Bourell, D., Kruth, J.P., Leu, M., Levy, G., Rosen, D., Beese, A.M., Clare, A., 2017. Materials for additive manufacturing. *CIRP Ann.* 66, 659–681. <https://doi.org/10.1016/j.cirp.2017.05.009>
- Bourhis, F.L., Kerbrat, O., Hascoet, J.-Y., Mognol, P., 2013. Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing. *Int. J. Adv. Manuf. Technol.* 69, 1927–1939. <https://doi.org/10.1007/s00170-013-5151-2>
- Braanker, G.B., Flohil, J.J., Tokaya, G.E., 2010. Developing a plastics recycling add-on for the RepRap 3D printer (PhD thesis). Delft University of Technology.
- Brenken, B., Barocio, E., Favaloro, A., Kunc, V., Pipes, R.B., 2018. Fused filament fabrication of fiber-reinforced polymers: A review. *Addit. Manuf.* 21, 1–16. <https://doi.org/10.1016/j.addma.2018.01.002>
- Brooks, A.L., Wang, S., Jambeck, J.R., 2018. The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* 4, eaat0131. <https://doi.org/10.1126/sciadv.aat0131>
- Budgen, D., Brereton, P., 2006. Performing systematic literature reviews in software engineering, in: *Proceeding 28th Int. Conf. Softw. Eng. - Icse '06*. ACM Press, New York, New York, USA, p. 1051. <https://doi.org/10.1145/1134285.1134500>
- Buitenhuis, A.J., Zelenika, I., Pearce, J., 2010. Open Design-Based Strategies to Enhance Appropriate Technology Development, in: *Proc. 14th Annu. Natl. Coll. Invent. Innov. Alliance Conf. Open*. pp. 1–12.
- Buren, N. van, Demmers, M., Heijden, R. van der, Witlox, F., 2016. Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments. *Sustainability* 8, 647. <https://doi.org/10.3390/su8070647>

- Byard, D.J., Woern, A.L., Oakley, R.B., Fiedler, M.J., Snabes, S.L., Pearce, J.M., 2019. Green fab lab applications of large-area waste polymer-based additive manufacturing. *Addit. Manuf.* 27, 515–525. <https://doi.org/10.1016/j.addma.2019.03.006>
- Canessa, E., Baruzzo, M., Fonda, C., 2017. Study of Moineau-based pumps for the volumetric extrusion of pellets. *Addit. Manuf.* 17, 143–150. <https://doi.org/10.1016/j.addma.2017.08.015>
- Carneiro, O., Silva, A., Gomes, R., 2015. Fused deposition modeling with polypropylene. *Mater. Des.* 83, 768–776. <https://doi.org/10.1016/j.matdes.2015.06.053>
- Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J.G., Thiede, S., 2015. Direct digital manufacturing: definition, evolution, and sustainability implications. *J. Clean. Prod.* 107, 615–625. <https://doi.org/10.1016/j.jclepro.2015.05.009>
- Chen, L., He, Y., Yang, Y., Niu, S., Ren, H., 2017. The research status and development trend of additive manufacturing technology. *Int. J. Adv. Manuf. Technol.* 89, 3651–3660. <https://doi.org/10.1007/s00170-016-9335-4>
- Chong, S., Chiu, H.-L., Liao, Y.-C., Hung, S.-T., Pan, G.-T., 2015. Cradle to Cradle Design for 3D Printing. *Chem. Eng. Trans.* 45, 1669–1674. <https://doi.org/10.3303/CET1545279>
- Chong, S., Pan, G.-T., Khalid, M., Yang, T.C., Hung, S.-T., Huang, C.-M., 2017. Physical Characterization and Pre-assessment of Recycled High-Density Polyethylene as 3D Printing Material. *J. Polym. Environ.* 25, 136–145. <https://doi.org/10.1007/s10924-016-0793-4>
- Cicala, G., Pergolizzi, E., Piscopo, F., Carbone, D., Recca, G., 2018. Hybrid composites manufactured by resin infusion with a fully recyclable bioepoxy resin. *Compos. Part B Eng.* 132, 69–76. <https://doi.org/10.1016/j.compositesb.2017.08.015>
- Clemon, L., Zohdi, T., 2018. On the tolerable limits of granulated recycled material additives to maintain structural integrity. *Constr. Build. Mater.* 167, 846–852. <https://doi.org/10.1016/j.conbuildmat.2018.02.099>
- Clift, R., 1997. Overview Clean Technology—The Idea and the Practice*. *J. Chem. Technol. Biotechnol.* 68, 347–350. [https://doi.org/10.1002/\(SICI\)1097-4660\(199704\)68:4<347::AID-JCTB667>3.0.CO;2-L](https://doi.org/10.1002/(SICI)1097-4660(199704)68:4<347::AID-JCTB667>3.0.CO;2-L)
- Clift, R., Druckman, A., 2016. Taking Stock of Industrial Ecology. <https://doi.org/10.1007/978-3-319-20571-7>
- Conlon, K., 2020. Adaptive injustice: Responsibility to act in the plastics economy. *Resour. Conserv. Recycl.* 153, 104563. <https://doi.org/10.1016/j.resconrec.2019.104563>
- Craighill, A.L., Powell, J.C., 1996. Lifecycle assessment and economic evaluation of recycling: A case study. *Resour. Conserv. Recycl.* 17, 75–96. [https://doi.org/10.1016/0921-3449\(96\)01105-6](https://doi.org/10.1016/0921-3449(96)01105-6)
- Cramer, J., 2018. Key Drivers for High-Grade Recycling under Constrained Conditions. *Recycling* 3, 16. <https://doi.org/10.3390/recycling3020016>
- Cruz, F., Lanza, S., Boudaoud, H., Hoppe, S., Camargo, M., 2015. Polymer Recycling and Additive Manufacturing in an Open Source context : Optimization of processes and methods, in: *Solid Free. Fabr.* Austin, Texas, pp. 1591–1600.
- Cruz Sanchez, F.A., Boudaoud, H., Hoppe, S., Camargo, M., 2017. Polymer recycling in an open-source additive manufacturing context: Mechanical issues. *Addit. Manuf.* 17, 87–105. <https://doi.org/10.1016/j.addma.2017.05.013>

- Cruz Sanchez, F.A., Boudaoud, H., Muller, L., Camargo, M., 2014. Towards a standard experimental protocol for open source additive manufacturing. *Virtual Phys. Prototyp.* 9, 151–167. <https://doi.org/10.1080/17452759.2014.919553>
- Culmone, C., Smit, G., Breedveld, P., 2019. Additive manufacturing of medical instruments: A state-of-the-art review. *Addit. Manuf.* 27, 461–473. <https://doi.org/10.1016/j.addma.2019.03.015>
- Cunico, M.W.M., Kai, D.A., Cavalheiro, P.M., Carvalho, J. de, 2019. Development and characterisation of 3D printing finishing process applying recycled plastic waste. *Virtual Phys. Prototyp.* 14, 37–52. <https://doi.org/10.1080/17452759.2018.1521248>
- Curtzwiler, G.W., Schweitzer, M., Li, Y., Jiang, S., Vorst, K.L., 2019. Mixed post-consumer recycled polyolefins as a property tuning material for virgin polypropylene. *J. Clean. Prod.* 239, 117978. <https://doi.org/10.1016/j.jclepro.2019.117978>
- Czyżewski, P., Bieliński, M., Sykutera, D., Jurek, M., Gronowski, M., Ryl, Ł., Hoppe, H., 2018. Secondary use of ABS co-polymer recyclates for the manufacture of structural elements using the FFF technology. *Rapid Prototyp. J.* 24, 1447–1454. <https://doi.org/10.1108/RPJ-03-2017-0042>
- Data, R.A., 2019. Additive Manufacturing Market To Reach USD 23.33 Billion By 2026. <http://www.globenewswire.com/news-release/2019/03/18/1756526/0/en/Additive-Manufacturing-Market-To-Rreach-US-D-23-33-Billion-By-2026.html> (accessed 13 August 2019).
- Dertinger, S.C., Gallup, N., Tanikella, N.G., Grasso, M., Vahid, S., Foot, P.J., Pearce, J.M., 2020. Technical pathways for distributed recycling of polymer composites for distributed manufacturing: Windshield wiper blades. *Resour. Conserv. Recycl.* 157, 104810. <https://doi.org/10.1016/j.resconrec.2020.104810>
- Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S., Garmulewicz, A., Knowles, S., Minshall, T., Mortara, L., Reed-Tsochas, F., Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: A research agenda. *Technol. Forecast. Soc. Change* 115, 75–84. <https://doi.org/10.1016/j.techfore.2016.09.021>
- Diehl, J.-C., Stroober, M., Majumdar, P., Mink, A., 2018. Do-it-Yourself (DIY) Workspaces Run by Local Entrepreneurs that Transform Plastic Waste Into Valuable Water and Sanitation Products, in: 2018 IEEE Glob. Humanit. Technol. Conf. IEEE, pp. 1–8. <https://doi.org/10.1109/GHTC.2018.8601880>
- Dizon, J.R.C., Espera, A.H., Chen, Q., Advincula, R.C., 2018. Mechanical characterization of 3D-printed polymers. *Addit. Manuf.* 20, 44–67. <https://doi.org/10.1016/j.addma.2017.12.002>
- Domingues, J., Marques, T., Mateus, A., Carreira, P., Malça, C., 2017. An Additive Manufacturing Solution to Produce Big Green Parts from Tires and Recycled Plastics. *Procedia Manuf.* 12, 242–248. <https://doi.org/10.1016/j.promfg.2017.08.028>
- Drizo, A., Pegna, J., 2006. Environmental impacts of rapid prototyping: an overview of research to date. *Rapid Prototyp. J.* 12, 64–71. <https://doi.org/10.1108/13552540610652393>
- Dunnigan, R., Clemens, J., Cavalli, M.N., Kaabouch, N., Gupta, S., 2018. Beneficial usage of recycled polymer particulates for designing novel 3D printed composites. *Prog. Addit. Manuf.* 3, 33–38. <https://doi.org/10.1007/s40964-018-0046-2>

European Commission, 2015. Summary for Policymakers, in: Intergovernmental Panel on Climate Change (Ed.), *Clim. Chang.* 2013 - Phys. Sci. Basis. Cambridge University Press, Cambridge, pp. 1–30. <https://doi.org/10.1017/CBO9781107415324.004>

European Commission, 2018. A European strategy for plastics in a circular economy, COM (2018). Brussels. <https://doi.org/10.1021/acs.est.7b02368>

Ewijk, S. van, Stegemann, J.A., 2020. Recognising waste use potential to achieve a circular economy. *Waste Manag.* 105, 1–7. <https://doi.org/10.1016/j.wasman.2020.01.019>

Fateri, M., Kaouk, A., Cowley, A., Siarov, S., Palou, M.V., González, F.G., Marchant, R., Cristoforetti, S., Sperl, M., 2018. Feasibility study on additive manufacturing of recyclable objects for space applications. *Addit. Manuf.* 24, 400–404. <https://doi.org/10.1016/j.addma.2018.09.020>

Feeley, S.R., Wijnen, B., Pearce, J.M., 2014. Evaluation of Potential Fair Trade Standards for an Ethical 3-D Printing Filament. *J. Sustain. Dev.* 7, 1–12. <https://doi.org/10.5539/jsd.v7n5p1>

Filabot, 2012. Filament Maker – Filabot . <http://www.filabot.com/> (accessed 13 March 2020).

Fisher, M.M., 2004. Plastics Recycling, in: *Plast. Environ.* John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 563–627. <https://doi.org/10.1002/0471721557.ch14>

Ford, S., Despeisse, M., 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *J. Clean. Prod.* 137, 1573–1587. <https://doi.org/10.1016/j.jclepro.2016.04.150>

Fox, S., 2014. Third Wave Do-It-Yourself (DIY): Potential for prosumption, innovation, and entrepreneurship by local populations in regions without industrial manufacturing infrastructure. *Technol. Soc.* 39, 18–30. <https://doi.org/10.1016/j.techsoc.2014.07.001>

Freitas, D., Almeida, H.A., Bártolo, H., Bártolo, P.J., 2016. Sustainability in extrusion-based additive manufacturing technologies. *Prog. Addit. Manuf.* 1, 65–78. <https://doi.org/10.1007/s40964-016-0007-6>

Gaikwad, V., Ghose, A., Cholake, S., Rawal, A., Iwato, M., Sahajwalla, V., 2018. Transformation of E-Waste Plastics into Sustainable Filaments for 3D Printing. *ACS Sustain. Chem. Eng.* 6, 14432–14440. <https://doi.org/10.1021/acssuschemeng.8b03105>

Gantenbein, S., Masania, K., Woigk, W., Sesseg, J.P.W., Tervoort, T.A., Studart, A.R., 2018. Three-dimensional printing of hierarchical liquid-crystal-polymer structures. *Nature* 561, 226–230. <https://doi.org/10.1038/s41586-018-0474-7>

Garmulewicz, A., Holweg, M., Veldhuis, H., Yang, A., 2018. Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold? *Calif. Manage. Rev.* 60, 112–132. <https://doi.org/10.1177/0008125617752695>

Geissdoerfer, M., Savaget, P., Bocken, N.M., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. <https://doi.org/10.1016/j.jclepro.2015.09.007>

- Gibson, I., Rosen, D.W., Stucker, B., 2010. Additive Manufacturing Technologies. Springer US, Boston, MA. <https://doi.org/10.1007/978-1-4419-1120-9>
- Girdis, J., Gaudion, L., Proust, G., Löschke, S., Dong, A., 2017. Rethinking Timber: Investigation into the Use of Waste Macadamia Nut Shells for Additive Manufacturing. *JOM* 69, 575–579. <https://doi.org/10.1007/s11837-016-2213-6>
- Goyanes, A., Buanz, A.B., Basit, A.W., Gaisford, S., 2014. Fused-filament 3D printing (3DP) for fabrication of tablets. *Int. J. Pharm.* 476, 88–92. <https://doi.org/10.1016/j.ijpharm.2014.09.044>
- Guo, N., Leu, M.C., 2013. Additive manufacturing: technology, applications and research needs. *Front. Mech. Eng.* 8, 215–243. <https://doi.org/10.1007/s11465-013-0248-8>
- Gwamuri, J., Wittbrodt, B.T., Anzalone, N.C., Pearce, J.M., 2014. Reversing the Trend of Large Scale and Centralization in Manufacturing: The Case of Distributed Manufacturing of Customizable 3-D-Printable Self-Adjustable Glasses. *Challenges Sustain.* 2, 30–40. <https://doi.org/10.12924/cis2014.02010030>
- Hahladakis, J.N., Iacovidou, E., 2018. Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity? *Sci. Total Environ.* 630, 1394–1400. <https://doi.org/10.1016/j.scitotenv.2018.02.330>
- Hakkens, D., 2016. Precious Plastic. <http://preciousplastic.com/> (accessed 14 March 2020)
- Hart, K.R., Frketic, J.B., Brown, J.R., 2018. Recycling meal-ready-to-eat (MRE) pouches into polymer filament for material extrusion additive manufacturing. *Addit. Manuf.* 21, 536–543. <https://doi.org/10.1016/j.addma.2018.04.011>
- He, H., Zhan, Z., Zhu, Z., Xue, B., Li, J., Chen, M., Wang, G., 2020. Microscopic morphology, rheological behavior, and mechanical properties of polymers: Recycled acrylonitrile-butadiene-styrene/polybutylene terephthalate blends. *J. Appl. Polym. Sci.* 137, 48310. <https://doi.org/10.1002/app.48310>
- Hebda, M., McIlroy, C., Whiteside, B., Caton-Rose, F., Coates, P., 2019. A method for predicting geometric characteristics of polymer deposition during fused-filament-fabrication. *Addit. Manuf.* 27, 99–108. <https://doi.org/10.1016/j.addma.2019.02.013>
- Heikkinen, I., Savin, H., Partanen, J., Seppälä, J., Pearce, J., 2020. Towards national policy for open source hardware research: The case of Finland. *Technol. Forecast. Soc. Change* 155, 119986. <https://doi.org/10.1016/j.techfore.2020.119986>
- Hennlock, M., Castell-Rüdenhausen, M. zu, Wahlström, M., Kjær, B., Milios, L., Veia, E., Watson, D., Hanssen, O.J., Fråne, A., Stenmarc, Å., Tekie, H., 2015. Economic policy instruments for plastic waste, TemaNord. Nordic Council of Ministers. <https://doi.org/10.6027/TN2014-569>
- Herzberger, J., Serrine, J.M., Williams, C.B., Long, T.E., 2019. Polymer Design for 3D Printing Elastomers: Recent Advances in Structure, Properties, and Printing. *Prog. Polym. Sci.* 97, 101144. <https://doi.org/10.1016/j.progpolymsci.2019.101144>
- Heyer, S., Nishino, N., Muschard, B., Seliger, G., 2014. Enabling of local value creation via openness for emergent synthesis. *Int. J. Precis. Eng. Manuf.* 15, 1489–1493. <https://doi.org/10.1007/s12541-014-0496-5>
- Hienerth, C., Hippel, E. von, Berg Jensen, M., 2014. User community vs. producer innovation development efficiency: A first empirical study. *Res. Policy* 43, 190–201. <https://doi.org/10.1016/j.respol.2013.07.010>
- Hippel, E.A. von, 2005. Democratizing innovation: The evolving phenomenon of user innovation. MIT Press.

- Hofstätter, T., Pedersen, D.B., Tosello, G., Hansen, H.N., 2017. State-of-the-art of fiber-reinforced polymers in additive manufacturing technologies. *J. Reinf. Plast. Compos.* 36, 1061–1073. <https://doi.org/10.1177/0731684417695648>
- Holmström, J., Holweg, M., Khajavi, S.H., Partanen, J., 2016. The direct digital manufacturing (r)evolution: definition of a research agenda. *Oper. Manag. Res.* 9, 1–10. <https://doi.org/10.1007/s12063-016-0106-z>
- Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 2115–2126. <https://doi.org/10.1098/rstb.2008.0311>
- Horta, J.F., Simões, F.J.P., Mateus, A., 2018. Large scale additive manufacturing of eco-composites. *Int. J. Mater. Form.* 11, 375–380. <https://doi.org/10.1007/s12289-017-1364-5>
- Horta Arduin, R., Mathieux, F., Huisman, J., Blengini, G.A., Charbuillet, C., Wagner, M., Baldé, C.P., Perry, N., 2020. Novel indicators to better monitor the collection and recovery of (critical) raw materials in WEEE: Focus on screens. *Resour. Conserv. Recycl.* 157, 104772. <https://doi.org/10.1016/j.resconrec.2020.104772>
- Horvath, B., Mallinguh, E., Fogarassy, C., 2018. Designing Business Solutions for Plastic Waste Management to Enhance Circular Transitions in Kenya. *Sustainability* 10, 1664. <https://doi.org/10.3390/su10051664>
- Hu, X., Kang, H., Li, Y., Geng, Y., Wang, R., Zhang, L., 2017. Preparation, morphology and superior performances of biobased thermoplastic elastomer by in situ dynamical vulcanization for 3D-printed materials. *Polymer (Guildf)*. 108, 11–20. <https://doi.org/10.1016/j.polymer.2016.11.045>
- Hunt, E.J., Zhang, C., Anzalone, N., Pearce, J.M., 2015. Polymer recycling codes for distributed manufacturing with 3-D printers. *Resour. Conserv. Recycl.* 97, 24–30. <https://doi.org/10.1016/j.resconrec.2015.02.004>
- Iacovidou, E., Velenturf, A.P., Purnell, P., 2019. Quality of resources: A typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example. *Sci. Total Environ.* 647, 441–448. <https://doi.org/10.1016/j.scitotenv.2018.07.344>
- Idrees, M., Jeelani, S., Rangari, V., 2018. Three-Dimensional-Printed Sustainable Biochar-Recycled PET Composites. *ACS Sustain. Chem. Eng.* 6, 13940–13948. <https://doi.org/10.1021/acssuschemeng.8b02283>
- Irwin, J.L., Pearce, J.M., OppligerDouglas, Anzalone, G., 2014. The RepRap 3-D Printer Revolution in STEM Education, in: 121st Asee Annu. Conf. Expo. Indianapolis, IN.
- Jaksic, N., 2016. Sustainable Undergraduate Engineering 3-D Printing Lab, in: 2016 Asee Annu. Conf. Expo. Proc. ASEE Conferences, p. p.25992. <https://doi.org/10.18260/p.25992>
- Jasiuk, I., Abueidda, D.W., Kozuch, C., Pang, S., Su, F.Y., McKittrick, J., 2018. An Overview on Additive Manufacturing of Polymers. *JOM* 70, 275–283. <https://doi.org/10.1007/s11837-017-2730-y>
- Jian, H., Xu, M., Zhou, L., 2019. Collaborative collection effort strategies based on the “Internet + recycling” business model. *J. Clean. Prod.* 241, 118120. <https://doi.org/10.1016/j.jclepro.2019.118120>
- Jiang, P., Fan, Y.V., Zhou, J., Zheng, M., Liu, X., Klemeš, J.J., 2020. Data-driven analytical framework for waste-dumping behaviour analysis to facilitate policy regulations. *Waste Manag.* 103, 285–295. <https://doi.org/10.1016/j.wasman.2019.12.041>

- Jiang, R., Kleer, R., Piller, F.T., 2017. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technol. Forecast. Soc. Change* 117, 84–97. <https://doi.org/10.1016/j.techfore.2017.01.006>
- Karlsson, S., 2004. Recycled Polyolefins. Material Properties and Means for Quality Determination, in: *Adv. Polym. Sci.* pp. 201–230. <https://doi.org/10.1007/b94173>
- Keating, S., Oxman, N., 2013. Compound fabrication: A multi-functional robotic platform for digital design and fabrication. *Robot. Comput. Integr. Manuf.* 29, 439–448. <https://doi.org/10.1016/j.rcim.2013.05.001>
- Khorram Niaki, M., Nonino, F., Palombi, G., Torabi, S.A., 2019. Economic sustainability of additive manufacturing. *J. Manuf. Technol. Manag.* 30, 353–365. <https://doi.org/10.1108/JMTM-05-2018-0131>
- Kim, Y., Yoon, C., Ham, S., Park, J., Kim, S., Kwon, O., Tsai, P.-J., 2015. Emissions of Nanoparticles and Gaseous Material from 3D Printer Operation. *Environ. Sci. Technol.* 49, 12044–12053. <https://doi.org/10.1021/acs.est.5b02805>
- King, D.L., Babasola, A., Rozario, J., Pearce, J.M., 2014. Mobile Open-Source Solar-Powered 3-D Printers for Distributed Manufacturing in Off-Grid Communities. *Challenges Sustain.* 2. <https://doi.org/10.12924/cis2014.02010018>
- Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- Ko, Y.S., Herrmann, D., Tolar, O., Elspass, W.J., Brändli, C., 2019. Improving the filament weld-strength of fused filament fabrication products through improved interdiffusion. *Addit. Manuf.* 29, 100815. <https://doi.org/10.1016/j.addma.2019.100815>
- Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. *J. Clean. Prod.* 106, 654–668. <https://doi.org/10.1016/j.jclepro.2014.09.039>
- Kohtala, C., Hyysalo, S., 2015. Anticipated environmental sustainability of personal fabrication. *J. Clean. Prod.* 99, 333–344. <https://doi.org/10.1016/j.jclepro.2015.02.093>
- Korhonen, J., Honkasalo, A., Seppälä, J., 2018a. Circular Economy: The Concept and its Limitations. *Ecol. Econ.* 143, 37–46. <https://doi.org/10.1016/j.ecolecon.2017.06.041>
- Korhonen, J., Nuur, C., Feldmann, A., Birkie, S.E., 2018b. Circular economy as an essentially contested concept. *J. Clean. Prod.* 175, 544–552. <https://doi.org/10.1016/j.jclepro.2017.12.111>
- Kostakis, V., Latoufis, K., Liarakapis, M., Bauwens, M., 2018. The convergence of digital commons with local manufacturing from a degrowth perspective: Two illustrative cases. *J. Clean. Prod.* 197, 1684–1693. <https://doi.org/10.1016/j.jclepro.2016.09.077>
- Kostakis, V., Papachristou, M., 2014. Commons-based peer production and digital fabrication: The case of a RepRap-based, Lego-built 3D printing-milling machine. *Telemat. Informatics* 31, 434–443. <https://doi.org/10.1016/j.tele.2013.09.006>
- Kranzinger, L., Pomberger, R., Schwabl, D., Flachberger, H., Bauer, M., Lehner, M., Hofer, W., 2018. Output-oriented analysis of the wet mechanical processing of polyolefin-rich waste for feedstock recycling. *Waste Manag. Res.* 36, 445–453. <https://doi.org/10.1177/0734242X18764294>

- Kreiger, M., Anzalone, G.C., Mulder, M.L., Glover, A., Pearce, J.M., 2013. Distributed Recycling of Post-Consumer Plastic Waste in Rural Areas. *MRS Proc.* 1492, 91–96. <https://doi.org/10.1557/opl.2013.258>
- Kreiger, M., Mulder, M., Glover, A., Pearce, J., 2014. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. *J. Clean. Prod.* 70, 90–96. <https://doi.org/10.1016/j.jclepro.2014.02.009>
- Kreiger, M., Pearce, J.M., 2013. Environmental Impacts of Distributed Manufacturing from 3-D Printing of Polymer Components and Products. *MRS Proc.* 1492, 85–90. <https://doi.org/10.1557/opl.2013.319>
- Kucherov, F.A., Gordeev, E.G., Kashin, A.S., Ananikov, V.P., 2017. Three-Dimensional Printing with Biomass-Derived PEF for Carbon-Neutral Manufacturing. *Angew. Chemie Int. Ed.* 56, 15931–15935. <https://doi.org/10.1002/anie.201708528>
- Kumar, S., Czekanski, A., 2018. Roadmap to sustainable plastic additive manufacturing. *Mater. Today Commun.* 15, 109–113. <https://doi.org/10.1016/j.mtcomm.2018.02.006>
- Kumar, S., Czekanski, A., 2017. Development of filaments using selective laser sintering waste powder. *J. Clean. Prod.* 165, 1188–1196. <https://doi.org/10.1016/j.jclepro.2017.07.202>
- Kumar, S., Singh, R., Singh, T., Batish, A., 2019. On investigation of rheological, mechanical and morphological characteristics of waste polymer-based feedstock filament for 3D printing applications. *J. Thermoplast. Compos. Mater.* 089270571985606. <https://doi.org/10.1177/0892705719856063>
- Lanzotti, A., Martorelli, M., Maietta, S., Gerbino, S., Penta, F., Gloria, A., 2019. A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. *Procedia CIRP* 79, 143–146. <https://doi.org/10.1016/j.procir.2019.02.030>
- Laplume, A.O., Petersen, B., Pearce, J.M., 2016. Global value chains from a 3D printing perspective. *J. Int. Bus. Stud.* 47, 595–609. <https://doi.org/10.1057/jibs.2015.47>
- Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective. *Resour. Conserv. Recycl.* 55, 246–259. <https://doi.org/10.1016/j.resconrec.2010.09.014>
- Lee, D., Lee, Y., Lee, K., Ko, Y., Kim, N., 2019. Development and Evaluation of a Distributed Recycling System for Making Filaments Reused in Three-Dimensional Printers. *J. Manuf. Sci. Eng.* 141, 021007. <https://doi.org/10.1115/1.4041747>
- Letcher, T., Waytashek, M., 2014. Material Property Testing of 3D-Printed Specimen in PLA on an Entry-Level 3D Printer, in: Vol. 2A Adv. Manuf. American Society of Mechanical Engineers, p. V02AT02A014. <https://doi.org/10.1115/IMECE2014-39379>
- LF2L, 2020. Lorraine Fab Living Lab: The Green Fablab. <http://lf2l.fr/projects/green-fablab/> (accessed 13 March 2020).
- Ligon, S.C., Liska, R., Stampfl, J., Gurr, M., Mülhaupt, R., 2017. Polymers for 3D Printing and Customized Additive Manufacturing. *Chem. Rev.* 117, 10212–10290. <https://doi.org/10.1021/acs.chemrev.7b00074>
- Lyman, H., 2016. Lyman / Mulier Filament Extruder V5 by hlyman. <http://www.thingiverse.com/thing:380987> (accessed 20 January 2020).

- Matos, F., Jacinto, C., 2019. Additive manufacturing technology: mapping social impacts. *J. Manuf. Technol. Manag.* 30, 70–97. <https://doi.org/10.1108/JMTM-12-2017-0263>
- Matt, D.T., Rauch, E., Dallasega, P., 2015. Trends towards Distributed Manufacturing Systems and Modern Forms for their Design. *Procedia CIRP* 33, 185–190. <https://doi.org/10.1016/j.procir.2015.06.034>
- Mägi, P., Krumme, A., Pohlak, M., 2016. Recycling of PA-12 in Additive Manufacturing and the Improvement of its Mechanical Properties. *Key Eng. Mater.* 674, 9–14. <https://doi.org/10.4028/www.scientific.net/KEM.674.9>
- Mägi, P., Krumme, A., Pohlak, M., 2015. Material recycling and improvement issues in additive manufacturing, in: *Proc. Int. Conf. DAAAM Balt. "Industrial Eng.* pp. 63–68.
- McNaney, T., 2012. Filament Maker – Filabot. <http://www.filabot.com/> (accessed 20 March 2020).
- Mellor, S., Hao, L., Zhang, D., 2014. Additive manufacturing: A framework for implementation. *Int. J. Prod. Econ.* 149, 194–201. <https://doi.org/10.1016/j.ijpe.2013.07.008>
- Milios, L., 2018. Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix. *Sustain. Sci.* 13, 861–878. <https://doi.org/10.1007/s11625-017-0502-9>
- Milios, L., Holm Christensen, L., McKinnon, D., Christensen, C., Rasch, M.K., Hallstrøm Eriksen, M., 2018. Plastic recycling in the Nordics: A value chain market analysis. *Waste Manag.* 76, 180–189. <https://doi.org/10.1016/j.wasman.2018.03.034>
- Mognol, P., Lepicart, D., Perry, N., 2006. Rapid prototyping: energy and environment in the spotlight. *Rapid Prototyp. J.* 12, 26–34. <https://doi.org/10.1108/13552540610637246>
- Mohammed, M.I., Mohan, M., Das, A., D. Johnson, M., Singh Badwal, P., McLean, D., Gibson, I., 2017. A low carbon footprint approach to the reconstitution of plastics into 3D-printer filament for enhanced waste reduction. *KnE Eng.* 2, 234. <https://doi.org/10.18502/keg.v2i2.621>
- Mohammed, M.I., Wilson, D., Gomez-Kervin, E., Rosson, L., Long, J., 2018a. EcoPrinting: Investigation of Solar Powered Plastic Recycling and Additive Manufacturing for Enhanced Waste Management and Sustainable Manufacturing, in: *2018 IEEE Conf. Technol. Sustain. IEEE*, pp. 1–6. <https://doi.org/10.1109/SusTech.2018.8671370>
- Mohammed, M.I., Wilson, D., Gomez-Kervin, E., Tang, B., Wang, J., 2019. Investigation of Closed-Loop Manufacturing with Acrylonitrile Butadiene Styrene over Multiple Generations Using Additive Manufacturing. *ACS Sustain. Chem. Eng.* 7, 13955–13969. <https://doi.org/10.1021/acssuschemeng.9b02368>
- Mohammed, M.I., Wilson, D., Gomez-kervin, E., Vidler, C., Rosson, L., Long, J., 2018b. The recycling of E-Waste ABS plastics by melt extrusion and 3D printing using solar powered devices as a transformative tool for humanitarian aid, in: *Solid Free. Fabr. Proc.* pp. 80–92.
- Mohan, N., Senthil, P., Vinodh, S., Jayanth, N., 2017. A review on composite materials and process parameters optimisation for the fused deposition modelling process. *Virtual Phys. Prototyp.* 12, 47–59. <https://doi.org/10.1080/17452759.2016.1274490>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med.* 6, e1000097. <https://doi.org/10.1371/journal.pmed.1000097>

- Morrow, W., Qi, H., Kim, I., Mazumder, J., Skerlos, S., 2007. Environmental aspects of laser-based and conventional tool and die manufacturing. *J. Clean. Prod.* 15, 932–943. <https://doi.org/10.1016/j.jclepro.2005.11.030>
- Morseletto, P., 2020. Targets for a circular economy. *Resour. Conserv. Recycl.* 153, 104553. <https://doi.org/10.1016/j.resconrec.2019.104553>
- Mosaddek, A., Kommula, H.K.R., Gonzalez, F., 2018. Design and Testing of a Recycled 3D Printed and Foldable Unmanned Aerial Vehicle for Remote Sensing, in: 2018 Int. Conf. Unmanned Aircr. Syst. IEEE, pp. 1207–1216. <https://doi.org/10.1109/ICUAS.2018.8453284>
- Mota, C., 2011. The rise of personal fabrication, in: Proc. 8th Acm Conf. Creat. Cogn. - c&C '11. ACM Press, New York, New York, USA, p. 279. <https://doi.org/10.1145/2069618.2069665>
- Muscard, B., Seliger, G., 2015. Realization of a Learning Environment to Promote Sustainable Value Creation in Areas with Insufficient Infrastructure. *Procedia CIRP* 32, 70–75. <https://doi.org/10.1016/j.procir.2015.04.095>
- Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Rocha-Lona, L., Tortorella, G., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context. *J. Manuf. Technol. Manag.* 30, 607–627. <https://doi.org/10.1108/JMTM-03-2018-0071>
- Niaki, M.K., Torabi, S.A., Nonino, F., 2019. Why manufacturers adopt additive manufacturing technologies: The role of sustainability. *J. Clean. Prod.* 222, 381–392. <https://doi.org/10.1016/j.jclepro.2019.03.019>
- Nilsiam, Y., Pearce, J.M., 2017. Free and Open Source 3-D Model Customizer for Websites to Democratize Design with OpenSCAD. *Designs* 1, 5. <https://doi.org/10.3390/designs1010005>
- Turner, B.N., Strong, R., A. Gold, S., 2014. A review of melt extrusion additive manufacturing processes: I. Process design and modeling. *Rapid Prototyp. J.* 20, 192–204. <https://doi.org/10.1108/RPJ-01-2013-0012>
- Osorio, F., Dupont, L., Camargo, M., Sandoval, C., Peña, J.I., 2020. Shaping a Public Innovation Laboratory in Bogota: Learning through Time, Space and Stakeholders. *J. Innov. Econ. Manag.* 31, 69–100. <https://doi.org/10.3917/jie.pr1.0066>
- Pan, G.-T., Chong, S., Tsai, H.-J., Lu, W.-H., Yang, T.C., 2018. The Effects of Iron, Silicon, Chromium, and Aluminum Additions on the Physical and Mechanical Properties of Recycled 3D Printing Filaments. *Adv. Polym. Technol.* 37, 1176–1184. <https://doi.org/10.1002/adv.21777>
- Paulic, M., Irgolic, T., Balic, J., Cus, F., Cupar, A., Brajljih, T., Drstvensek, I., 2014. Reverse Engineering of Parts with Optical Scanning and Additive Manufacturing. *Procedia Eng.* 69, 795–803. <https://doi.org/10.1016/j.proeng.2014.03.056>
- Pavlo, S., Fabio, C., Hakim, B., Mauricio, C., 2018. 3D-Printing Based Distributed Plastic Recycling: A Conceptual Model for Closed-Loop Supply Chain Design, in: 2018 IEEE Int. Conf. Eng. Technol. Innov. IEEE, pp. 1–8. <https://doi.org/10.1109/ICE.2018.8436296>
- Pearce, J.M., 2017a. Emerging Business Models for Open Source Hardware. *J. Open Hardw.* 1. <https://doi.org/10.5334/joh.4>
- Pearce, J.M., 2017b. Impacts of open source hardware in science and engineering. *Bridge* 47, 24–31.

- Pearce, J.M., 2015. A novel approach to obviousness: An algorithm for identifying prior art concerning 3-D printing materials. *World Pat. Inf.* 42, 13–18. <https://doi.org/10.1016/j.wpi.2015.07.003>
- Pearce, J.M., 2014. Open-Source Lab, in: *Open-Source Lab*. Elsevier, pp. 95–162. <https://doi.org/10.1016/B978-0-12-410462-4.00005-6>
- Peeters, B., Kiratli, N., Semeijn, J., 2019. A barrier analysis for distributed recycling of 3D printing waste: Taking the maker movement perspective. *J. Clean. Prod.* 241, 118313. <https://doi.org/10.1016/j.jclepro.2019.118313>
- Peng, T., Kellens, K., Tang, R., Chen, C., Chen, G., 2018. Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. *Addit. Manuf.* 21, 694–704. <https://doi.org/10.1016/j.addma.2018.04.022>
- Pepi, M., Zander, N., Gillan, M., 2018. Towards Expeditionary Battlefield Manufacturing Using Recycled, Reclaimed, and Scrap Materials. *JOM* 70, 2359–2364. <https://doi.org/10.1007/s11837-018-3040-8>
- Perugini, F., Mastellone, M.L., Arena, U., 2005. A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. *Environ. Prog.* 24, 137–154. <https://doi.org/10.1002/ep.10078>
- Petersen, E., Kidd, R., Pearce, J., 2017. Impact of DIY Home Manufacturing with 3D Printing on the Toy and Game Market. *Technologies* 5, 45. <https://doi.org/10.3390/technologies5030045>
- Petersen, E., Pearce, J., 2017. Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers. *Technologies* 5, 7. <https://doi.org/10.3390/technologies5010007>
- Petrick, I.J., Simpson, T.W., 2013. 3D Printing Disrupts Manufacturing: How Economies of One Create New Rules of Competition. *Res. Manag.* 56, 12–16. <https://doi.org/10.5437/08956308X5606193>
- Petruzzi, C., Lucchio, L.D., MARIA Cafiero, L., Tuffi, R., Ubertini, A., Caretto, F., 2017. Hospital of Objects. Recycling plastic from the small electronic devices to redesign old objects by the 3d printers. *Des. J.* 20, S2716–S2723. <https://doi.org/10.1080/14606925.2017.1352783>
- Phan, T.T.P., Phan, T.Q., Sherif El-Gizawy, A., 2019. Development of a combined analytical and experimental approach for the determination of the cohesive strength between material extrusion layers using the true area of contact. *Addit. Manuf.* 30, 100832. <https://doi.org/10.1016/j.addma.2019.100832>
- Picuno, C., Alassali, A., Sundermann, M., Godosi, Z., Picuno, P., Kuchta, K., 2020. Decontamination and recycling of agrochemical plastic packaging waste. *J. Hazard. Mater.* 381, 120965. <https://doi.org/10.1016/j.jhazmat.2019.120965>
- Piemonte, V., 2011. Bioplastic Wastes: The Best Final Disposition for Energy Saving. *J. Polym. Environ.* 19, 988–994. <https://doi.org/10.1007/s10924-011-0343-z>
- Plastics, E., 2019. *Plastics - the Facts 2019* <https://www.plasticseurope.org/fr/resources/publications/1804-plastics-facts-2019> (accessed 10 March 2020).
- Plast'if, 2020. *Plast'if*. <https://www.plastif.com/> (accessed 10 December 2019).
- PPP, 2020. Perpetual plastics project. <http://www.perpetualplasticproject.com/> (accessed 10 March 2020).
- Pringle, A.M., Rudnicki, M., Pearce, J., 2017. Wood Furniture Waste-Based Recycled 3-D Printing Filament. *For. Prod. J.* 68, FPJ-D-17-00042. <https://doi.org/10.13073/FPJ-D-17-00042>

Qactus, 2020. Quactus. <https://qactus.cl> (accessed 10 March 2020).

Raasch, C., Herstatt, C., Balka, K., 2009. On the open design of tangible goods. *R&D Manag.* 39, 382–393. <https://doi.org/10.1111/j.1467-9310.2009.00567.x>

Radharamanan, R., 2011. Design and development of a 3D printer with Recycling system in: 2011 Asee Annu. Conf. Expo. Vancouver, pp. 22.424.1–22.424.12.

Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. *Waste Manag.* 69, 24–58. <https://doi.org/10.1016/j.wasman.2017.07.044>

Rahimizadeh, A., Kalman, J., Fayazbakhsh, K., Lessard, L., 2019. Recycling of fiberglass wind turbine blades into reinforced filaments for use in Additive Manufacturing. *Compos. Part B Eng.* 175, 107101. <https://doi.org/10.1016/j.compositesb.2019.107101>

Rahman, Z., Barakh Ali, S.F., Ozkan, T., Charoo, N.A., Reddy, I.K., Khan, M.A., 2018. Additive Manufacturing with 3D Printing: Progress from Bench to Bedside. *AAPS J.* 20, 101. <https://doi.org/10.1208/s12248-018-0225-6>

Ramakrishna, S., Zhang, T.-Y., Lu, W.-C., Qian, Q., Low, J.S.C., Yune, J.H.R., Tan, D.Z.L., Bressan, S., Sanvito, S., Kalidindi, S.R., 2019. Materials informatics. *J. Intell. Manuf.* 30, 2307–2326. <https://doi.org/10.1007/s10845-018-1392-0>

Rani, M., Marchesi, C., Federici, S., Rovelli, G., Alessandri, I., Vassalini, I., Ducoli, S., Borgese, L., Zacco, A., Bilo, F., Bontempi, E., Depero, L.E., 2019. Miniaturized Near-Infrared (MicroNIR) Spectrometer in Plastic Waste Sorting. *Materials (Basel)*. 12, 2740. <https://doi.org/10.3390/ma12172740>

Rayna, T., Striukova, L., 2016. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technol. Forecast. Soc. Change* 102, 214–224. <https://doi.org/10.1016/j.techfore.2015.07.023>

Reddy, S., Raju, T., 2018. Design and Development of mini plastic shredder machine. *IOP Conf. Ser. Mater. Sci. Eng.* 455, 012119. <https://doi.org/10.1088/1757-899X/455/1/012119>

Reich, M.J., Woern, A.L., Tanikella, N.G., Pearce, J.M., 2019. Mechanical Properties and Applications of Recycled Polycarbonate Particle Material Extrusion-Based Additive Manufacturing. *Materials (Basel)*. 12, 1642. <https://doi.org/10.3390/ma12101642>

Romero-Alva, V., Alvarado-Diaz, W., Roman-Gonzalez, A., 2018. Design of a 3D Printer and Integrated Supply System, in: 2018 IEEE Xp Int. Conf. Electron. Electr. Eng. Comput. IEEE, pp. 1–4. <https://doi.org/10.1109/INTERCON.2018.8526458>

Rosa, P., Sassanelli, C., Terzi, S., 2019. Towards Circular Business Models: A systematic literature review on classification frameworks and archetypes. *J. Clean. Prod.* 236, 117696. <https://doi.org/10.1016/j.jclepro.2019.117696>

Ryberg, M.W., Hauschild, M.Z., Wang, F., Averous-Monnery, S., Laurent, A., 2019. Global environmental losses of plastics across their value chains. *Resour. Conserv. Recycl.* 151, 104459. <https://doi.org/10.1016/j.resconrec.2019.104459>

Rylands, B., Böhme, T., Gorkin, R., Fan, J., Birtchnell, T., 2016. The adoption process and impact of additive manufacturing on manufacturing systems. *J. Manuf. Technol. Manag.* 27, 969–989. <https://doi.org/10.1108/JMTM-12-2015-0117>

- Safai, L., Cuellar, J.S., Smit, G., Zadpoor, A.A., 2019. A review of the fatigue behavior of 3D printed polymers. *Addit. Manuf.* 28, 87–97. <https://doi.org/10.1016/j.addma.2019.03.023>
- Santander, P., Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., 2020. Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. *Resour. Conserv. Recycl.* 154, 104531. <https://doi.org/10.1016/j.resconrec.2019.104531>
- Sa'ude, N., Kamarudin, K., Ibrahim, M., Ibrahim, M.H.I., 2015. Melt Flow Index of Recycle ABS for Fused Deposition Modeling (FDM) Filament. *Appl. Mech. Mater.* 773-774, 3–7. <https://doi.org/10.4028/www.scientific.net/AMM.773-774.3>
- Sauerwein, M., Doubrovski, E., 2018. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. *Mater. Today Commun.* 15, 214–217. <https://doi.org/10.1016/j.mtcomm.2018.02.028>
- Savonen, B., Mahan, T., Curtis, M., Schreier, J., Gershenson, J., Pearce, J., 2018. Development of a Resilient 3-D Printer for Humanitarian Crisis Response. *Technologies* 6, 30. <https://doi.org/10.3390/technologies6010030>
- Schelly, C., Pearce, J., 2019. Bridging the Social and Environmental Dimensions of Global Sustainability in STEM Education with Additive Manufacturing, in: *Integr. 3D Print. Into Teach. Learn.* Brill | Sense. https://doi.org/10.1163/9789004415133_008
- Siddaway, A.P., Wood, A.M., Hedges, L.V., 2019. How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses. *Annu. Rev. Psychol.* 70, 747–770. <https://doi.org/10.1146/annurev-psych-010418-102803>
- Signoret, C., Caro-Bretelle, A.-S., Lopez-Cuesta, J.-M., Ienny, P., Perrin, D., 2019. MIR spectral characterization of plastic to enable discrimination in an industrial recycling context: I. Specific case of styrenic polymers. *Waste Manag.* 95, 513–525. <https://doi.org/10.1016/j.wasman.2019.05.050>
- Simon, B., 2019. What are the most significant aspects of supporting the circular economy in the plastic industry? *Resour. Conserv. Recycl.* 141, 299–300. <https://doi.org/10.1016/j.resconrec.2018.10.044>
- Singh, A.K., Patil, B., Hoffmann, N., Saltonstall, B., Doddamani, M., Gupta, N., 2018. Additive Manufacturing of Syntactic Foams: Part 1: Development, Properties, and Recycling Potential of Filaments. *JOM* 70, 303–309. <https://doi.org/10.1007/s11837-017-2734-7>
- Singh, N., Hui, D., Singh, R., Ahuja, I.P.S., Feo, L., Fraternali, F., 2017. Recycling of plastic solid waste: A state of art review and future applications. *Compos. Part B Eng.* 115, 409–422. <https://doi.org/10.1016/j.compositesb.2016.09.013>
- Singh, N., Singh, R., Ahuja, I., 2019. Thermomechanical investigations of SiC and Al₂O₃ –reinforced HDPE. *J. Thermoplast. Compos. Mater.* 32, 1347–1360. <https://doi.org/10.1177/0892705718796544>
- Singh, N., Singh, R., Ahuja, I.P.S., 2018a. Recycling of polymer waste with SiC/Al₂O₃ reinforcement for rapid tooling applications. *Mater. Today Commun.* 15, 124–127. <https://doi.org/10.1016/j.mtcomm.2018.02.008>
- Singh, N., Singh, R., Ahuja, I.P.S., 2018b. On Development of Functionally Graded Material Through Fused Deposition Modelling Assisted Investment Casting from Al₂O₃/SiC Reinforced Waste Low Density Polyethylene. *Trans. Indian Inst. Met.* 71, 2479–2485. <https://doi.org/10.1007/s12666-018-1378-9>

- Singh, R., Kumar, R., Farina, I., Colangelo, F., Feo, L., Fraternali, F., 2019a. Multi-Material Additive Manufacturing of Sustainable Innovative Materials and Structures. *Polymers (Basel)*. 11, 62. <https://doi.org/10.3390/polym11010062>
- Singh, R., Kumar, R., Ranjan, N., 2019b. Sustainability of Recycled ABS and PA6 by Banana Fiber Reinforcement: Thermal, Mechanical and Morphological Properties. *J. Inst. Eng. Ser. C* 100, 351–360. <https://doi.org/10.1007/s40032-017-0435-1>
- Singh, R., Kumar, R., Singh, I., 2019c. Investigations on 3D printed thermosetting and ceramic-reinforced recycled thermoplastic-based functional prototypes. *J. Thermoplast. Compos. Mater.* 089270571986462. <https://doi.org/10.1177/0892705719864623>
- Singh, R., Singh, H., Farina, I., Colangelo, F., Fraternali, F., 2019d. On the additive manufacturing of an energy storage device from recycled material. *Compos. Part B Eng.* 156, 259–265. <https://doi.org/10.1016/j.compositesb.2018.08.080>
- Singh, R., Singh, J., Singh, S., 2016. Investigation for dimensional accuracy of AMC prepared by FDM assisted investment casting using nylon-6 waste based reinforced filament. *Measurement* 78, 253–259. <https://doi.org/10.1016/j.measurement.2015.10.016>
- Singh, S., Ramakrishna, S., Gupta, M.K., 2017a. Towards zero waste manufacturing: A multidisciplinary review. *J. Clean. Prod.* 168, 1230–1243. <https://doi.org/10.1016/j.jclepro.2017.09.108>
- Singh, S., Ramakrishna, S., Singh, R., 2017b. Material issues in additive manufacturing: A review. *J. Manuf. Process.* 25, 185–200. <https://doi.org/10.1016/j.jmapro.2016.11.006>
- Stansbury, J.W., Idacavage, M.J., 2016. 3D printing with polymers: Challenges among expanding options and opportunities. *Dent. Mater.* 32, 54–64. <https://doi.org/10.1016/j.dental.2015.09.018>
- Steinle, P., 2016. Characterization of emissions from a desktop 3D printer and indoor air measurements in office settings. *J. Occup. Environ. Hyg.* 13, 121–132. <https://doi.org/10.1080/15459624.2015.1091957>
- Stephens, B., Azimi, P., El Orch, Z., Ramos, T., 2013. Ultrafine particle emissions from desktop 3D printers. *Atmos. Environ.* 79, 334–339. <https://doi.org/10.1016/j.atmosenv.2013.06.050>
- Stoof, D., Pickering, K., 2018. Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene. *Compos. Part B Eng.* 135, 110–118. <https://doi.org/10.1016/j.compositesb.2017.10.005>
- Subramanian Senthilkannan Muthu, M.M.S., 2016. Handbook of Sustainability in Additive Manufacturing, Environmental footprints and eco-design of products and processes. Springer Singapore, Singapore. <https://doi.org/10.1007/978-981-10-0606-7>
- Sun, Q., Wang, C., Zhou, Y., Zuo, L., Tang, J., 2020. Dominant platform capability, symbiotic strategy and the construction of “Internet + WEEE collection” business ecosystem : A comparative study of two typical cases in China. *J. Clean. Prod.* 254, 120074. <https://doi.org/10.1016/j.jclepro.2020.120074>
- Tanikella, N.G., Wittbrodt, B., Pearce, J.M., 2017. Tensile strength of commercial polymer materials for fused filament fabrication 3D printing. *Addit. Manuf.* 15, 40–47. <https://doi.org/10.1016/j.addma.2017.03.005>
- Thompson, R.C., Moore, C.J., Saal, F.S. vom, Swan, S.H., 2009. Plastics, the environment and human health: current consensus and future trends. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 2153–2166. <https://doi.org/10.1098/rstb.2009.0053>

- Tian, X., Liu, T., Wang, Q., Dilmurat, A., Li, D., Ziegmann, G., 2017. Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. *J. Clean. Prod.* 142, 1609–1618. <https://doi.org/10.1016/j.jclepro.2016.11.139>
- Toffler, A., 1980. *The third wave*. Bantam books New York, New York.
- Torrado, A.R., Shemelya, C.M., English, J.D., Lin, Y., Wicker, R.B., Roberson, D.a., 2015. Characterizing the effect of additives to ABS on the mechanical property anisotropy of specimens fabricated by material extrusion 3D printing. *Addit. Manuf.* 6, 16–29. <https://doi.org/10.1016/j.addma.2015.02.001>
- Tröger, C., Bens, A.T., Bermes, G., Klemmer, R., Lenz, J., Irsen, S., 2008. Ageing of acrylate-based resins for stereolithography: thermal and humidity ageing studies. *Rapid Prototyp. J.* 14, 305–317. <https://doi.org/10.1108/13552540810907983>
- Turner, B.N., Gold, S.A., 2015. A review of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness. *Rapid Prototyp. J.* 21, 250–261. <https://doi.org/10.1108/RPJ-02-2013-0017>
- Vaezi, M., Chianrabutra, S., Mellor, B., Yang, S., 2013. Multiple material additive manufacturing – Part 1: a review. *Virtual Phys. Prototyp.* 8, 19–50. <https://doi.org/10.1080/17452759.2013.778175>
- Veer, F.A., Setaki, F., Riemslog, A.C., Sakkas, P., 2017. The strength and ductility of glass fibre reinforced 3D-printed polypropylene. *Heron* 62, 85–97.
- Verma, R., Vinoda, K., Papireddy, M., Gowda, A., 2016. Toxic Pollutants from Plastic Waste- A Review. *Procedia Environ. Sci.* 35, 701–708. <https://doi.org/10.1016/j.proenv.2016.07.069>
- Vilaplana, F., Karlsson, S., 2008. Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review. *Macromol. Mater. Eng.* 293, 274–297. <https://doi.org/10.1002/mame.200700393>
- Volpato, N., Kretschek, D., Foggiatto, J.A., Gomez da Silva Cruz, C.M., 2015. Experimental analysis of an extrusion system for additive manufacturing based on polymer pellets. *Int. J. Adv. Manuf. Technol.* 81, 1519–1531. <https://doi.org/10.1007/s00170-015-7300-2>
- West, J., Kuk, G., 2016. The complementarity of openness: How MakerBot leveraged Thingiverse in 3D printing. *Technol. Forecast. Soc. Change* 102, 169–181. <https://doi.org/10.1016/j.techfore.2015.07.025>
- Whyman, S., Arif, K.M., Potgieter, J., 2018. Design and development of an extrusion system for 3D printing biopolymer pellets. *Int. J. Adv. Manuf. Technol.* 96, 3417–3428. <https://doi.org/10.1007/s00170-018-1843-y>
- Wittbrodt, B., Glover, A., Laureto, J., Anzalone, G., Oppliger, D., Irwin, J., Pearce, J., 2013. Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. *Mechatronics* 23, 713–726. <https://doi.org/10.1016/j.mechatronics.2013.06.002>
- Woern, A., Byard, D., Oakley, R., Fiedler, M., Snabes, S., Pearce, J., 2018a. Fused Particle Fabrication 3-D Printing: Recycled Materials' Optimization and Mechanical Properties. *Materials (Basel)*. 11, 1413. <https://doi.org/10.3390/ma11081413>
- Woern, A.L., McCaslin, J.R., Pringle, A.M., Pearce, J.M., 2018b. RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament. *HardwareX* 4, e00026. <https://doi.org/10.1016/j.ohx.2018.e00026>

- Woern, A., Pearce, J., 2018. 3-D Printable Polymer Pelletizer Chopper for Fused Granular Fabrication-Based Additive Manufacturing. *Inventions* 3, 78. <https://doi.org/10.3390/inventions3040078>
- Woern, A., Pearce, J., 2017. Distributed Manufacturing of Flexible Products: Technical Feasibility and Economic Viability. *Technologies* 5, 71. <https://doi.org/10.3390/technologies5040071>
- Wong, K.V., Hernandez, A., 2012. A Review of Additive Manufacturing. *ISRN Mech. Eng.* 2012, 1–10. <https://doi.org/10.5402/2012/208760>
- Xu, C., Wu, Q., L'Espérance, G., Lebel, L.L., Therriault, D., 2018. Environment-friendly and reusable ink for 3D printing of metallic structures. *Mater. Des.* 160, 262–269. <https://doi.org/10.1016/j.matdes.2018.09.024>
- Yadollahi, A., Shamsaei, N., 2017. Additive manufacturing of fatigue resistant materials: Challenges and opportunities. *Int. J. Fatigue* 98, 14–31. <https://doi.org/10.1016/j.ijfatigue.2017.01.001>
- Yin, S., Cavaliere, P., Aldwell, B., Jenkins, R., Liao, H., Li, W., Lupoi, R., 2018. Cold spray additive manufacturing and repair: Fundamentals and applications. *Addit. Manuf.* 21, 628–650. <https://doi.org/10.1016/j.addma.2018.04.017>
- Yoon, H.-S., Lee, J.-Y., Kim, H.-S., Kim, M.-S., Kim, E.-S., Shin, Y.-J., Chu, W.-S., Ahn, S.-H., 2014. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *Int. J. Precis. Eng. Manuf. Technol.* 1, 261–279. <https://doi.org/10.1007/s40684-014-0033-0>
- Zander, N.E., 2019. Recycled Polymer Feedstocks for Material Extrusion Additive Manufacturing, in: *ACS Symp. Ser.* American Chemical Society, pp. 37–51. <https://doi.org/10.1021/bk-2019-1315.ch003>
- Zander, N.E., Gillan, M., Burckhard, Z., Gardea, F., 2019. Recycled polypropylene blends as novel 3D printing materials. *Addit. Manuf.* 25, 122–130. <https://doi.org/10.1016/j.addma.2018.11.009>
- Zander, N.E., Gillan, M., Lambeth, R.H., 2018. Recycled polyethylene terephthalate as a new FFF feedstock material. *Addit. Manuf.* 21, 174–182. <https://doi.org/10.1016/j.addma.2018.03.007>
- Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., Perona, M., 2019. Supply chain implications of additive manufacturing: a holistic synopsis through a collection of case studies. *Int. J. Adv. Manuf. Technol.* 102, 3325–3340. <https://doi.org/10.1007/s00170-019-03430-w>
- Zhang, B., Kowsari, K., Serjouei, A., Dunn, M.L., Ge, Q., 2018. Reprocessable thermosets for sustainable three-dimensional printing. *Nat. Commun.* 9, 1831. <https://doi.org/10.1038/s41467-018-04292-8>
- Zhang, J., Yu, Z., 2016. Overview of 3D printing technologies for reverse engineering product design. *Autom. Control Comput. Sci.* 50, 91–97. <https://doi.org/10.3103/S0146411616020073>
- Zhao, P., Rao, C., Gu, F., Sharmin, N., Fu, J., 2018. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. *J. Clean. Prod.* 197, 1046–1055. <https://doi.org/10.1016/j.jclepro.2018.06.275>
- Zhong, S., Pearce, J.M., 2018. Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. *Resour. Conserv. Recycl.* 128, 48–58. <https://doi.org/10.1016/j.resconrec.2017.09.023>

Zhong, S., Rakhe, P., Pearce, J., 2017. Energy Payback Time of a Solar Photovoltaic Powered Waste Plastic Recyclebot System. *Recycling* 2, 10. <https://doi.org/10.3390/recycling2020010>

Zhuo, C., Levendis, Y.A., 2014. Upcycling waste plastics into carbon nanomaterials: A review. *J. Appl. Polym. Sci.* 131, n/a–n/a. <https://doi.org/10.1002/app.39931>

Appendix A. Table A.1 Primary studies considered in the literature review

| Author | Year | Categ | Recycled.Material | Source | Closing the loop | | Raw | | | Feedstock | | | Printed part | | | Sust. dimensions | | | |
|----------------------------|------|------------|---------------------------|------------------------------|-------------------------------|-----------------------------------|-----|----|------|-----------|----|------|--------------|----|------|------------------|-----|-----|-----|
| | | | | | Feedstock quality | Application | SM | FP | LMWC | SM | FP | LMWC | SM | FP | LMWC | Tech | Eco | Soc | Env |
| Recovery | | | | | | | | | | | | | | | | | | | |
| Pavlo et al. (2018) | 2018 | I | | | | | | | | | | | | | | | | | X |
| Hart et al. (2018) | 2018 | I | MRE meal bags | Military (Meal Ready to Eat) | Diameter | Military | X | | | X | | | X | X | X | X | X | X | X |
| Czyżewski et al. (2018) | 2018 | I, III | ABS | E-waste | | | | X | | | X | | | X | | X | | | |
| Gaikwad et al. (2018) | 2018 | I, III, VI | E-Waste,ABS | E-waste | | | X | | | | X | | X | X | | X | | | X |
| Preparation | | | | | | | | | | | | | | | | | | | |
| Hunt et al. (2015) | 2015 | II | | | | | | | | | | | | | | | X | | X |
| Woern and Pearce (2018) | 2018 | II | | | Size Distribution | | | | | | | | | | | | X | | |
| Reddy and Raju (2018) | 2018 | II | | | | | | | | | | | | | | | X | | |
| Romero-Alva et al., 2018 | 2018 | II | | | | | | | | | | | | | | | X | | |
| Compounding | | | | | | | | | | | | | | | | | | | |
| Cruz et al. (2015) | 2015 | III | PLA | | | | X | X | | X | X | | | X | | X | | | |
| Singh et al. (2016) | 2016 | III | Nylon-6 | | | Investment casting | | | | | X | | | X | | X | | | |
| Boparai et al. (2016) | 2016 | III | Nylon6 | | | | | | | X | X | | | | | X | | | |
| Mohammed et al. (2017) | 2017 | III | ABS,HDPE | | Diameter | | | | | | | | | X | | X | | | |
| Woern and Pearce (2017) | 2017 | III | | | | Printability (3D models) | | | | | | | | | | | X | X | |
| Anderson (2017) | 2017 | III | PLA | | | | | | | | | | | X | | X | | | |
| Chong et al. (2017) | 2017 | III | HDPE | | Diameter, Extrusion rate | | | | | X | X | | | | | X | | | |
| Cruz Sanchez et al. (2017) | 2017 | III | PLA | | | | | X | | | X | | | X | | X | | | |
| Hu et al. (2017) | 2017 | III | PLBSI,PLA | | | | | | | X | X | | | X | X | X | | | X |
| Girdis et al. (2017) | 2017 | III | Macadamia nutshell | | | Wood-plastic composites | | | | | X | | | X | | X | | | |
| Veer et al. (2017) | 2017 | III | PP | | | | | | | | | | | X | | X | | | |
| Kucherov et al. (2017) | 2017 | III | | | | | | | | | | | | X | | X | | | |
| A. K. Singh et al. (2018) | 2018 | III | HDPE | | | | | | | | X | | | | | X | | | |
| Dunnigan et al. (2018) | 2018 | III | PolyLite® Nylon | | | | | | | | | | | X | X | X | | | |
| Xu et al. (2018) | 2018 | III | Chitosan | | | | | | | | | | | X | | X | | | |
| Cicala et al. (2018) | 2018 | III | SuperSap epoxy monomers | | | | | | | | X | | | X | | X | | | |
| N. Singh et al., (2018b) | 2018 | III | LDPE | | | Investment casting, Rapid tooling | | | | | X | | | X | X | X | | | |
| Zander et al. (2018) | 2018 | III | PET | Bottles and Packaging | | Military | X | X | | X | X | | | X | X | X | | X | |
| Tian et al. (2017) | 2018 | III | PLA,carbon fiber | | | | | | | | X | X | | X | X | X | X | X | X |
| N. Singh et al., (2018a) | 2018 | III | HDPE | | | Printability (Pins) | | | | X | X | | | X | | X | | | |
| Zhang et al. (2018) | 2018 | III | 2-hydroxy-3-phenoxypropyl | | | | X | | | | X | | | X | | X | | | |
| R. Singh et al., (2019b) | 2018 | III | ABS,PA6 | | | | X | | | X | X | | | X | | X | | | |
| Stoof and Pickering (2018) | 2018 | III | PP | | | | | | | | X | | | X | | X | | | |
| Pan et al. (2018) | 2018 | III | HDPE,PP | | Diameter | | | X | | X | X | | | | | X | | | |
| Gantenbein et al. (2018) | 2018 | III | Liquid-Crystal-Polymer | | | | | | | X | X | | | X | | X | | | |
| Idrees et al. (2018) | 2018 | III | PET | PET bottles | | | X | | | X | | | | X | X | X | | | |
| Pepi et al. (2018) | 2018 | III | PET,HDPE,PP | Milk juges, Soda bottles, | | Military | | | | | | | | X | X | X | | | |
| Alkadi et al. (2019) | 2019 | III | Ground Tire Rubber | Tire Rubber | | | | | | | | | | X | | X | | | |
| Mohammed et al. (2019) | 2019 | III | ABS | | Diameter, Extrusion flow rate | | | | | | | | | X | X | X | | | |
| R. Singh et al., (2019c) | 2019 | III | ABS,Bakelite | | | | | | | | | | | X | X | X | | | |
| He et al. (2020) | 2019 | III | ABS,PBT Resin | | | | X | | | X | | | | | | X | | | |
| R. Singh et al., (2019a) | 2019 | III | ABS,PLA,HIPS | | | Load-bearing structures | X | | | X | | | | X | | X | | | |
| Kumar et al. (2019) | 2019 | III | HDPE,LDPE | | | Nondestructive testing (civil) | | | | X | | | | X | | X | | | |
| Zander et al. (2019) | 2019 | III | PET,PS,PP | Soda bottles, Yogurt | | | | | | X | X | | | X | | X | | | |
| Rahimizadeh et al. (2019) | 2019 | III | PLA,Fiber glass | Wind turbines | Size distribution | | | | | X | X | | | X | | X | | | |
| N. Singh et al., (2019) | 2019 | III | HDPE | | | Rapid tooling | | | | X | X | | | X | | X | | | |
| Kumar and Czepakski (2018) | 2018 | III, IV | Polyamide 12 (PA2200) | | | | | | | X | X | | | | | X | X | | |

| Author | Year | Categ | Recycled.Material | Closing the loop | | | Raw | | | Feedstock | | | Printed part | | | Sust. dimensions | | | |
|---------------------------------|------|---------|-------------------|--------------------|----------------------------------|--------------------------------------|-----|----|------|-----------|----|------|--------------|----|------|------------------|-----|-----|-----|
| | | | | Source | Feedstock quality | Application | SM | FP | LMWC | SM | FP | LMWC | SM | FP | LMWC | Tech | Eco | Soc | Env |
| Zhao et al. (2018) | 2018 | III, VI | PLA | | | | | | | | | | X | X | | X | | | X |
| Feed stock | | | | | | | | | | | | | | | | | | | |
| Baechler et al. (2013) | 2013 | IV | HDPE | | Diameter, Lineal density | | | | | | X | | | | | X | | | X |
| Mägi et al. (2015) | 2015 | IV | PA 12 | | | | | | | | X | | | X | | X | | | |
| Mägi et al. (2016) | 2016 | IV | PA 12 | | | Hand prostheses | | X | | | | | | X | | X | | | |
| Kumar and Czekanski (2017) | 2017 | IV | PA 12 | SLS wastes | | | | | X | X | | | | X | | X | X | | X |
| Zhong et al. (2017) | 2017 | IV | | | | | | | | | | | | | | | X | | X |
| Petruzzi et al. (2017) | 2017 | IV | | | | Hospital of Objects | | | | | | | | | | | | X | |
| Sauerwein and Doubrovski (2018) | 2018 | IV | Mussel shells | | | | | | | | | | | X | | X | | | |
| Woern et al. (2018b) | 2018 | IV | PLA | | Diameter | | | | | | | | | | | X | | | |
| Printing | | | | | | | | | | | | | | | | | | | |
| Keating and Oxman (2013) | 2013 | V | ABS,HDPE,Urethane | | | | | | | | | | | X | | X | | | |
| Volpato et al. (2015) | 2015 | V | PP | | | | | | | X | X | | | | | X | | | |
| Jaksic (2016) | 2016 | V | | | | Educational | | | | | | | | | | | X | X | |
| Domingues et al. (2017) | 2017 | V | PP,Tires Wastes | Tires Wastes | | | | | | | | | X | X | | X | | | |
| Sa'ude et al. (2015) | 2017 | V | ABS | | MFI | | | | | | X | | | | | X | | | X |
| Canessa et al. (2017) | 2017 | V | PLA | | Diameter | | | | | | | | | X | | X | | | |
| Pringle et al. (2017) | 2017 | V | PLA,Wood | | Diameter | | | | | | | | | X | | X | | | |
| Whyman et al. (2018) | 2018 | V | | | | | X | | | | | | | X | | X | | | |
| Mosaddek et al. (2018) | 2018 | V | PET | PET bottles | | Unmanned Aerial Vehicules | | | | | X | | | X | | X | X | | |
| Mohammed et al., (2018a) | 2018 | V | ABS,HDPE | e-waste, Jerry can | Diameter, Electrical consumption | Humanitarian aid | | | | | | | | X | | X | | X | |
| Fateri et al. (2018) | 2018 | V | PVA | | | Space | X | X | | X | | | | X | | X | | | |
| Woern et al. (2018a) | 2018 | V | ABS,PLA,PET,PP | | Size distribution | | | | | | | | | X | | X | | | |
| Horta et al. (2018) | 2018 | V | HDPE | | | | | | | | | | | X | | X | | | |
| Clemon and Zohdi (2018) | 2018 | V | | | | | | | | | | | | | | X | | | X |
| Mohammed et al., (2018b) | 2018 | V | ABS | | Size distribution, Energy | Humanitarian | | | | | | | X | | | X | | | |
| Zhong and Pearce (2018) | 2018 | V | ABS | | Diameter | | | | | | | | | | | X | X | | X |
| Lanzotti et al. (2019) | 2019 | V | ABS | | | | | | | | | | | X | | X | | | |
| Cunico et al. (2019) | 2019 | V | ABS | | | Chemical plastic welding | | | | | | | | X | | X | | | X |
| Reich et al. (2019) | 2019 | V | PC | | Size distribution | High-strength Applications, High- | | | | | | | | X | | X | X | | |
| R. Singh et al. (2019) | 2019 | V | ABS | | | Electrical (Energy storage devices), | X | | | | | | | X | X | X | | | |
| Conceptual | | | | | | | | | | | | | | | | | | | |
| Radharamanan (2011) | 2011 | VII | | | | | | | | | | | | X | | X | | | |
| Kreiger et al. (2013) | 2013 | VII | HDPE | | | | | | | | | | | | | | | | X |
| Kreiger and Pearce (2013) | 2013 | VII | | | | | | | | | | | | | | | | X | X |
| Wittbrodt et al. (2013) | 2013 | VII | PLA | | | | | | | | | | | | | | | | X |
| Heyer et al. (2014) | 2014 | VII | | | | | | | | | | | | | | | | | X |
| Feeley et al. (2014) | 2014 | VII | | | | | | | | | | | | | | | | | X |
| Kreiger et al. (2014) | 2014 | VII | HDPE | | | | | | | | | | | | | | X | | X |
| King et al. (2014) | 2014 | VII | | | | | | | | | | | | | | | | | X |
| Pearce (2015) | 2015 | VII | | | | | | | | | | | | | | | | | X |
| Chong et al. (2015) | 2015 | VII | | | | | | | | | | | | | | X | | | X |
| Muschard and Seliger (2015) | 2015 | VII | | | | | | | | | | | | | | | | | X |
| Petersen et al. (2017) | 2017 | VII | | | | Toy market | | | | | | | | | | | X | X | |
| Ramakrishna et al. (2019) | 2017 | VII | | | | | | | | | | | | X | | | | X | |
| Lee et al. (2019) | 2018 | VII | ABS,PLA | | | | | | | X | | | | X | | X | | | |
| Garmulewicz et al. (2018) | 2018 | VII | | | | | | | | | | | | | | | X | X | |
| Peeters et al. (2019) | 2019 | VII | | | | | | | | | | | | | | | | | X |
| Nascimento et al. (2019) | 2019 | VII | | | | | | | | | | | | | | | X | X | |
| Byard et al. (2019) | 2019 | VII | ABS,PP | | Size distribution | | | | | | | | | | | | X | | |