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Review

Additive manufacturing in cities: Closing circular resource loops

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ABSTRACT

Cities are the core of social interactions and resource consumption in our current times. However, urban systems are still largely based on linear activities in which resources are discarded after usage. Current practices around waste reduce possibilities of circularity, mainly due to low percentages of sorting and recycling practices in high- and middle-income countries and landfill practices in middle- and low-income countries. This resulted in a continuous increase in urban waste and negative environmental impact over the last decades. The development of circular practices and innovations, such as additive manufacturing, is crucial to modify the current supply chain and return valuable discarded materials to urban industries. Additive manufacturing is a novel technology based on the creation of objects layer by layer involving the use of a diverse range of materials. Several materials such as plastics, metal or concrete, for example, can be transformed into functional products for cities. Based on a literature review, this paper showcases the potential of urban waste for 3D printing with a main focus on recycling practices at the end of the supply chain. This paper aims to examine the current knowledge, regulations, and practices in circularity and additive manufacturing in the urban context, to identify opportunities and practices for material recovery applications, and showcase applications for additive manufacturing at the last stage of the supply chain. Furthermore, it identifies the needs for further research that could support the implementation and diffusion of additive manufacturing in society.

1. Introduction

Cities are known to be the epicenter of human interactions. This is often accompanied by large scale resource consumption. Currently, cities recycle less than 9% of their discarded resources (Schmidt et al., 2020). In particular, solid waste is a worldwide problem for cities, and when not recycled it ends up in landfills or incinerate after usage. New insights into the circularity of materials are required for restructuring solid waste practices, so that waste can be reused or recycled at the end of the supply chain, and resources are brought back to the city (Schmidt et al., 2020).

Waste flows in cities are often difficult to treat due to mixed materials in products and because of complex supply chains. It is a major challenge to create economic value with new practices that could benefit several actors through the supply chain. Plastics constitute one of the most consumed materials in cities. Plastic products come in multiple applications and types, from high value products such as electronics, to single-use bottles and food packaging. Most plastics, however, lose both their functionality and economic value after usage. Without the right treatment, polymers end up becoming a hazardous component in natural ecosystems. Cycle these materials with new technologies can bring new ways to reuse resources and mitigate this risk.

Additive manufacturing (AM), also known as 3D printing, is a novel technology that supports reducing waste and increasing material lifetime. There are several techniques regarding AM, the most common is fused deposition modelling (FDM). This technique entails the extrusion of material at different temperatures with the use of a cartesian coordinate system (Wong & Hernandez, 2012). AM creates objects layer by layer from three-dimensional digital files using a diverse spectrum of materials such as plastics, resins, pastes and metals (Nascimento et al., 2019). AM innovations can be used at all parts of the supply chain for manufacturing, including the end of the supply chain to develop new applications. As such, it can be a feasible and relatively fast solution to waste problems in cities (Oladapo et al., 2021). AM can support the reduction of waste

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flows by the production of products that extend the lifetime of resources used and, recover economic value (Nascimento et al., 2019; Sacco & Cerreta, 2020). Fast prototyping is inherent to AM and can lead to the creation of customized local solutions for multiple industries, for instance in the construction and health sector (Esirger & Ali Örnek, 2020; Nascimento et al., 2019; Oladapo et al., 2021).

A key component of minimizing waste is the product design stage (Esirger & Ali Örnek, 2020), which along with determining use of new technologies, facilitates the creation of new links in the supply chain. Furthermore, the application of 3D design software with technologies like AM allows industries to optimize products and minimize waste (Garmulewicz et al., 2018). The use of AM technology and 3D digital design can increase the impact of circular applications at the local scale (Nascimento et al., 2019). For instance, COVID-19 revealed the need for cities to respond quickly to global crises and use locally available resources as efficiently as possible in the health sector (Ben-Ner & Siemsen, 2017; Oladapo et al., 2021).

There is an opportunity for technologies such as AM to provide solutions with fast prototyping and localized production in urban areas (Croxford et al., 2020). AM provides new alternatives for recycling material, as well as a reduction in the manufacturing process (Croxford et al., 2020; Verhoef et al., 2018). AM has proven to be a reliable solution for customized objects from 3D design, reducing the required amount of resources, logistics and production time (Oladapo et al., 2021).

Beyond changing the structure of the currently linear economic system, closing cycle gaps with AM could help to reduce CO_2 emissions (Schmidt et al., 2020; Verhoef et al., 2018), and to achieve multiple Sustainable Development Goals of the 2030 Agenda i.e., Goal 9 Industry, Innovation and Infrastructure, Goal 11 Sustainable Cities and Communities and Goal 12 Responsible Consumption and Production (Arora & Mishra, 2019). There are however limited spatial, social, environmental and economic means to implement material recovery within the urban context, as few studies investigated what the conditions and implications are for cities aiming to enable such processes.

Circular urban AM is a novel approach to recovering waste and creating new products for cities. Circular urban AM provides insights into ways to cycle materials back through the supply chain and showcases new approaches for local manufacturing. Through 3D design, AM can become an innovative technology insofar as it brings local and customized solutions to extend the lifetime, like for instance plastic food packaging or soil materials (Bañón & Raspall, 2022; Parece et al., 2022; Pariona et al., 2023). The use of these novel technologies, such as AM, in combination with the closing of material loops within cities still needs to be further studied. This holds in particular regarding the lack of regulations and the limited number of realized examples (Tsui et al., 2022).

The stated urban manufacturing (UM) perspective helps to identify city plastic waste flows, main supply chain actors, and their collaborations at an urban scale (Tsui et al., 2022). UM can be described as the transformation of physical material, through labour, tools and/or machines; resulting in a final product produced at an urban scale (Croxford et al., 2020). Related to waste as resource, UM uses a combination of processes to sort and transform materials into new products. AM aims to provide more solutions for cities regarding waste recovery (Birgen & Becidan, 2022; Esirger & Ali Örnek, 2020; Zhang et al., 2020). Main activities such as collection and sorting are key to recycling materials useful for AM and, in doing so, reduce waste (Fahim et al., 2019; Nascimento et al., 2019; Senetra et al., 2019).

In this context, this paper aims to examine the current knowledge and practices in circular additive manufacturing (AM) within the urban context. To achieve this aim, the following four objectives are specified. First, to summarize existing urban solid waste recycling practices based on AM, and their role in a circular economy. Second, to identify new opportunities to close cycles through AM in cities. Third, to identify applications for 3D printing for the last stage of the supply chain, enabling AM and thus closing local loops. And finally fourth, to identify needs for further research that could support the implementation and diffusion of circular AM in society.

By implementing AM at the end of the supply chain, new AM processes and material recovery practices can strengthen the relationship between manufacturers and end users, thereby extending the lifespan of materials and products. In this context, the key contribution of this paper is to understand circular AM in the urban context and its current role in the supply chain. This key contribution is structured around several innovative points that we identified, the potential of AM at the end of the supply chain, improvements around product design, local production at scale and the utilization of multiple materials.

2. Methods

This article is based on a literature review evaluating the state-of-the-art of additive manufacturing (AM) in the urban context. It provides a qualitative analysis of articles focusing on AM and explains how this is applied in an urban context. A Scopus query focused on the aim of this paper was carried out. The Scopus query used was "TITLE-ABS-KEY "urban OR cities OR metropolitan" AND TITLE-ABS-KEY "Circular economy" OR "Urban manufacturing" OR "Additive manufacturing" OR "3D printing" AND TITLE-ABS-KEY plastic".

The search includes papers published in English between 2009 and 2023, and produced an initial sample of 148 articles. To manage the large diversity of articles resulting from the search, we filtered the articles on the basis of their relevance to the main research question and objectives. After screening the abstracts, 70 articles were excluded, because of the lack of application of circular practices. In a second round, selected articles were read and analyzed in detail. After reading the articles, 25 more were excluded because of their lack of connection between AM and circular practices. Therefore, reviewing the remaining 53 articles provides an extensive summary of the available research on the interrelationship between additive manufacturing and local circularity. We specifically analyzed this topic with a focus on solid waste at the end of the supply chain, and what are the implications for sustainability transitions. Fig. 1 shows the steps to get the final sample consisting of 53 articles.

The selected pool of articles brings a diverse and growing array of AM applications related to circularity in the urban context. The final sample contains papers from more than 50 countries. The countries with the most numerous articles were Italy, China, Spain, the United Kingdom, the United States, Portugal, Germany, Chile and Mexico. There is an increase in the number of papers related to circularity and AM in the last five years, from less than 10 annual publications until 2017 to more than 20 after 2023.

The following keywords and phrases relating the circular economy with AM emerged from the pool of articles: recycling, waste management, plastic, municipal solid waste, plastics, human, plastic recycling, plastic waste, 3D printers, cities, city, solid waste, sustainable development, waste disposal, 3D printing, economics, rubber, sustainability, and additive manufacturing.

Along the literature review, we were able to identify circular practices at different stages of the supply chain, while focusing on AM practices at its end. According to Farooque et al. (2019), the transition from linear to circular solid waste is about material recovery. The main actors and processes are distributed around

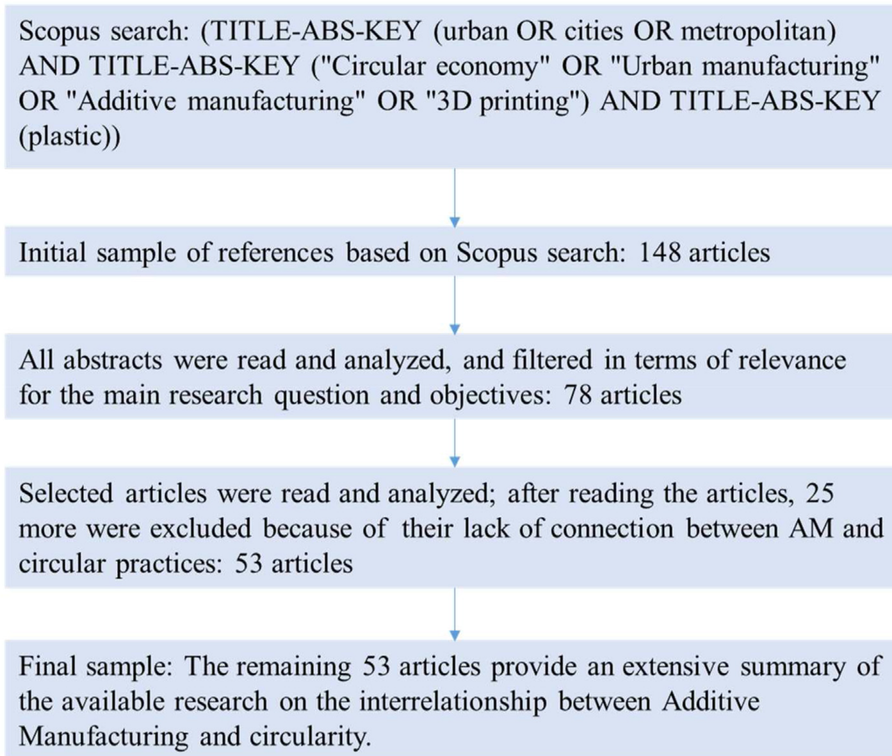

Fig. 1. Flowchart summarizing the steps taken for the selection of materials in this literature review.

suppliers, manufacturers, sales and customers. At the end of the supply chain, these actors interact in different processes such as sorting and collection in waste management.

In the process of reviewing the literature, while organizing and classifying the information, a number of topics became apparent by providing common ground between cities and across the selected articles. These topics provide a rationale for classifying the results of the literature review, and helped us to identify the following five areas of interest for circularity and AM regarding solid waste:

- Waste flow assessment, indicators and monitoring
- Solid waste context in cities
- Citizen consumption practices
- 3D product design
- Circular practices in cities

The five areas selected cover the main elements of the supply chain, including material extraction and usage, manufacturing processes, logistics and end users.

3. Additive manufacturing in an urban context

Fig. 2 provides a summary of the main areas within the body of knowledge about circular AM in cities. Each of these areas is explored in the following sub-sections.

3.1. Waste flow assessment, indicators and monitoring

The first important topic that emerged from the literature review is the monitoring of waste. Six articles out of our sample highlight the importance of applying the right indicators for a constant and precise analysis of waste flows (Gravagnuolo et al., 2019; Hidalgo-Crespo, Moreira, et al., 2022; Liu et al., 2021; Nolasco et al., 2021; Russo et al., 2019; Salguero-Puerta et al., 2019). Through all the supply chain stages, the use of indicators and the monitoring of waste flows bring insights into the systems and the opportunity for their optimization. From the literature review, several methods emerged around solid waste and circular practices.

Life cycle assessment, monetary material flow or material flow analysis provide insights through the supply chain putting emphasis on a specific system flow (Cottafava et al., 2019; Neo et al., 2021; Tangwanichagapong et al., 2020). Life cycle assessment is used to assess material flows for the reuse of end-life plastics (Neo et al., 2021). Monetary material flow was used to integrate new business models and economic incentives into the

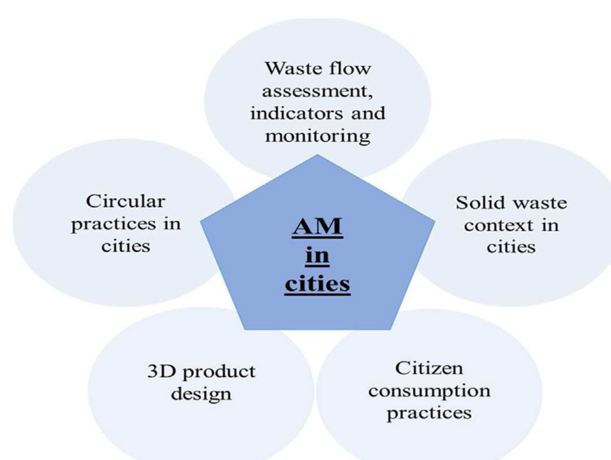

Fig. 2. Five areas of knowledge emerging from the literature review regarding AM.

system (Cottafava et al., 2019). Another example is the use of Material Flow Analysis for quantifying packaging waste flows and possible sustainable resource management (Tangwanichagapong et al., 2020). The use of different performance indicators supports the assessment of the system along the supply chain through time, inducing the implementation of the circular economy (Bertanza et al., 2021). At the same time, these indicators limit the research by determining specific variables for the measurement of a city flow. The flexibility of system flow analysis should be considered to make them easy to replicate and adapt to a specific setting based on local conditions and materials (Saade et al., 2020). Other papers refer to other sustainability, technological, recycling and sorting methods. AM can be used with these methods to better understand which waste flows can be recovered and look for areas of opportunity.

Another example concerns urban strategies based on key performance indicators (KPI), to evaluate waste management metabolism (Voukkali et al., 2021). These initiatives use system flow analysis to identify valuable resources in the system through the entire supply chain (Bertanza et al., 2021; Delgado-Antequera et al., 2021; Savastano et al., 2019; Voukkali et al., 2021). Indicators allow main stakeholders to have a better understanding of the materials and their distribution through the supply chain (Gravagnuolo et al., 2019; Hidalgo-Crespo et al., 2021; Salguero-Puerta et al., 2019). Salguero-Puerta et al. (2019) used a multivariable analysis to enable a variety of benefits from a multi-dimensional perspective of social, economic and environmental sustainability. Delgado-Antequera et al. (2021) reflect on an approach based on a global inefficiency score and individual inefficiency scores for solid waste.

These techniques imply the need to include different variables based on environmental and economic indicators regarding waste. Saade (2020) argues for the need to address other improvements achieved with AM, such as customization, fewwer labour work hours and local impact based on environmental indicators Based on waste monitoring, AM can provide insights around material recovery, resource quality and application in cities (Bañón & Raspall, 2022; Garmulewicz et al., 2018).

3.2. Solid waste context in cities

Current practices in solid waste collection are regulated at different levels of government (Delgado-Antequera et al., 2021). Regional and local public institutions oversee the creation and application of regulations and the incentives to implement new practices (Ghisellini & Ulgiati, 2020). Some of the articles reflect on solid waste practices by citizens and how governments can improve conditions. Countries such as Italy, Brazil or Mexico look for national and regional patterns in order to provide advice in the entire country, while others such as Poland, Norway or Ecuador focus on local practices tailored to each municipality (Birgen & Becidan, 2022; Chlopecký et al., 2020; Ghisellini & Ulgiati, 2020; Hidalgo-Crespo et al., 2021; Hidayat et al., 2022; Pablo Emilio et al., 2022; Sereda & Flores-Sahagun, 2023). Both approaches point out that waste production ultimately depends on the daily behavior of citizens (Wilkinson & Williams, 2020). Other actors such as electronics, food, drink, and packaging companies are involved in the creation of the current systems supply chain, the interactions between these actors create new regulations, social movements, or new products (Tsui et al., 2021; 2022; Voukkali et al., 2021). Other authors address the importance of sorting for waste recycling treatment (Rhodes, 2018; Schuch et al., 2023; Tejaswini et al., 2022a; Tejaswini et al., 2022b; Tejero-Olalla et al., 2023); and strategies to develop initiatives locally based on material sorting (Bagheri et al., 2020; Chlopecký et al., 2020; Ezeudu & Ezeudu, 2019; Tsui et al., 2022). Wu and Yabar (2021) reflects on the impacts of AM and addresses the importance of activities such as collection, recycling and manufacturing.

In high- and middle-income countries, sorting and recycling regulations are being implemented, while landfill practices in middle- and low-income countries still take place. Regulations are a prerequisite for switching to a circular system because they enable and foster the adoption of circular economy (CE) practices (Ghisellini & Ulgiati, 2020). The use of CE concepts is reflected in several papers as a framework for the creation of regulations and initiatives (Ghisellini & Ulgiati, 2020; Zorpas, 2020). These initiatives include the need to negotiate and interact between main actors (Delgado-Antequera et al., 2021). In the creation of regulations, public and private actors collaborate to bring solutions suited to local needs (Shin et al., 2020). Zorpas (2020) reflects on the importance of a local strategy specific to a given place, which also includes flexibility and further adjustments. There is a need to negotiate an interaction between actors for the successful creation and implementation of circular policies, strategies and incentives (Delgado-Antequera et al., 2021). Husgafvel et al. (2022) reflects on circular practices in Finland and addresses the need of responsible public procurement for faster implementation.

CE is seen as a solution for global environmental problems with a broad framework for implementing circular practices (Ghisellini & Ulgiati, 2020). On the other hand, Shin et al. (2020) reflect on the steps for proper implementation of circular practices in a local context. The different application of CE concepts varies as to the spatial scale and main objectives of each initiative, making it hard to create a concrete methodology to follow. For now, CE is a flexible framework for the closing of waste loops and material recovery in different sectors and industries (Ghisellini & Ulgiati, 2020; Shin et al., 2020). The use of CE is considered more as strategies and practices rather than regulations (Cruz Sanchez et al., 2020; Gambino et al., 2020). The lack of regulations based on CE and AM reduces the capacity to replicate and implement innovations into a city system through the supply chain (Saade et al., 2020). Klementis (2020) points out the importance of businesses adopting circular practices. The interaction with the private sector can be a good combination for public institutions to create new regulations and initiatives for companies and society at different stages of the supply chain. Further research based on AM can benefit circular practices by material recovery at the end of the supply chain. AM can bring new solutions and combinations for waste industries interesting for the public and private sector. Waste flows from the construction, manufacturing and packaging sectors can be introduced to the city as functional products.

3.3. Consumption practices

Consumer practices are strongly related to urban solid waste and sorting practices (Gambino et al., 2020; Hidalgo-Crespo et al., 2021; Nolasco et al., 2021; Roche Cerasi et al., 2021; Sacco & Cerreta, 2020; Tangwanichagapong et al., 2020; Wilkinson & Williams, 2020). Some authors reflect on citizen practices and different incentives as a way to improve collection and sorting activities (Roche Cerasi et al., 2021). Citizen participation is key for sorting waste, and CE practices can accelerate sustainable transitions (Ghisellini & Ulgiati, 2020) Cities are an epicenter of consumer interactions and major producers of waste. Local governments provide solid waste services to cities, this scenario is seen all over the world (Bagheri et al., 2020; Bertanza et al., 2021; Xiao et al., 2022).

Linear consumption is often seen in cities, where solid waste is disposed of and recycled in small percentages (Ahmed et al., 2023; Hidalgo-Crespo et al., 2022; Hidalgo-Crespo, Moreira, et al., 2022; Parece et al., 2022). As regards consumption practices, companies need to implement strategies that considered waste generation, material recovery and closed loops of waste in different industries based on technological availability (Nolasco et al., 2021). To accomplish this, the collaboration of the main actors and the involvement of citizens are essential to keep the system going. Roche Cerasi et al. (2021) argue that the constant interaction between actors determines the results of practices. Others have noted how decisive local practices are for sorting activities and addressed the importance of collection centers (Nolasco et al., 2021). Based on waste plastic sorting and collection practices, CE activities involve citizens and consumption habits (Ratner et al., 2020). A city context allows the use of spatial aspects to empower citizens and promote local solutions (Gambino et al., 2020). According to Sacco and Cerreta (2020), these solutions need to be made based on economic cultural and social values to increase the impact of implementations. Other authors suggest the use of abandoned buildings and inclusion for marginal communities to collect and recycle solid waste locally in urban areas (Husgafvel et al., 2022; Tsui et al., 2021; Wilhelmsson, 2022). Plastics, in particular related to packaging, are one of the biggest waste flows in cities (Hidalgo-Crespo et al., 2021). The need to close loops here is often already identified in cities, e.g. related to plastics in the supply chains of food, packaging and electronics, and thus it can represent an opportunity for circular practices and participation of local stakeholders (Gan et al., 2021; Pindar & Dhawan, 2021; Wilkinson & Williams, 2020). Ratner et al. (2020) reflect on the lack of infrastructure and knowledge in cities around circularity, limiting consumer behavior practices locally. Other limitations relate to the availability of materials in the regions, the need of import specific resources and the capacity of the material to be reused (Shah & Paul, 2022; Tsui et al., 2022). Reusing materials doesn't imply an infinite recycling possibility. Regarding plastics, a maximum of around 6 times is mentioned, before mechanical and other characteristics couldnot be secured anymore (Li et al., 2022; Preka et al., 2022; Tsui et al., 2020).

3.4. AM *product design*

AM can be used all along the supply chain (Domingues et al., 2017). This allows actors and citizens to have tangible objects as products of recycled materials (Garmulewicz et al., 2018). Fahim et al. (2019) reflect on the creation of new biomaterials out of waste for additive manufacturing filaments. Simultaneously, recycling plastic into filament extends the life of the material and thereby upscales the value of the resource (Domingues et al., 2017; Garmulewicz et al., 2018). Crolla et al. (2017) reflect on the design and production not only of fast prototyping but of manufactured customized components applied to the building sector. Several examples of AM product design found in our sample show how AM can be useful to change the current linear system (Esirger & AliÖrnek, 2020; Fetterman et al., 2014; Kumar & Agrawal, 2021; Narazani et al., 2019; Narazani, Eghtebas, Klinker, et al., 2019). These initiatives give space for new practices and knowledge creation useful for main actors related to policy, solid waste regulation, circularity and AM (Andriya et al., 2022; Bañón & Raspall, 2022; Crolla et al., 2017; Esirger & AliÖrnek, 2020; Kumar & Agrawal, 2021; Nascimento et al., 2019; Varo-Martínez et al., 2022).

Most of the research tends to analyze the optimization of design and prototyping (Crolla et al., 2017; Varo-Martínez et al., 2022), rather than examine the potential for circular practices related to the material used (Bañón & Raspall, 2022; Mantelli et al., 2019). Some AM examples do reflect on the development of urban solutions, such as the production of urban furniture and the local application of circularity for material recovery (Kumar & Agrawal, 2021; Narazani et al., 2019; Narazani, Eghtebas, Klinker, et al., 2019). Moreover, the use of AM in prototyping and product development enables the identification of other opportunities for this novelty (Cruz Sanchez et al., 2020). The creation of prototypes and functional pieces allows us to implement AM in different sectors such as construction, manufacturing industries, medicine and material recovery for cities (Esirger & AliÖrnek, 2020; Fetterman et al., 2014; Rochman et al., 2018, 2020; Vincitorio et al., 2021; Zhang et al., 2020). Through AM, design can serve to create and improve solutions in different sectors using local resources (Ajwani-Ramchandani & Bhattacharya, 2022; Li et al., 2022; Setaki et al., 2023; Tsui et al., 2021, 2022; Varo-Martínez et al., 2022).

3.5. *Circular practices in cities*

At an urban level, several articles addressed the need for collection and sorting plants for sustainable treatment of waste in cities (Liu et al., 2021; Neo et al., 2021; Voukkali et al., 2021). Collection and sorting processes are based on population consumption habits and spatial aspects (Delgado-Antequera et al., 2021; Neo et al., 2021; Roche Cerasi et al., 2021). There is a debate around the kind of collection methods, e.g. whether it should be in house or though collection points in neighborhoods. This, as AM is closely linked to the need of securing resources, e.g. by sorting practices in households and businesses to avoid the mixing of waste flows (Assi et al., 2020; Liu et al., 2021; Polygalov et al., 2021; Savastano et al., 2019; Tangwanichagapong et al., 2020).

Several techniques are focused on energy recovery by incineration (Dashti et al., 2021; Hossain et al., 2021) and chemical plastic transformation (Dogu et al., 2020; Hermoso-Orzáez et al., 2020). Roche Cerasi et al. (2021) reflect on post-consumption practices and the problem of mixing waste flows in cities. These practices reduce the possibility to reuse resources by mechanical material transformation in the first stage (Ellen & Company, 2014). After all, recycling techniques depend on the purity of resources, the quality of the local system and the way waste is sorted (Roche Cerasi et al., 2021).

There are several initiatives related to plastic recycling and the use of new technologies. Often, these circular practices are used to engage actors and improve consciousness regarding disposal and sorting of waste (Ghisellini & Ulgiati, 2020; Hermoso-Orzáez et al., 2020; Moscato, Munoz, & Gonzalez, 2020; Oyake-Ombis et al., 2015; Satchatippavarn et al., 2016; Tangwanichagapong et al., 2020). Materials can be recycled at different levels in an urban context (Ellen & Company, 2014). Other authors reflect on the need for investment in solid waste infrastructure related to collection and sorting for further recycling processes (Neo et al., 2021; Tsui et al., 2022).

To ensure a better local implementation, eco-efficiency indicators to monitor regulations, practices and processes related to solid waste should be included (Delgado-Antequera et al., 2021; Tangwanichagapong et al., 2020). With the right implementation, polymers and other materials can be recycled and given new shapes and uses without modifying their material properties (Ghisellini & Ulgiati, 2020; Nascimento et al., 2019; Tangwanichagapong et al., 2020). The use of AM covers a wide range of applications, locally re-introducing materials to different sectors such as food, industry, and construction (Bañón & Raspall, 2022; Garmulewicz et al., 2018). CE strategies can be supported in the cities' supply chains through strategies, regulations, activities, monitoring and constant feedback (Gravagnuolo et al., 2019; Nascimento et al., 2019). Ghisellini & Ulgiati (2020) reflects on the value of CE for a sustainable transition in a local and national context (Ghisellini & Ulgiati, 2020). CE studies the transition from linear to circular systems in which material can be looped, in this context, AM can serve as a strategic tool to reuse resources (Birgen & Becidan, 2022; Ghisellini & Ulgiati, 2020).

In this case, AM uses recycled materials either from organic sources such as PLA (Confente et al., 2020) or recycled materials such as PET and carbon fibers (Domingues et al., 2017; Garmulewicz et al., 2018; Mantelli et al., 2019). Several examples of the recycling of plastics as 3D printing materials are described in the literature (Cruz Sanchez et al., 2020; Ghisellini & Ulgiati, 2020; Nascimento et al., 2019). Mantelli et al. (2019) and Tsui et al. (2020, 2022) state that the use of 3D printing can close small loops and bring design-customized solutions at a local scale. To foster circular systems at an urban level, Landrigan et al. (2020) suggest the need to emphasize implementation and further R&D of recycling techniques instead of a focus on plastic waste energy recovery. There is a need to further develop solutions regarding AM and the optimization of design and materials for industries, in order to provide local solutions suited to the urban context while extending the life of urban waste as new products (Crolla et al., 2017; Domingues et al., 2017; Esirger & AliÖrnek, 2020; Kumar & Agrawal, 2021; Rochman et al., 2020; Saade et al., 2020; Tsui et al., 2021).

Valenzuela et al. (2021) argues for the need of reverse logistics and stakeholders' participation for a better system design and implementation in cities. New solutions are put forward based on new technologies, while the use of the Internet of Things (IoT) introduces new tools for the participation and monitoring of different actors through the supply chain (Ponis, 2021). Mo et al. (2009) point out the lack of infrastructure for new processing and sorting practices, limiting R&D based on material recovery. An emphasis on sorting techniques is suggested to boost systems thinking and collaboration between actors (Polygalov et al., 2021).

There is a lack of regulations on the application of AM in the building environment, as well as a gap related to the implementation of new technologies available and collection and recycling practices for solid waste. The use of AM can create opportunities for circularity at the end of the supply chain (Bañón & Raspall, 2022; de Oliveira Faria et al., 2021; Esirger & AliÖrnek, 2020; Pariona et al., 2023; Setaki et al., 2023). The combination of AM and circularity allows solutions that can be applied in cities over time, while putting emphasis on replicability and closed material loops (Bañón & Raspall, 2022; de Oliveira Faria et al., 2021; Esirger & AliÖrnek, 2020; Garmulewicz et al., 2018; Kumar & Agrawal, 2021; Pariona et al., 2023; Setaki et al., 2023).

4. Discussion

4.1. Potential gaps and opportunities for circular AM

In this section, we discuss the main outcomes of our literature research with respect to gaps, and opportunities of AM in cities, and provide insights for further research, practice, and policy implementation with a focus on systemic issues and cross-scale synergies.

A number of new insights emerged after consolidating the information from all the papers included in the review. A broad perspective from global to local helps to translate an international framework of the plastic supply chain into regional and local policies, practices and actions. Plastic waste comes from a global supply chain that ends up at a local scale through the distribution of goods and packaging of products consumed by citizens (Gambino et al., 2020). From the global to the local scale; non-profit organizations, governments, the private sector and the broader society are connected at different levels focusing on local actions (Ghisellini & Ulgiati, 2020). In this context, AM in an urban scope allows us to limit the territorial boundaries, providing specific opportunities for regulations to deliver by reducing transportation and increasing reverse logistics (Bañón & Raspall, 2022; de Oliveira Faria et al., 2021; Delgado-Antequera et al., 2021; Nascimento et al., 2019; Roche Cerasi et al., 2021; Wu & Yabar, 2021).

Since most products are developed with multiple materials and thus result in mixed waste flows at a city level, sorting at a local scale help to sort these flows into pure and high quality materials for recovery (Chlopecký et al., 2020; Pariona et al., 2023; Wilkinson & Williams, 2020; Xiao et al., 2022). Global manufacturing channels such as the plastic bottles industry, result at the end of the supply chain in creation of waste which is handled by local actors in charge of regulations and collection activities (Ghisellini & Ulgiati, 2020; Russo et al., 2019; Rutkowski & Rutkowski, 2017; Velis, 2015). The distribution of responsibilities regarding waste treatment is at times still unclear for the public and private sectors, and is dependent on the local context. In low- and some middle-income countries, after usage, the resources are dumped in landfills, and in high- and some middle-income countries, part of the waste is recovered (Hidalgo-Crespo et al., 2021; Neo et al., 2021). Urban waste must be treated without losing value to close material loops, based on the recovery of the materials and resources in a specific place (Bertanza et al., 2021; Pindar & Dhawan, 2021).

The creation of regulations around AM, as well as constant monitoring regarding sorting and collection, allow both public and private actors to participate in their implementation. Resource recovery monitoring provides useful information for later feedback on regulations and better practices (Gravagnuolo et al., 2019; Senetra et al., 2019; Stengos et al., 2019). The use of AM at a local level can contribute to plastic waste recovery at the end of the supply chain. Some of the literature addressed how these initiatives can help to set regulations and practices at national, regional and local levels (Ghisellini & Ulgiati, 2020; Nascimento et al., 2019). In the last years, the application of AM has taken place at a niche level (Garmulewicz et al., 2018; Nascimento et al., 2019; Tsui et al., 2021; 2022; Wu & Yabar, 2021). There is a gap between AM applications and the availability of this innovation, due to size, resources used and the current local needs (Garmulewicz et al., 2018). The lack of interaction between the private and public institutions reduces the potential of novelties such as AM to be implemented in cities (Domingues et al., 2017; Ferronato et al., 2020; Wu & Yabar, 2021).

4.2. Limitations for circular AM

Nevertheless, severe limitations and broad research gaps still appear in the literature. For instance, there is limited experience in required steps and conditions needed for the implementation. Studies and innovations have been developed in different scenarios, but there is a need to have a more organized intervention in the various local contexts (Hossain et al., 2021; Klementis, 2020; Mo et al., 2009; Nascimento et al., 2019; Neo et al., 2021; Sacco & Cerreta, 2020; Voukkali et al., 2021; Zorpas, 2020). The transition to local practices and continuity of initiatives are key for the success of AM in cities. To create value and regulations out of these interactions, there is a need for constant collaboration among the main actors involved in the collection and sorting of waste. Several methodologies have been created to identify waste flows, but the implementation level at a local scale remains low (Ali & Geng, 2018; Delgado-Antequera et al., 2021; Gravagnuolo et al., 2019; Hossain et al., 2021; Liu et al., 2021; Neo et al., 2021; Voukkali et al., 2021). Local regulations can present possible options for circular AM solutions, for instance focusing on the separation of waste flows, which is crucial to develop innovation based on material recovery for circular AM. Similarly, the lack of resource circularity between businesses and industries reduces the impact of circular practices and the possibility to become circular at an urban scale (Ezeudu & Ezeudu, 2019). Further research based on recovered materials for AM in cities should take place at the last stage of the supply chain. (Garmulewicz et al., 2018; Nascimento et al., 2019).

4.3. Future of circular AM in the urban context

To close AM gaps, research would be needed to address pending questions (see Section 3 above) and to produce new insights about the interaction between (i) actors related to material production in the supply chain, (ii) waste collection companies regarding the feasibility of material recovery, and (iii) industries that could benefit from AM while contributing to CE with new applications at the end of the supply chain.

4.4. Product design to reshape current supply chain

A focus on product design could reshape the supply chain, and at the same time, the supply chain needs to be reshaped to secure further uptake of circular AM. There is a need to create incentives focused on local needs, and to take the differences between locations into account (Mo et al., 2009; Satchatippavarn et al., 2016; Savastano et al., 2019; Shin et al., 2020; Tangwanichagapong et al., 2020). The creation of value with circular design can mobilize actors and close the gaps between sectors, creating space for regulations, replication and the scaling up of practices for cities (Garmulewicz et al., 2018; Ghisellini & Ulgiati, 2020; Nascimento et al., 2019). The recycling of urban plastic waste is different depending on the different local contexts (Tsui et al., 2022). AM serves as a solution to several waste sources besides plastics, such as metal and concrete in construction and industrial design for other manufacturing industries (Bañón & Raspall, 2022; Kumar & Agrawal, 2021; Narazani et al., 2019; Narazani, Eghtebas, Klinker, et al., 2019).

4.5. Regulations in cities for material recovery around circular AM

The current lack of specific policy and regulation around circular AM provides an opportunity for cities to create and implement them, and thus enable material recovery. Policies and regulations play an important role, not only in the implementation of new practices, but also in the replication in other locations and contexts (Garmulewicz et al., 2018; Hossain et al., 2021; Mo et al., 2009; Shin et al., 2020; Tangwanichagapong et al., 2020; Voukkali et al., 2021). It is important to take into consideration the incentives used for AM implementation at an urban scale, to take the main actors into account, and to identify common interests between them and the existing local issues (Tangwanichagapong et al., 2020). The use of 3D design to create suitable solutions for cities can present an opportunity for continuous replication of AM, material recovery and circular-based products responding to current city needs.

4.6. Cross-scale regulation interactions for material recovery in cities

A cross-scale regulation interaction can provide constant feedback loops leading to material recovery. AM brings insights into material recovery, creates new paths to close loops and the local customization of urban plastic waste (Bañón & Raspall, 2022; de Oliveira Faria et al., 2021; Mantelli et al., 2019; Nascimento et al., 2019). The use of 3D design and software tools to optimize prototypes allows industries, businesses and communities to rethink the way they manufacture their goods (Crolla et al., 2017). Further research on this aspect is needed on local waste practices and the potential for material recovery used for the manufacturing industries (Domingues et al., 2017; Esirger & AliÖrnek, 2020; Garmulewicz et al., 2018; Mantelli et al., 2019; Nascimento et al., 2019). This technology allows us to introduce new materials, such as biodegradable polymers or recycled materials, making industries more sustainable (Fahim et al., 2019; Garmulewicz et al., 2018). The interaction of the public sector, AM industry and solid waste management actors at local, regional and national levels can lead to the creation of policies around circular AM.

AM can bring back recovered resources to the city through renewed purposing, close materials loops and apply them in different industries. Several authors identify the last phase of the supply chain as the stage where materials can best be recovered in several ways (Ahmed et al., 2023; Bañón & Raspall, 2022; Birgen & Becidan, 2022; Kumar & Agrawal, 2021; Nascimento et al., 2019; Pariona et al., 2023; Rutkowski & Rutkowski, 2017; Velis, 2015). The upgrade of plastic waste by design proves to scale up materials into goods for cities (Bañón & Raspall, 2022; Crolla et al., 2017; Domingues et al., 2017; Fetterman et al., 2014; Kumar & Agrawal, 2021; Setaki et al., 2023; Velis, 2015). The application of AM with local materials can be useful to develop customized items in shorter periods of time, providing opportunities to industries such as construction or health (Bañón & Raspall, 2022; de Oliveira Faria et al., 2021; Garmulewicz et al., 2018; Kumar & Agrawal, 2021; Narazani, Eghtebas, Klinker, et al., 2019; Nascimento et al., 2019; Oladapo et al., 2021; Setaki et al., 2023). The examples given are based on product development, the creation of sound absorbers, modular floating farms, prototyping and furniture (Bañón & Raspall, 2022; Crolla et al., 2017; de Oliveira Faria et al., 2021; Narazani, Eghtebas, Klinker, et al., 2019; Setaki et al., 2023). Garmulewicz (2018) reflects on AM as a potential novelty to alter the current linear system in places where the collection and sorting of waste are already underway (Berry et al., 2022; Chlopecký et al., 2020; Garmulewicz et al., 2018; Kumar & Agrawal, 2021; Li et al., 2022). Also, the amount of waste in cities can provide enough resources for cities in terms of quality and quantity (Garmulewicz et al., 2018; Tsui et al., 2021; 2022). AM and its implementation in cities can be the basis for the development of clear paths for material recovery. Based on the insights of this literature review, further research related to collection and sorting practices, circular practices between stakeholders, incentives and product design can bring opportunities for AM implementation at an urban scale based on local needs and resource availability.

5. Conclusions

While providing a broad perspective on circular practices and their implementation in solid waste, this literature review identifies the current situation of AM. Amongst the most relevant applications, we summarize urban solid waste recycling practices based on AM, material recovery involving 3D design and manufacturing in cities, discuss relevant regulations, and identify opportunities for these processes at the last stage of the supply chain. We conceptualize the spatial use of infrastructure, and the combination of technologies used to manufacture goods, taking advantage of opportunities provided by the spatial aggregation of activities in a city.

From the regulations and policy perspective, AM still does not have a strong enough basis to become a key factor in a specific industry. This lack of strategies and actions manifests at the local level and is a consequence of the lack of regulations at the regional and national level, which so far has led to a failure to standardize AM in industries with application opportunities – such as construction and health. The combination of several parts of the supply chain makes it hard to achieve an agreement incorporating the interests of the four main actors involved: public and private sectors, non-profit organizations, as well as citizens themselves, need to all be involved in the process of making decisions and co-creating regulations.

Collection, recycling and AM take place in the last stage of the supply chain. The diffusion of new functional designs that have already been prototyped can help citizens to be in contact with materials and 3D printing, creating solutions suited to their needs. The constant feedback from citizen involvement provides plenty of opportunities for monitoring and knowledge co-creation. To realize the full potential of waste collection and derive transformative activities based on AM, it is important to consider the needs of different actors such as government, various industries (e.g., construction, health), and public institutions, in order to set the best context for co-creating regulations.

Several technologies and methods have been used along time to transform materials. Before materials go into chemical transformation or energy recovery processes, the use of AM to recycle plastic materials allows us to close the loops at different levels. Focusing on plastics, AM provides new alternatives for material circularity in cities. The advantage of AM regarding waste creation, energy saving and resource consumption during the manufacturing process (in comparison with traditional manufacturing processes) makes it an ideal tool for plastic waste recovery, particularly in cities. The elaboration of hardware and software related to 3D printing is crucial for a good implementation that can be easily reached and replicated in other locations and at larger production scale. There are still some open questions with respect to AM, e.g., about collection and sorting practices that could help bringing material back to the materials flows in use in the urban system: collection and sorting practices are dependent on consumer consumption practices at the local level.

Finally, an often forgotten key element of AM is product design. In order to have circular practices, 3D design provides us with local solutions based on current needs. The customization around AM allows to reduce the cost of manufacturing and material waste. 3D design offers feasible solutions that can be used later, replicated and customized without high production costs. The combination of solid waste material recovery in cities and 3D design allow local actors to create solutions based on their needs. This approach can help implement better practices based on actors' interests. The use of incentives to upscale opportunities for AM beyond the local niche, combining multiple solutions at the end of the supply chain, can make a significant contribution to closing loops of waste for cities. Circular AM solutions can be replicated in other regions and are adaptable to other local needs. More research about how to scale up AM-related technology needs to be performed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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