The benefits and barriers of Additive Manufacturing for Circular Economy: a framework proposal

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ABSTRACT

According to preliminary research, additive manufacturing (AM) is a promising technology for developing circular material flow. However, the impact of AM on the circular economy (CE) is unclear. To address this issue, this study proposes a framework that presents the benefits and barriers of AM for CE. This framework is valuable for generating a new path for AM production and restructuring the supply chain. This study uses a multi-method research approach to propose this framework. (i) Secondary qualitative data were used to find the best way to categorise the results; (ii) literature review was applied to understand how the phenomenon of AM adoption meets or does not meet CE requirements; and (iii) interviews with experts were conducted to evaluate the results. The findings help to systematically highlight the benefits and barriers of AM for the CE and provide a research agenda that identifies specific actions that AM stakeholders should take to align with the CE. The broader potential of AM as a beneficial technology for CE is contingent on overcoming the identified critical barriers, and the economic viability of circular AM activities. The findings could be relevant because they clearly show how AM technology brings companies and society closer to or farther from CE.

Keywords: Additive manufacturing; Three-dimensional printing; Circular economy; Sustainability

1. Introduction

Additive manufacturing, one of the cornerstones of Industry 4.0 (I4.0), has recently gained popularity (Petsiuk & Pearce, 2020). Three-dimensional (3D) printing technology is a part of additive manufacturing, operating at the heart of the new technology (Ivan & Yin, 2017). The growing competitiveness has prompted considerable changes in the product development process for corporations and their designers. In this context, AM advancements have emerged as a solution since they allow enterprises to customise items to match clients' expectations (Sun et al., 2020), once AM technical characteristics enable personalised manufacturing. In contrast to conventional subtractive manufacturing, where a product is shaped by removing material to achieve a desired shape, AM creates parts by adding material in layers (ASMT, 2013). This provides the advantage of building customised parts with geometric complexities, facilitating the creation of personalised products (Kohtala and Hyysalo, 2015).

Over the last decade, AM has been used almost exclusively for prototyping purposes. However, its use has recently been extended to industrial applications (Hassani, 2020), and small-scale mass production (3D HUBS, 2019). AM is particularly relevant in the aerospace and automotive industries (Stentoft et al., 2020) and drives significant innovations in medicine (Tejo-Otero et al., 2020), manufacturing and engineering (Gibson et al., 2014), and customised production (Kohtala and Hyysalo, 2015). For instance, Nike and Adidas use AM for customised shoes (Glenday, 2017). In the medical field, 3D printing has applications in many areas. For example, in orthopaedics, a start-up company, Sols, offers business models to distribute its 3D printed customised insoles (Jansen et al., 2014). In the automotive industry, custom parts can be produced to serve customers in the car tuning (Jansen et al., 2014).

Also, other factors such as delivery speed (Berman, 2012) and product and process innovation possibilities (Niaki & Nonino, 2017a) can influence a company's decision to adopt AM. The development of complex shapes based on traditional geometric modelling in CAD (Computer Aided Design) systems drives the creation of such innovative products. It is the case of complex shapes optimized for highly efficient fluid-dynamic performances, such as device blowers and diffusers (Raffaeli et al., 2021). Also, the complexity is necessary for some biomedical applications (e.g., to increase the osteointegration of the prostheses thanks to a porous layer) (Raffaeli et al., 2021). Another factor to consider is the potential competitive advantage gained by operating in uncertain markets that require a diverse range of products and adaptability to changing customer demands (Weller et al., 2015).

Given the wide range of factors that can boost AM adoption, the pace of its diffusion depends on how different organizations employ AM and the extent to which AM makes a company's products marketable (Martinsuo & Luomaranta, 2018). Accordingly, changes in strategic production plans are likely to be necessary, as decision-making demands manufacturing organizations to examine the broad effects of technology on their supply chains, operations, and management (Martinsuo & Luomaranta, 2018).

Petsiuk and Pearce (2020) predicted that AM would grow rapidly owing to numerous advantages and adoption factors. Therefore, AM growth is expected due to its advantages and significant social and economic impact. 3D HUBS (2019) predicts a 23.5% annual growth in the 3D printing market over the next five years. Given these forecasts, concerns regarding the impact of AM on the Circular Economy context have recently emerged (Sun et al., 2020). Circular economy is a worldwide trending academic and business field (Nikolaou and Tsagarakis, 2021). Companies all over the world are exploring ways to transition to CE business models (Knable et al., 2022) to improve sustainability performance (Mora-Contreras et al., 2022) and economic performance (Giampietro & Funtowicz, 2020). A growing number of recent studies have revealed the superiority of circularity versus linearity in the supply chain (Atabaki et al., 2020; Saccani et al., 2022; Shekarian et al., 2021).

Some studies have already perceived the importance of verifying the influence of I4.0 technologies on CE (De Sousa Jabbour et al., 2018; Laskurain-Iturbe et al., 2021; Rosa et al., 2020; Viles et al., 2022), since it represents important industrial paradigms. Furthermore, because the ability of CE to add value while keeping resources looping back into the economy, it has become an essential competitive advantage (Giampietro & Funtowicz, 2020). Additionally, making circular products can be justified from a business perspective (Rabta, 2020). Accordingly, the need for more circular business models has also begun to grow with an emphasis on new smart factories, including the AM industry (Centobelli et al., 2020), since CE can be combined with many business and industry sectors, suggesting high entrepreneurial diversity and adaptability (Tsironis et al., 2022).

Owing to this, the link between AM and CE has also recently begun to be examined in some studies (Ferreira et al., 2021; Hettiarachchi et al., 2022; Ponis et al., 2021; Romani 2021.) Ferreira et al. (2021) describe how wastes can be used as input materials for additive manufacturing processes in an industrial symbiosis scenario. Ponis et al. (2021) examine six thematic categories, including AM methods, AM materials, recycling, reusing, remanufacturing, and mending, to identify research gaps and potential future applications at the confluence of AM and CE. Case studies of design, materials, and extrusion-based AM for waste valorization are found and gathered by Romani et al. (2021). More recently, Hettiarachchi et al. (2022) investigated the interrelationships between major AM decisions, drivers, operational practices, and CE implementation techniques to operationalise AM in the CE context. However, despite recent research, some issues surrounding the intersection of AM and EC remain unclear.

As an incompletely developed technology, the future trajectory of AM remains uncertain. There are several uncertainties regarding this technology's alignment with the system's redesign preconised by the CE (Despeisse et al., 2017). Therefore, there is no clarity on how additive manufacturing supports a circular economy. This lack of understanding is further highlighted by the limited research on the beneficial impacts of AM on operations management within a CE context (Rosa et al., 2020). Additionally, there is a lack of literature on the specific applications of AM that support a CE (Sanchez et al., 2020). Therefore, the first gap to be addressed in this study is the need to better understand and explore how AM can contribute to a circular economy.

AM technology has intrinsic features that may support CE. Due to its ability to adapt products to changing demands and circumstances, AM may be able to offer new design solutions with prospects for product life extension because it permits reuse and recovery (Santander et al., 2020; Sauerwein et al., 2019; Sauerwein and Doubrovski, 2018). However, it is unclear whether AM can actually promote a more circular usage of resources (Despeisse et al., 2017). The circular flow of materials is a key component of CE (Kirchherr et al., 2017; Yuan et al., 2006), however, the AM technique has several challenges with recycling (Garmulewicz et al., 2018; Sanchez et al 2020; Vidakis et al., 2020). Additionally, biodegradable materials have been hardly used in AM (Faludi et al., 2019). Instead, AM often uses virgin plastics derived from fossil fuels, which can exist in the environment for centuries after disposal and are toxic to aquatic organisms (Behm et al., 2018). Furthermore, AM may stimulate higher levels of consumerism, immediate gratification, and a disposable society owing to its intrinsic characteristics (Unruh, 2018), which can negatively impact the environment (Rejeski et al., 2018; Kunkel & Matthess, 2020). Thus, some barriers for AM to reach CE have been sporadically reported by these researches. However, the state of art regarding those barriers still missing in literature. Therefore, the second gap in this study is: the barriers that limit AM from fitting into a CE context need to be better understood and addressed.

In this context, it is important to understand the alignment of AM with CE and existing research gaps. This work aims to fill these gaps by exploring, through a multi-method study, how AM technology brings companies or society closer to or pushes them further away from the CE. Following these research gaps, the research questions (RQ) that guide our research are:

RQ1: How does AM support the implementation of the CE?

RQ2: In what ways does AM prevent greater circularity from being achieved?

The multi-method approach combines secondary data collection, literature review, and expert interviews. The results paved the way for a critical discussion and elaboration of a future agenda to advance towards a circular AM.

The remainder of this study is organised as follows. In Section 2, the methodological procedures are presented and the research steps are described in detail. Section 3 presents the results, which are discussed in Section 4. Also in section 4 are presented future research avenues, and study limitations. Section 5 provides conclusions.

2. Research method

The research method used in this study involved a combination of consulting secondary qualitative data (reports on the CE), a literature review, following Denyer and Tranfield (2009), and interviews with experts. The logical structure of the combination of these methods is illustrated in Fig. 1.

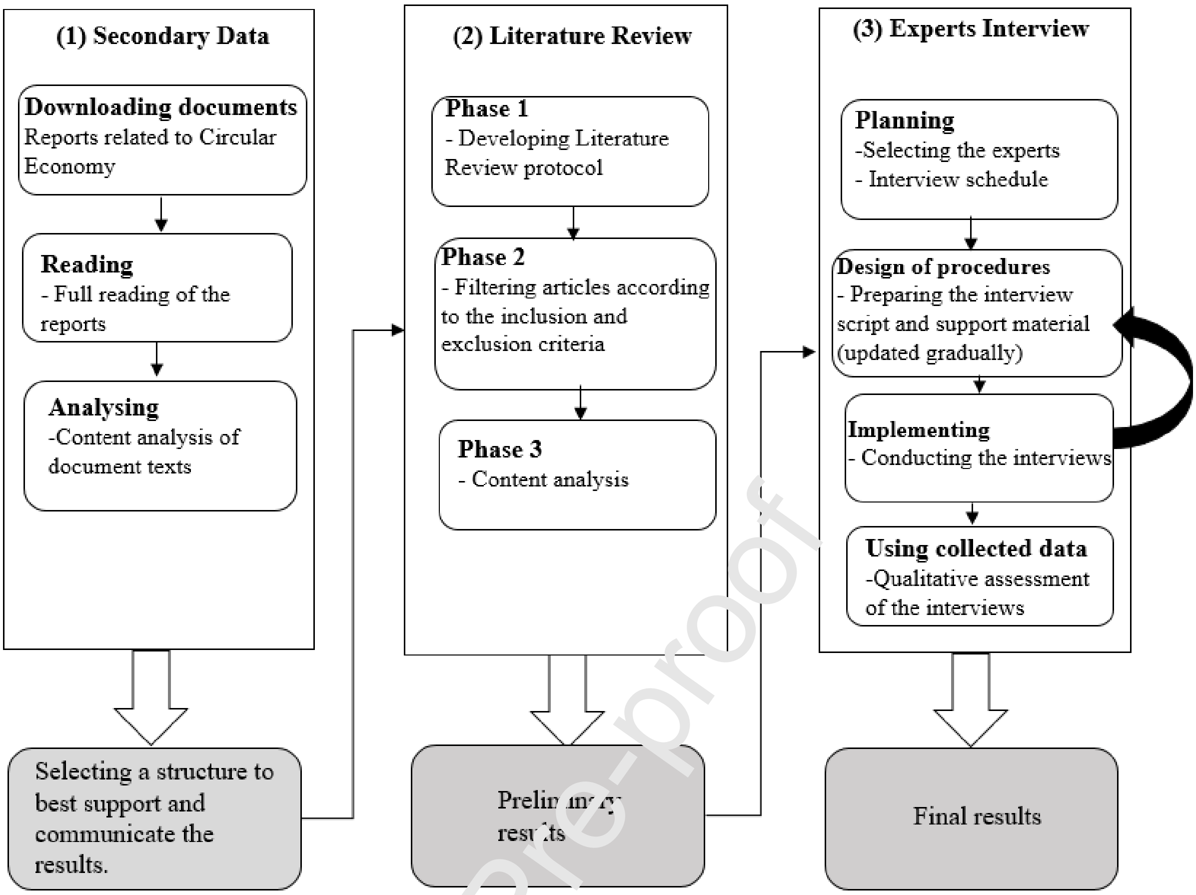

Fig. 1. Methodological study flow diagram.

2.1. First step: looking through secondary data

Having identified the gaps in the study, there is a need to establish a model in which the study results can be communicated efficiently. It was unclear how the research would be conducted because the link between AM and CE can be approached from different perspectives. Therefore, a CE approach capable of addressing AM thoroughly is required. To achieve this, research must be conducted using secondary data. Secondary data was used based on the method described by Son et al. (2016), which allowed for the replication of the research results. The content of the reports was analysed to understand the CE's characteristics, principles, and implementation. The reports were downloaded without time restrictions because CE is a recent topic. A sample of 37 documents that included manuals and reports by searching for a “circular economy report” on Google was downloaded and read in full. After reading the documents, the CE principles and characteristics were understood and analysed. This step is essential for understanding a given topic (Harris et al., 2015). In this phase, a report was identified: the Ellen Macarthur Foundation’s (2015) “Delivering the circular economy: a toolkit for policymakers” report. This document was selected because it describes a methodology for formulating CE policies using the ReSOLVE framework. The framework identifies six areas of action for companies and countries that wish to move toward CE and serves as a practical approach to help organisations implement CE principles.

Several frameworks have been developed to assist organizations in the implementation of circular products and processes. One of the most frequently used frameworks is ReSOLVE (De Sousa Jabbour et al., 2019). ReSOLVE was chosen because it was identified through reports as a leading CE tool used by businesses to implement CE business models. Many studies have exploited the ReSOLVE framework for identifying business models at a strategic level (De Sousa Jabbour et al., 2018; Mendoza et al., 2017; Mhatre et al., 2020;). Therefore, because moving AM towards circularity depends on intensive strategies, such as systematic choices beyond new additive technologies (Unruh, 2018), the ReSOLVE framework was adopted.

This structure represents a crucial tool in CE and is currently the most important tool for its implementation. In addition, the ReSOLVE framework is relatively comprehensive on CE processes, and many studies have aimed to comprehensively assess all processes (Bueren et al., 2021; Dias et al., 2022; Jabbour et al., 2020). The ReSOLVE model offers real-world application results (Mastos et al., 2021).

Furthermore, several researchers have highlighted the importance of the ReSOLVE framework in achieving circular practices (e.g., Dias et al., 2022; Ellen MacArthur Foundation, 2015; Mendoza et al., 2017; Jobbour et al., 2020). This framework has already been used by some authors in the context of the emergence of new technologies in I4.0 (De sousa Jabbour et al., 2018; Mastos et al., 2021). The framework was used to generate a more efficient way of communicating the results of the literature review to understand how AM adoption meets the CE implementation requirements.

Six actions form the ReSOLVE framework: regenerate, share, optimise, loop, virtualize, and exchange. Each of the six actions represents a significant circular business opportunity and, in different ways, increases the use of physical assets, extends life, and transfers resources from finite to renewable sources. Thus, each action reinforces and accelerates the performance of other actions (Ellen MacArthur Foundation, 2015).

2.2. Second step: developing a literature review

A literature review approach was used to analyse and understand how AM adoption meets or does not meet CE requirements. This literature review ensured no critical research was neglected and minimised bias, allowing a neutral data collection and analysis (Bryman, 2006; Denyer & Tranfield, 2009). This approach is suitable for gaining more insight into and understanding quantitative and qualitative problems compared to automatic filtering. Following guidelines provided by Denyer and Tranfield's (2009), the literature review was conducted in three phases based on two proposed research questions.

In the first phase, the literature review protocol is developed to provide an explicit description of the activities to be performed (Tranfield et al., 2003). Keywords were chosen to focus on two primary constructs of the research: AM and CE. The following search string was used to study the relationship between the two constructs: "((“3D print*” OR “additive manufactur*” OR “additive technique*” OR “additive process*” OR “digital manufactur*” OR “additive fabricat*” OR “three dimensional print*” OR “rapid manufactur*” OR “rapid tooling”

OR “rapid prototyp*” OR “layer* manufactur*” OR “digital fabricat*”) AND (“circular economy” OR “shar*” OR “lifespan” OR “regenerat*” OR “renewable energy” OR “optimis*” OR “loop *” OR “recycl*” OR “virtualis*” OR “virtual product” OR “exchang*” OR “reduc*” OR “reus*” OR “remanufactur*”) AND (“affec*” OR “potentiat*” OR “relation” OR “restrict*” OR “limit*”))”.

The Web of Science and Scopus databases were chosen because they are regularly updated with comprehensive coverage of scientific disciplines (Chadegani et al., 2013). The Engineering Village database was also chosen as it has many journals and international scope in the research area. In addition, the review was limited to articles published in peer-reviewed journals to ensure high quality (Denyer & Tranfield, 2009), thus excluding conference proceedings and book chapters. Articles that met the inclusion criteria were considered in the literature review, thus guaranteeing the quality of the selected papers (Tranfield et al., 2003). Both analytical and empirical research were included in the analysis. According to the classification proposed by Wacker (1998), analytical research is classified into conceptual, mathematical and statistical; empirical research is classified into experimental design, Statistical sampling, and Case studies.

The second phase of the research process involved filtering the articles from the initial search string. A total of 5,335 articles were returned from the three databases, of which 1,083 were duplicates and were removed. The remaining articles were then filtered in two stages to ensure that only relevant studies were included according to pre-determined inclusion and exclusion criteria, as outlined in Table 1. The first filter involved reading the titles and abstracts of 4,252 articles and rejecting those that did not meet the selection criteria. After this initial filtering, 115 articles were left for full reading, which served as the second filter. Ultimately, 69 papers that addressed the intersection between AM and CE were selected for analysis. We later included four additional papers derived from the reference lists of the 69 papers that were deemed relevant to the scope of our analysis. In total, 73 papers (available on Appendix A and B) were considered eligible for o the literature review. Figure 2 illustrates the filtering phase.

Criteria	Inclusion criteria	Exclusion criteria
Focus	Dealing with additive manufacturing related to the circular economy or some construct of the ReSOLVE framework.	Refers to additive manufacturing without relating it to the circular economy or any construct of the ReSOLVE framework.
Access	Papers written in English.	No access to the paper or it is not written in English.
Quality	Scientific periodical with peer review	Scientific periodical without peer review, business newspapers, magazines, conferences, books, and websites.
Analysis unit	Papers that address additive manufacturing and the circular economy	Papers that do not address the relationship between additive manufacturing and the circular economy.
Theoretical framework	Concepts of additive manufacturing and the circular economy (or ReSOLVE constructs) in a context of operations management, sustainability, environment, or supply chain management as the focus of the paper.	Concepts related to psychology, physiology, and health as the focus of the paper.

Table 1 - Literature review inclusion and exclusion criteria.

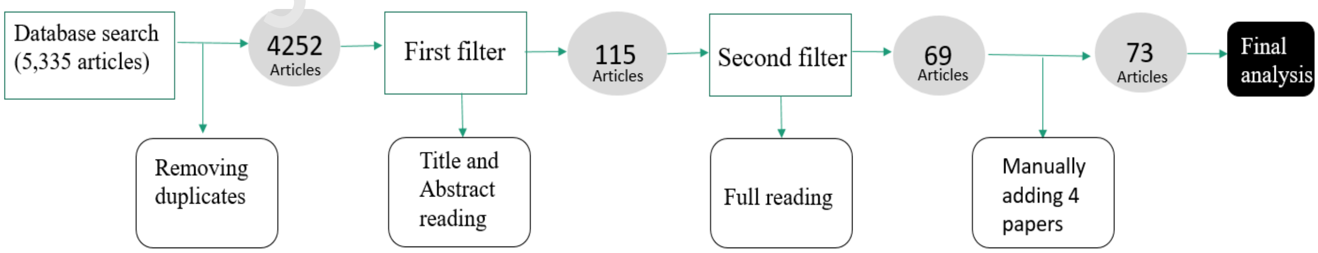

Fig. 2. Filtering process.

In phase 3, the content analysis procedure proposed by Bringer et al. (2006) and Krippendorff (2018) was adopted. Content analysis is an empirically grounded method

(Krippendorff, 2018) that was performed using NVivo 12 Plus software for Windows. After reading the full texts, the chosen articles were loaded into the NVivo (2019) software for further analysis. NVivo enables the gathering and analysis of all data in a meaningful and reliable way, in addition to efficiently organising, storing and retrieving data, and generating rigorous output. It allows complex relationships to be established from data and provides excellent research reliability (NVivo, 2019).

Following the requirements described by Krippendorff (2018), categories were created from available data. This allowed us to identify the relationships and connections between authors examining the same constructs. Specific codes were created for each research question. For question 1, six codes were created: one for each ReSOLVE action; and 15 subcodes, referring to the 15 benefits of AM for the CE. For question 2, 2 categories were created. This study followed a simple categorisation. The first group comprises barriers related to the ReSOLVE dimensions (specific barriers), and the second group comprises barriers related to the general circular economy approach (general barriers). For specific barriers, the literature found 10 subcategories, coded SB1 to SB10 in the software. For general barriers, the literature identified three subcategories, coded GB1–GB3.

2.3. Step 3: Evaluating results with experts

Consultation with specialists was performed to consolidate the results of the literature review. The results were evaluated through a semi-structured interview with a group of experts in AM and CE to achieve sufficient robustness. The reason for carrying out this stage was to guarantee methodological rigor based on an iterative process that enabled a successive refinement of the data related to the benefits and barriers. This step was essential for adjusting the lists, adding items, and readjusting the phrases.

The semi-structured interview technique was chosen as it offers a rich and in-depth understanding of the research topic, while also addressing the validity constraints of self-report data (Naem, 2020). The use of semi-structured interviews has been widely recognized in qualitative studies, as noted in various studies such as Aslam et al. (2018), Naem (2020) and Muqadas et al. (2017). Additionally, expert interviews are a valuable data collection technique when researching new and emerging fields, as Yingli Wang et al. (2019) highlighted.

To establish a systematic procedure for collecting, analysing, and synthesising data from the interviews, the procedures recommended by Silveira et al. (2017) were adopted, as summarised in Figure 1. This approach can be summarised using four primary characteristics: entry points, procedures, project management, and participation. Experts' acceptance characterises the entry point to participate in the interviews and contextualise the research. Project management is characterised as an internal part of the research effort, in which the researcher manages a schedule for conducting interviews. The procedure consisted of four steps (planning, design of procedures, implementation, and use of data).

General planning was the step in which experts were selected. This selection was based mainly on the experience of experts in AM or CE. Accordingly, six experts were selected. The process of determining the number of experts involved in the study utilized purposive sampling, which is an effective strategy for gathering data based on the willingness of respondents to provide information related to a specific subject. Several researchers have adopted this strategy to define the sample of research participants (Aslam et al., 2018, Naeem, 2020, Yingli Wang et al., 2019). Studies using methodologies based on a panel of similar experts have proven that the number of experts chosen is a good number for research (Adebanjo et al., 2016; Callefi et al., 2022; Wong et al., 2011).

To ensure the validity and reliability of the research results, the group of experts' selection criteria for final refinement and validation followed the guidelines proposed by Bokrantz et al. (2017), emphasising the combination of expertise in Additive Manufacturing and Circular Economy, and years of experience in the field. In this regard, as a criterion for choosing experts, it was considered that professionals or academics should have at least 7 years of experience in Additive Manufacturing and Circular Economy or sustainability.

In the design of the procedures, the interview questionnaire reports with the literature review results, and all support materials were prepared. The implementation of the procedures and the third step corresponded to the completion of the interviews.

The sequence of interviews was random and based on the availability of experts. Meetings with these experts took place remotely through the videoconferencing platform Google Meet. The interview guide was gradually updated according to the experts' recommendations until saturation was reached. Interviews lasted an average of one hour and were conducted as follows: first, the objective of the interview was explained; second, the respondents were provided with the lists of benefits and barriers and with the preliminary results; and then they were asked about their general perceptions and whether they agreed with the preliminary results for each item. The following questions were used to validate the proposed benefits and preliminary results:

- "In your view, are these benefits consistent?"
- "Do you agree with the proposed categorization?"
- "Would you add or remove any benefits? If so, which? Why?"

The discussion results are presented in Section 3.1 with the list of validated benefits (Table 2), and the results are summarised in tables 3 to 8.

Sample questions were included for the proposed barriers:

- "As for the barriers presented, are they consistent with your opinion?"
- "Do you agree with the proposed categorisation?"
- "Would you add or remove any barriers? If so, which one? Why?"

After each interview, the support material was updated based on the refinements suggested by the interviewees. In addition, a final section was included with general critical reflections or insights from the researcher. This procedure enabled to enhance the qualitative analysis of the study. The last step corresponds to a qualitative analysis of the collected material. The outputs are the lists shown in the results section (Table 2 and Table 9).

3. Results

Sections 3.1 and 3.2 answer the first and second research questions and provide the results after expert evaluation.

3.1. Additive manufacturing boosting the circular economy

AM boosts CE in many diverse aspects. In the content analysis, studies that included one or more of the six actions of the ReSOLVE framework were considered. Table 2 shows, at specific points, the 15 benefits (coded from B1 to B15) of the AM-supporting CE approach, followed by its references. The results are presented in detail in the following subsection.

Action	Code	Benefit	References

Regenerate	B1	AM promotes the use of biodegradable materials and the use of energy from renewable sources.	Behm et al., 2018; Garmulewicz et al., 2018; Ghaffar et al., 2018; Sauerwein & Doubrovski, 2018; Strack, 2019; Tang et al., 2016; Unruh, 2018; Yadav et al., 2020
	B2	AM promotes the recovery, retention, and restoration of ecosystem health.	Cappa et al., 2016; Faludi et al., 2015; Ford & Despeisse, 2016; Garmulewicz et al., 2018; Gebler et al., 2014; Peng et al., 2018; Tang et al., 2016
Share	B3	AM promotes asset sharing.	Bogers et al., 2016; Ford & Despeisse, 2016; Laplume et al., 2016; Millard et al., 2018
	B4	AM promotes reuse and second-hand use.	Bloomfield & Borstrock, 2018; Sitotaw et al., 2020
	B5	AM allows life extension through design for durability and upgradeability.	Bloomfield & Borstrock, 2018; Sitotaw et al., 2020; Millard et al., 2018
Optimise	B6	AM allows for growth in product performance/efficiency.	Jin et al., 2017; Laverne et al., 2019; Ma et al., 2018; Majeed et al., 2019; Yuanbin Wang et al., 2019; Yang et al., 2019
	B7	AM promotes the removal of waste in production and supply chain.	Ahsan et al., 2015; Bogers et al., 2016; Cerdas et al., 2017; Ford & Despeisse, 2016; Ghaffar et al., 2018; Jiang, 2020; Jin et al., 2017; Kellens et al., 2017; Kunovjanek & Reiner, 2019; Laverne et al., 2019; Peng et al., 2018; Tang et al., 2016; Turner et al., 2019; Tziantopoulos et al., 2019; Unruh, 2018
	B8	AM leverages the use of big data and automation.	Huang, 2015; Kim et al., 2015a; Majeed et al., 2021; Majeed et al., 2019; Nascimento et al., 2019; Yuanbin Wang et al., 2019
Loop	B9	AM encourages the remanufacturing of products or components.	Kellens et al., 2017; Le et al., 2018; Matsumoto et al., 2016; Saboori et al, 2019; Tian et al., 2017
	B10	AM encourages the recycling of materials.	Chong et al., 2015; Clemon; Zohdi, 2018; Colorado et al., 2020; Cunico et al., 2018; Despeisse et al., 2017; Garmulewicz et al., 2018; Giurco et al., 2014; Nascimento et al., 2019; Sanchez et al., 2020; Santander et al., 2020; Sauerwein & Doubrovski, 2018; Tian et al., 2017; Woern & Pearce, 2017; Zhao et al., 2018; Zhong & Pearce, 2018

	B11	AM expands the scale of waste recovery and resource reuse.	Behm et al., 2018; Bloomfield & Borstrock, 2018; Chong et al., 2015; Depalma et al., 2020; Despeisse et al., 2017; Ford & Despeisse, 2016; Garmulewicz et al., 2018; Nascimento et al., 2019; Sauerwein & Doubrovski, 2018; Sauerwein et al., 2019; Unruh, 2018
Virtualise	B12	AM encourages indirect dematerialisation.	Bogers et al., 2016; Cappa et al., 2016; Ford & Despeisse, 2016; Garmulewicz et al., 2018; Gabler et al., 2014; Huang, 2015; Majeed et al., 2019; Millard et al., 2018; Tziantopoulos et al., 2019; Unruh, 2018; Yuanbin Wang et al., 2019
Exchange	B13	AM promotes the replacement of old materials with advanced materials.	Bloomfield & Borstrock, 2018; Ghaffar et al., 2018
	B14	AM promotes the application of new technologies.	Kim et al., 2015a; Majeed et al., 2021; Majeed et al., 2019; Yuanbin Wang et al., 2019
	B15	AM promotes the choice of new products and services (capacity for innovation).	Behm et al., 2018; Bloomfield & Borstrock, 2018; Candi & Beltagui, 2019

Table 2 - Additive manufacturing benefits for the circular economy (Legend: AM- Additive Manufacturing)

3.1.1. Additive manufacturing contributing to "regenerate"

Studies included in "regenerate" focus on how AM encourages using materials and energy from renewable sources and biodegradable materials. Several authors have studied the use of biodegradable materials produced using AM. Behm et al. (2018) detailed the application of AM for 3D printing of animal models in a field predation study. Models printed in 3D from cheaper and more sustainable materials made of 70% plastic and 30% recycled wood fibre were as durable as models made of 100% virgin plastic. Ghaffar et al. (2018) addressed the use of biodegradable materials in the construction sector, presenting new pathways for AM's role in achieving circularity in the construction sector, representing an environmentally and eco-innovative solution.

Sauerwein and Doubrovki (2018) presented a process for adapting mussel shell residues, which exist in large volumes in the Netherlands, to AM materials. The printing of this material resulted in a ceramic-like material. Yadav et al. (2020) studied the biocompatibility of orthopaedic implant biomaterials that are compatible with human anatomy. They identified classes of biomaterials based on their 3D printability to make their processing more oriented toward CE. The study showed 3D printed biomaterials require less material to manufacture, produce less waste, and can be made with precision that matches human anatomy.

Regarding renewable energy sources, Strack (2019) reviewed recent AM approaches for generating biological energy in the form of fuel cells. The objective was to provide an overview of AM approaches to biological energy generation and describe existing research tactics.

The health of ecosystems is of paramount importance in CE. Studies have shown how AM can be a powerful tool for environmental recovery, retention, and restoration. Some of them, analyse the AM environmental impact from a Life Cycle Assessment (LCA) perspective, that is, they evaluate the environmental impacts of a AM product throughout its entire life cycle. Tang et al. (2016) proposed a general framework that can integrate a design stage in LCA to minimise the product environmental impact of AM process. The results showed that the AM process can save energy and produce less CO_2, reducing environmental impact. Peng et al. (2018) focused on AM's energy and environmental impacts and statistically analysed the data to provide an overview of environmental impact predictions. The authors highlight Resource consumption is the most important environmental aspect for AM, as it holds the potential to reduce the amount of raw material required, reduce the need for energy-intensive, wasteful, and polluting manufacturing processes. Faludi et al. (2015) compared the environmental impacts of two 3D printers with a traditional computer-controlled milling machine to determine the most sustainable method. It was discovered that the percentage use of each machine primarily determined the sustainability of AM versus conventional machining. However, material waste became dominant for a computer numerical command machine at maximum utilisation.

Furthermore, AM has the potential to have a positive impact on resource depletion. In terms of fossil fuels, AM can reduce the need for transportation and logistics, as products can be manufactured on-demand and closer to the point of use. This can decrease the amount of fossil fuels used for transportation, and also reduces the carbon footprint of the manufacturing process (Ford and Despeisse, 2016). Gebler et al. (2014) quantified AM changes in life-cycle costs, energy emissions, and CO_2 by 2025. The authors concluded that the technology holds huge sustainability potential, mainly if it is applied to mass production markets. However, it's worth noting that the energy consumption of AM machines and the source of energy used to power them can also impact the technology's carbon footprint.

In terms of water, while AM processes vary in their water usage, in general, the water consumption of AM is relatively low compared to traditional manufacturing methods (Faludi et al., 2015). Some AM methods, such as powder bed fusion, do not require water at all. However, other methods, such as binder jetting or material extrusion, may require small amounts of water for cooling or material preparation (Fico et al., 2022). Overall, while water consumption is not a major concern for most AM processes, it is still an important aspect to consider when evaluating the environmental impact of AM and efforts can be made to minimize water consumption further.

Finally, AM has the potential to reduce the amount of waste generated by traditional manufacturing methods and decrease the amount of materials sent to landfills. Garmulewicz et al. (2018) highlighted that reducing landfill as a major benefit of using plastic waste for locally distributed manufacturing 3D printing. However, it is important to note that eutrophication, the over-enrichment of a body of water with nutrients, can still occur if the materials used in AM are not properly disposed of or if the printing process creates waste that ends up in waterways (Garmulewicz et al., 2018). Therefore, it is essential to implement proper waste management and disposal practices in conjunction with the use of AM.

It's important to note that the environmental impact of AM depends on the specific process and materials used, and it's important to ensure that the materials used are sustainable and the energy used to run the equipment is renewable. Table 3 summarises all topics covered in "regenerate", classifying studies that contain an empirical section or only contain a conceptual mention of the topic.

Regenerate	Summary of Results	Study containing empirical section regarding the topic	Study with conceptual mention regarding the topic
How AM promotes the use of biodegradable materials and the use of energy from renewable sources.	The use of biodegradable materials and energy from renewable sources for AM is in its infancy. However, the studies show great potential of using biodegradable and biomaterials for AM in many sectors, from construction to medicine.	Behm et al., 2018; Ghaffar et al., 2018; Sauerwein & Doubrovski, 2018; Yadav et al., 2020.	Garmulewicz et al., 2018; Tang et al., 2016; Unruh, 2018; Strack, 2019.

How AM promotes the recovery, retention, and restoration of ecosystem health.	AM can have a positive impact on reducing resource depletion. Through the on-demand manufacturing of products closer to the point of use, AM can decrease the dependence on fossil fuels for transportation and logistics. Additionally, AM's water consumption is low, however, it is important to properly dispose of materials used in the process to prevent eutrophication.	Tang et al., 2016; Faludi et al., 2015; Gebler et al., 2014.	Peng et al., 2016; Ford & Despeisse, 2016; Cappa et al., 2016.

Table 3- How studies refer to "Regenerate" (Legend: AM- Additive Manufacturing)

3.1.2. Additive manufacturing contributing to "share"

AM product flexibility allows for rapid adaptability and ensures utility for more than one user through reuse. Bloomfield and Borstrock (2018) presented a flexible 3D printed textile product that combined advanced manufacturing technologies. This ensured the adaptability and usability of the clothing for different users. In this study, the new modular technology encouraged the practice of reuse because garments can be reused by creating new clothes, accessories, toys, or other applications. Additionally, practices related to repairing, recycling, and reusing material life cycles can be extended and adapted to meet new requirements. Sitotaw et al. (2020) reviewed state-of-the-art AM in textiles. Supporting Bloomfield and Borstrock (2018), this study highlighted the advantages of rapid adaptability, customisation, and the sustainability of textiles.

It is critical to note that AM CAD systems play a crucial role in fostering the sharing of concepts and products. First of all, this CAD files may be used to create and share 3D models, which can be used to produce physical products using AM techniques. This allows individuals and organizations to share designs and concepts with others, facilitating the collaborative progress of AM technology (Ford & Despeisse, 2016).This leads to the second point: many AM CAD systems are open-source, which implies that the source code is available to the public. This enables for the creation of customised tools and features and stimulates collaborations among communities (Laplume et al., 2016). Furthermore, this also permits the construction of online platforms, which allow individuals and organizations to share and download 3D models and printable files. This has also made it possible to copy and share digital projects and files online easily. Platforms such as 3D hubs and Kazzata, as well as other service bureaus, offer these services (Ford & Despeisse, 2016). According to Bogers et al. (2016), This AM feature has led to design freedom, allowing personalised shapes, digital interaction with consumers, and direct manufacturing. They allow customers to access AM without high investment costs of capital. Additionally, the availability of these services provides benefits in the form of increased equipment utilisation.

Millard et al. (2018) also address the issue of digital sharing. Sharing occurs at the virtual level, when the right skills and equipment can produce digital content composed of virtual bits and provide accessibility instantly worldwide. For these authors, access to 3D printers and the freedom this technology brings are part of the creative movement, contributing to the collaborative production of intangible content. This culture of experimentation is a powerful engine of innovation that leads to social, economic, and environmental sustainability and strengthens CE. Table 4 summarises all topics covered in "share".

Share	Summary of Results	Study containing empirical section regarding the topic	Study with conceptual mention regarding the topic

How AM promotes asset sharing.	The machine (3D printing) sharing could be improved through use-oriented product-services, in the form of sharing, pooling or renting. Some companies, like 3D Hubs and Kazzata, for example, allow customers to access AM through digital projects and files over internet. The availability of these services provides benefits in the form of increased equipment utilisation.	Laplume et al., 2016;	Bogers et al., 2016; Ford & Despeisse, 2016; Millard et al., 2018.
How AM promotes reuse and second-hand use.	Flexibility provided by AM products allows their quickly adaptability, ensuring utility for more than one user through reuse. Studies highlighted some advantages of AM, like rapid adaptability and customisation, that support reuse and second-hand use.	Bloomfield & Borstrock, 2018.	Sitotaw et al., 2020.
How AM allows life extension through maintenance, design for durability and upgradeability.	AM flexibility enables modular and efficient manufacturing systems, allowing the manufacture of differentiated products in batches of only one product (or in spare parts), making products more adaptable for reuse. Also AM´s relatively freedom of design allows the design for durability.	Bloomfield & Borstrock, 2018.	Sitotaw et al., 2020; Millard et al., 2018.

Table 4 - How studies refer to “share” (Legend: AM- Additive Manufacturing, 3D-Three dimensional)

3.1.3. Additive manufacturing contributing to “optimise”

Current additive technologies are relatively slow and inefficient, requiring a longer production time (Holmström & Gutowski, 2017) because the layer-by-layer process takes a long time to manufacture a part completely. However, the increase in AM applications has encouraged researchers to improve AM processes to optimise and reduce waste in the production phase and along the supply chain. For instance, Jiang (2020) developed a novel strategy considerating that the 3D part does not need to be fabricated in a layer-by-layer manner, but in a multilayer-by-multilayer manner. The strategy includes five steps: i) Position the part in the best direction for printing; ii) Identify different parts of the object; iii) Measure the distance between the different parts in each layer; iv) Create a plan for how the printer should move to make the object; and v) Use this new plan to print the object using an AM machine. The strategy was tested in a case study and it was found that it saved over 1000 seconds of printing time compared to layer by layer method.

AM simplifies assemblies by encompassing fewer parts and materials. These technological characteristics allow for the reduction of waste in production (Ghaffar et al., 2018). In addition, the design freedom allowed by AM enables improvements in sustainability, which can be achieved by redesigning components, products, and the process itself (Ford & Despeisse, 2016; Tang et al., 2016). This process/product redesign enhances the manufacturing of products with fewer components, materials, stages, and interactions (Ford & Despeisse, 2016).

Numerous studies have addressed the issue of waste reduction in process planning during product design. Jin et al. (2017) found that a large volume of material is used to fill the interior of solid parts, but its function is not as significant as that of the materials forming the surface boundary. Therefore, this material can be saved based on acceptable geometric precision and mechanical strength. Thus, this study seeks to optimise the consumption of materials in 3D printing through methodologies in process planning. Kellens et al. (2017) reported savings of up to 50% in stamping tools and turbine blades manufacturing. Ahsan et al. (2015) developed an AM process-planning approach that minimises the use of resources. The proposed optimisation methodology offers an ideal manufacturing approach that minimises the consumption of resources and total manufacturing time, reduces the plurality of the contour, and improves the surface quality manufacturing complexity and overall surface quality.

Optimisation can also refer to the actions taken to remove waste from the AM-based supply chains. The expected effect of AM is shorter supply chains, as the need for centralised tools and manufacturing is reduced. Thus, chains become reconfigured with more innovative distribution models and less need for transport, shortening the production cycle (Bogers et al., 2016; Turner et al., 2019; Tziantopoulos et al., 2019). Turner et al. (2019) explored the feasibility of a redistributed business model for manufacturers that employs AM as part of a circular production and consumption system. The results showed that a reduction in transport and increased customer involvement were the main benefits of implementing a redistributed model in a given sector. Inventory in AM has another advantage regarding waste reduction, as decentralised AM can avoid the need for stock retention (Kellens et al., 2017; Despeisse et al., 2017; Kunovjanek & Reiner, 2019).

Some studies have shown that AM increases product performance and efficiency (Jin et al., 2017; Majeed et al., 2019; Yuanbin Wang et al., 2019). Laverne et al. (2019) provided insights into improving product performance by reducing the scale of material flow. Ma et al. (2018) developed an approach to assess the sustainability of AM product lifecycles. Yang et al. (2019) investigated the consolidation of parts made using AM, and the results showed weight reduction, extended life expectancy, and improved functional performance of the product (accelerator pedal set).

Other studies have shown another benefit in "optimise", i.e., the tendency to leverage the use of technologies associated with AM, such as the internet of things (IoT), sensors, big data, and cloud computing, to increase reliability and efficiency of processes (Majeeed et al., 2021). Majeed et al. (2019) proposed a framework for designing high-quality AM products using big data analytics (BDA). BDA can determine when imperfections occur by analysing each AM process and inspecting all elements, preventing future problems by analysing each AM process. It can also reveal the relationship between production performance and process parameters. Huang (2015) stated that by combining virtual manufacturing design and simulation of 3D digital manufacturing platforms, the time needed to develop products could be reduced, ensuring quality and increasing throughput, mitigating spatial limitations, and promoting the intelligent manufacturing of high-value products. Nascimento et al. (2019) used mobile application technology to generate a map of waste disposal locations. Combined with specialised software to optimise collection routes based on geographic data and real-time traffic conditions, it was possible to determine the type of vehicle needed to collect waste for 3D printing. Yuanbin Wang et al. (2019) developed a new architecture for cloud-based AM platforms. Artificial intelligence and cyber-physical system technologies have been used in the IoT environment to make the cloud platform more innovative and efficient for customers in product development processes. Kim et al. (2015a) optimised AM by proposing an architecture of federated information systems that provides a platform that enables the verification and validation of AM information across the digital spectrum. Table 5 summarises all topics covered in "optimisation".

Optimise	Summary of Results	Study containing empirical section regarding the topic	Study with conceptual mention regarding the topic
How AM allows growth in product performance/ efficiency.	Some studies have been conducted to reduce fabrication time and increase efficiency of AM product and processes.	Jin et al., 2017; Laverne et al., 2019; Majeed et al., 2019; Yuanbin Wang et al., 2019; Yang et al., 2019	Ma et al., 2018;

How AM promotes the removal of waste in production and supply chain.	The increase in AM applications encourages researchers to improve AM processes to optimise and reduce waste in the production phase and along supply chain. Also AM has the capacity of simplify assemblies, encompassing fewer parts and materials.	Ahsan et al., 2015; Cerdas et al., 2017; Jiang, 2020; Jin et al., 2017; Kunovjanek & Reiner, 2019; Laverne et al., 2019; Tang et al., 2016; Turner et al., 2019.	Bogers et al., 2016; Ford & Despeisse, 2016; Ghaffar et al., 2018; Kellens et al., 2017; Peng et al., 2018; Tziantopoulos et al., 2019; Unruh, 2018.
How AM leverages the use of big data and automation.	Some studies have been conducted to leverage the use of technologies associated with AM, such as the internet of things, sensors, and cloud computing, to promote the efficiency of processes.	Kim et al., 2015a; Majeed et al., 2021; Majeed et al., 2019; Yuanbin Wang et al., 2019.	Huang, 2015; Nascimento et al., 2019.

Table 5 - How studies refer to "optimise" (Legend: AM: Additive Manufacturing)

3.1.4. Additive manufacturing contributing to "loop"

Regarding "loop", this paper shows how AM encourages the reuse, remanufacture, and recycling of products and components. Many authors have suggested that AM products must be designed to promote reuse, remanufacturing, and recycling, thereby boosting the return of waste to the economy. However, for AM to support "loop", it is essential to integrate the supply chain through handling, transportation, and storage policies that support this reverse flow.

Table 6 summarises all technical cycles of the loop dimensions.

Loop	Summary of Results	Study containing empirical section regarding the topic	Study with conceptual mention regarding the topic
How AM encourages the recycling of materials.	Many studies have revealed that plastic is the most commonly recycled material in the context of AM. However, some research has been focused on investigating the recycling of metals in AM as they have high recyclability and are	Clemon & Zohdi, 2018; Cunico et al., 2018; Garmulewicz et al., 2018; Santander et al., 2020; Sauerwein & Doubrovski, 2018; Woern & Pearce, 2017;	Colorado et al., 2020; Despeisse et al., 2017; Giurco et al., 2014; Nascimento et al., 2019;

	more suitable for optimal closed-loop recycling. Additionally, other types of recycled composite materials such as bio-based, ceramic, glass, and others are also being explored.	Zhao et al., 2018; Zhong & Pearce, 2018.	Sanchez et al., 2020; Tian et al., 2017.
How AM expands the scale of waste recovery and resource reuse.	To leverage this activity, some studies have shown that it is important to redesign the product to encourage future reuse. However, AM technology already allows a product to have a longer cycle life due the great technology capability for repairs and upgrades. This is due to AM characteristics such as digital production and adaptability.	Behm et al., 2018; Bloomfield & Borstrock, 2018; Depalma et al., 2020; Garmulewicz et al., 2018; Sauerwein et al., 2019; Sauerwein & Doubrovski, 2018; .	Chong et al., 2015; Despeisse et al., 2017; Ford & Despeisse, 2016; Nascimento et al., 2019; Unruh, 2018.
How AM encourages the remanufacturing of products or components	Many studies have shown many benefits in remanufacturing for AM due the technology capability of adding new material to existing surfaces to repair and remanufacture used and worn parts.	Le et al., 2018; Tian et al., 2017.	Kellens et al., 2017; Matsumoto et al., 2016; Saboori et al., 2019.

Table 6 - How works refer to “loop” (Legend: AM- Additive Manufacturing, CE-Circular Economy)

The “loop” emphasizes product design to achieve greater circularity of resources. This means that a product should be designed to encourage its extended life in the future according to the cradle-to-cradle approach (Chong et al., 2015). Thus, product design should ensure the ease of repair, remanufacturing, recycling, and reusing resources to ensure longevity and a resource loop. In this context, Sauerwein et al. (2019) conducted a series of interviews with designers regarding their 3D printed design projects. They discovered that AM supports circular design strategies, creating opportunities to extend a product’s life and allowing repairs or upgrades (even if these products were not originally designed to facilitate repair or upgrading) owing to AM characteristics such as digital production and adaptability. Ford and Despeisse (2016) highlighted that the development of organisational skills in AM design allows digital projects to be developed to produce spare parts on demand when repair and remanufacturing are required. However, companies are still only beginning to discover the implications of using AM technologies to extend and close the product life cycle.

By recommending a circular model to reuse electronic scrap devices and integrating web technologies, reverse logistics, and AM to support EC practices, Nascimento et al. (2019) exemplified the reuse of resources. DePalma et al. (2020) investigated the potential of selective laser sintering (SLS) and fused deposition modelling (FDM) to provide a CE solution for plastic waste. This material reuse results showed that available industrial 3D printing technologies could help reduce plastic waste in manufacturing, although a total CE requires less thermal degradation than primary industrial 3D printing polymers.

In the material recycling approach, Clemon and Zohdi (2018) developed a design tool that can identify possibilities to reduce product development time and costs, significantly accelerating the recycling and reuse of materials for improved infrastructure. Plastics are among the most reviewed materials for material recycling because of their greater use in AM (Colorado et al., 2020). Cunico et al. (2018) presented and characterised the post-processing of a 3D printing surface finish made from recycled plastic waste. As a main result of this work, the proposed recycling process was confirmed to improve the object's properties. Polylactic acid (PLA) is a widely used plastic material. Zhao et al. (2018) studied the mechanical properties of recycled PLA obtained from printed parts made of virgin PLA that were subsequently re-extruded by FDM into filaments suitable for 3D printing.

Recent research and initiatives to propose a new approach based on distributed plastic recycling for AM technologies have also been analysed to reduce plastic waste and support CE. For example, Woern and Pearce (2017) proved that using recycled plastic instead of virgin plastic for AM could reduce the material costs by 98%. Santander et al. (2020) demonstrated positive economic and environmental benefits by developing a new recycling method for plastics using 3D printing. Despeisse et al. (2017) highlighted that local markets for more flexible materials may be more suitable for recycling highly distributed sources of waste by avoiding the loss of information due to large-scale recycling. Sanchez et al. (2020) showed how AM's rapid technical evolution allows a new path to a CE. To achieve this, a literature review was performed and a framework was proposed to identify the global value chain of distributed recycling via the AM approach. The authors proposed different future research paths at the micro, meso, and macro levels to understand better the connections between CE and distributing recycling.

Because of their high recyclability, metals are the best materials for optimal CE (Colorado et al., 2020). One of the first works on the subject by Giurco et al. (2014) explored the issue of metal recycling in AM, addressing interconnected future problems that arise in the CE context for supply chains, AM, and metal recycling. Additionally, Romani et al. (2021) conducted a review highlighting the use of secondary material (from waste and scrap) and recycled materials as raw materials for AM. The authors noted that, in addition to commonly used thermoplastics and metals, bio-based materials such as wood, biofiber, and mussel shells, as well as materials such as paper, ceramics, fiberglass, concrete, and even food, can also be used in the process.

AM techniques are revolutionizing the way we approach remanufacturing. Not only can they be used to repair or remanufacture damaged components, avoiding the need to produce new ones (Kellens et al., 2017) , but they can also be combined with recycled materials to create recyclable composite materials. Researchers such as Tian et al. (2017) have demonstrated this by using filaments impregnated with recycled carbon fibre and pure PLA as raw materials. This study proposed a recycling and remanufacturing process for thermoplastics reinforced with continuous 3D printed fibre, providing fully recyclable composite materials. Le et al. (2017) proposed an innovative strategy that combines subtractive and additive techniques to reuse end-of-life parts in new manufacturing directly. Matsumoto et al. (2016) discussed the latest trends, factors, and barriers to remanufacturing, highlighting the benefit of adding new material to existing surfaces for repair and remanufacturing. Saboori et al. (2019) even overviewed a flexible type of AM that uses energy deposition to repair metal components. They found it to be highly effective in repairing and remanufacturing complex geometries in industries such as automotive and aerospace. Finally, Abd Aziz et al., (2021) discuss using AI-based techniques to improve the design of products that are being remanufactured using AM, to make the remanufacturing process more efficient. With these advancements, remanufacturing is becoming more efficient and sustainable than ever before.

3.1.5. Additive manufacturing contributing to "virtualise"

Dimensional *virtualisation* involves *virtually* delivering utility and visualising materials and processes (Mastos, 2021). The dimension focuses on resource dematerialisation, which involves replacing physical products with virtual products (direct dematerialisation); for example, books, CDs, and DVDs.. Dematerialisation also occurs indirectly through online purchases, self-employed vehicles, or virtual offices (Ellen Macarthur, 2015). The CE concept may involve information availability and exchange that replaces or postpones actual physical good consumption (Kouhizadeh et al., 2019). The development of online platforms, such as 3D hubs and Kazzata, has pointed to this AM ability to provide consumers with information in the form of 3D CAD files that can help them use AM more efficiently (Ford & Despeisse, 2016; Yuanbin Wang et al., 2019).

Gebler et al. (2014) predicted that supply chains, combined with online platforms, will become more dynamic and digitised as they move to digital information processing, while physical supply chains will be eliminated. Ford and Despeisse (2016) emphasised that digital information processing will lead to digital projects being kept on file; the ability to reproduce these files as spare parts for repair and remanufacturing will extend product life and encourage product service business models. Huang (2015) predicted the development of large quantities of virtual products through digital manufacturing, combined with cloud platforms and cloud-enabled databases. Yuanbin Wang et al. (2019) explored how a cloud platform can help customers use AM more efficiently by providing sufficient information and support throughout the product development process. Cappa et al. (2016) studied an integrated approach based on collaborative production combined with three-dimensional (3D) production. Individuals collaborated with researchers via the web to develop a new product. The improvements achieved included a significant reduction in total costs and purchase price, and also a reduction in energy consumption and pollutant emissions.

Garmulewicz et al. (2018) and Borgers et al. (2016) predicted that the essential consequence of virtualisation in the context of AM is mass customisation. Garmulewicz et al. (2018) predicted that the 3D printing of products from local materials would be combined with a digital information system that integrates available raw materials, digital product designs, and consumer demand to form an online market. Bogers et al. (2016) discussed how virtualisation changes production systems. For these authors, a striking feature of the decentralised production system provided by AM is accessibility, which refers to the manufacturer offering online consumer platforms to print their pieces and provide knowledge to create a model if customers do not have the knowledge required to do so. This allows online interfaces and co-creation with users, contributing to mass customisation.

In addition to all of these transformations, dematerialisation may have direct consequences for logistics. For example, instead of long-distance logistics and shipping of physical products, digital files are downloaded to local, sustainable production platforms, with local materials that serve as inputs for AM. This shortens the production and logistics time (Tziantopoulos et al., 2019). Millard et al. (2018) pointed out that manufacturing distributed on a large scale can profoundly impact the future of manufacturing and our physical world, as well as world behaviour, development, along with politics globally. Table 7 summarises all the topics covered in the virtual dimension.

Virtualise	Summary of Results	Study containing empirical section regarding the topic	Study with conceptual mention regarding the topic
How AM encourages indirect dematerialisation	The development of online platforms, such as 3D hubs and Kazzata, has pointed to the AM ability of provide consumers with virtual information in form of 3D CAD files that can help them use AM more efficiently. In a CE context, it may shorten supply chains: instead of long-distance logistics and shipping of physical products, digital files are downloaded to local, sustainable production platforms, with local materials that serve as inputs for AM.	Cappa et al., 2016; Majeed et al., 2019; Millard et al., 2018; Yuanbin Wang et al., 2019.	Bogers et al., 2016; Ford & Despeisse, 2016; Garmulewicz et al., 2018; Gebler et al., 2014; Huang, 2015; Tziantopoulos et al., 2019; Unruh, 2018;

Table 7 - How studies refer to “virtualise” (Legend: AM- Additive Manufacturing, 3D- Three dimensional, CAD - Computer Aided Design, CE- Circular Economy).

3.1.6. Additive manufacturing contributing to “exchange”

New production technologies will be required to be applied and combined with AM based on "exchange" (Lv & Peng, 2019). A perceived trend in AM is that as the number of users of 3D technology increases, so does their dependence on big data. Majeed et al. (2019) reported that this new trend, from the viewpoint of CE, may allow BDA to guide more innovative and circular products. This is because AM combined with BDA can reduce manufacturing defects and energy consumption, and save time and money, thus benefiting customers, manufacturers, and the environment. Yuanbin Wang et al. (2019) highlighted the importance of 3D printing with the IoT. The advantage of the IoT is that it provides new features for a cloud-based platform, allowing customers to control and monitor the printing process remotely. Thus, local printers can automatically communicate with the cloud platform. Kim et al. (2015a) proposed integrating the AM of federated architectural technology for information systems. They proposed that a federated information system architecture provides a platform that verifies and verifies AM information across the digital spectrum. Majeed et al. (2021) combined BDA, AM, and sustainable smart manufacturing to form a new interdisciplinary research area, intelligent and sustainable AM based on big data. They proposed a framework that considers the combination of technologies applied at the beginning of a product's life cycle in the AM process. The results showed that the framework supports AM companies and produces energy-efficient products, which are helpful for intelligent and sustainable manufacturing.

Other studies have focused on highlighting the use of AM to replace old materials with advanced materials in the construction sector (Ghaffar et al., 2018) and in the textile sector (Bloomfield & Borstrock, 2018). Behm et al. (2018) and Candi and Beltagui (2019) addressed the choice of innovative products or services in the context of AM, which has also been addressed by Behm et al. (2018) and by Candi and Beltagui

(2019). The last analysis used survey data collected from 177 US companies that used AM for innovation. The results showed that AM in innovation is more effective for companies facing significant turbulence in their operating environments. This is because the main benefits of AM are derived from its ability to provide flexible responses to uncertainty. Table 8 summarises the topics covered in the exchange dimension.

Exchange	Summary of Results	Study containing empirical section regarding the topic	Study with conceptual mention regarding the topic
How AM promotes the replacement of old materials with advanced materials.	The practice related to this dimension in the AM industry is the exchange of traditional materials for advanced materials. It has been related in construction sector, textile sector and aerospace and automotive sectors.	Bloomfield & Borstrock, 2018;	Ghaffar et al., 2018
How AM promotes the application of new technologies.	A perceived trend in AM is that, as the number of users of 3D technology increases, so does their dependence on big data. AM combined with BDA can reduce manufacturing defects and energy consumption and save time and money. It may allow BDA to guide more innovative and circular products.	Kim et al., 2015a; Majeed et al., 2021; Majeed et al., 2019; Yuanbin Wang et al., 2019.	
How AM promotes the choice of new products and services (capacity for innovation).	AM´s flexibility allows its capacity of fabricating innovative products. One study showed innovation is more effective for companies facing more significant turbulence in their operating environments because of AM´s ability to allow flexible responses to uncertainty.	Bloomfield & Borstrock, 2018; Candi & Beltagui, 2019	Behm et al., 2018;

Table 8 - How studies refer to “Exchange” (Legend: AM- Additive Manufacturing, 3D- Three dimensional, BDA- Big Data Analytics).

3.2. Additive manufacturing limiting the circular economy

This section proposes barriers that hinder AM from meeting the CE requirements. This section also follows the qualitative content analysis and classifies barriers into a simple categorisation, as shown in Table 9. The first group is formed by barriers related to the general circular economy approach (general barriers). The second group comprises barriers related to the ReSOLVE dimensions (specific barriers). In N Vivo, each category was subcategorised into the barriers provided in Table 9, receiving a code.

	Code	Barriers	References
General barriers	GB1	Lack of eco-friendly AM legislation and public policies.	Ford & Despeisse, 2016; Garmulewicz et al., 2018; Unruh, 2018
	GB2	Lack of strategic alignment in the adoption of AM to achieve circular business models.	Bogers et al., 2016; Centobelli, 2020; De Sousa Jabbour et al., 2018; Martinsuo Luomaranta, 2018
	GB3	Lack of skills, experience, and awareness of workers concerning the use of AM.	Cerdas et al., 2017; Despeisse et al., 2017; Garmulewicz et al., 2018; Gebler et al., 2014; Martinsuo Luomaranta, 2018; Shukla et al., 2018
Specifics barriers	SB1	Possibility (risk) of irresponsible or excessive consumption of 3D printed products.	Bogers et al., 2016; Cerdas et al., 2017; Ford & Despeisse, 2016; Ghaffar et al., 2018; Giurco et al., 2014; Unruh, 2018
	SB2	Toxicological risks associated with the use of AM impacting the environment and occupational health of workers.	Behm et al., 2018; Chen et al., 2020; Chong et al., 2015; Kellens et al., 2017; Kim et al., 2015b; Rejeski, Zhao and Huang, 2018
	SB3	Low printing/production pace with currently available AM technology.	Ford & Despeisse, 2016; Holmstrom & Gutowski, 2017; Singh et al., 2017; Strange & Zucchella, 2017
	SB4	Lack of quality in items produced by AM technologies	Depalma et al., 2020; Despeisse et al., 2017; Ford & Despeisse, 2016; Niaki & Nonino, 2017b; Vidakis et al., 2020
	SB5	Limitation on the number of technical cycles of materials used in AM.	Depalma et al., 2020; Dal Fabbro et al., 2020; Garmulewicz et al., 2018; Mikula et al., 2020; Sanchez et al., 2020; Sun et al., 2020; Unruh, 2018; Vidakis et al., 2020; Zhao et al., 2018

SB6	Limited availability of recycled AM materials and limited efficiency of small-scale recycling technologies.	Ford & Despeisse, 2016; Garmulewicz et al., 2018; Mikula et al., 2020; Sanchez et al., 2020; Sauerwein et al., 2019; Sun et al., 2020
SB7	Low acceptance of recycled raw materials for AM.	Depalma et al., 2020; Sun et al., 2020; Zhao et al., 2018; Zhong & Pearce, 2018
SB8	Lack of sufficient match between novel or biodegradable materials and current 3D printing technologies.	Faludi et al., 2019; Ford & Despeisse, 2016; Lee et al., 2017; Ma et al., 2018
SB9	High raw material costs for AM use.	Ford & Despeisse, 2016; Niaki & Nonino, 2017b; Weller et al., 2015
SB10	High unit cost of AM.	Baumers and Holweg, 2019; Ford & Despeisse, 2016; Weller et al., 2015

Table 9 - Additive manufacturing barriers for circularity. (Legend: AM- Additive Manufacturing, 3D- three-dimensional)

3.2.1 Lack of eco-friendly additive manufacturing legislation and public policies.

Some studies identify how the lack of legislation and/or public policies that regulate the environmental impact generated by using AM impacts CE. There are situations in which the use of AM can cause waste. The literature does not mention specific laws or standards that provide, for example, reuse or recycling of this waste. Thus, technical cycles face a series of barriers in achieving CE's expected benefits. According to Garmulewicz et al. (2018), distributed circular business models are lacking to organise material recycling for use in AM. Ford and Despeisse (2016) highlighted the lack of standards in repair and remanufacturing processes in the context of AM. Thus, circular regulations and standards are required to enable AM to drive CE.

Additionally, this technology requires regulations related to toxicology. 3D technology generates harmful emissions from ultrafine particles and volatile organic compounds in certain materials. However, no laws describe the choice of material regarding the possible toxicological effects that can be generated. Policymakers should consider the toxicological implications of 3D printing material options and encourage choices of 3D printing materials that support the emergence of sustainable CE (Unruh, 2018).

3.2.2 *Lack of strategic alignment in the adoption of additive manufacturing to achieve circular business models.*

Some authors have also reported the lack of strategic alignment between AM and business models. In addition, according to Bogers et al. (2016), new business models must be developed because of emerging AM technologies. Developing such business models implies managing organisational changes and openness to external sources (Bogers et al., 2016). Martinsuo and Luomaranta (2018) emphasise that as AM differs significantly from traditional manufacturing technology, its adoption must begin with strategic management. Unruh (2018) suggested that government policies and private standards can help direct AM toward circular materials in the early stages of AM diffusion. However, this impulse depends on intensive strategies beyond new additive technologies, such as systematic choices.

However, the existing literature does not explain how companies design their business models according to CE principles. The transition to a circular economy (CE) necessitates businesses to participate in strategies such as reuse, repair, remanufacture, refurbishment, and resale to retain value from used goods (Johnson, 2022). There is fertile ground for research at the intersection between CE and the field of strategic management (Centobelli, 2020). However, much less empirical evidence exists on how digital technologies such as AM are applied in practice by companies to achieve specific goals of the CE (De Sousa Jabbour et al., 2018). This will require a better understanding of how these technologies can adequately support a chain of actors (customers, suppliers, and institutions) involved in a circular business model, enabling and supporting the active involvement of external actors throughout all phases of the circular life cycle (Centobelli, 2020).

3.2.3 Lack of skills, experience, and awareness of workers concerning the use of additive manufacturing.

How the lack of skills, experience, and awareness regarding the use of AM impacts CE could also be extracted from some studies. Although a lack of abilities can be perceived as a restrictive social/educational factor, it is also related to the current state of technology, which requires a high level of skill to work with (Garmulewicz et al., 2018; Martinsuo & Luomaranta 2018; Shukla et al., 2018).

To play a positive role in circularity, AM must be aligned with users' awareness of the impact of manufacturing. Democratising manufacturing, making technology available to individual entrepreneurs or the public, requires a change in mentality and behavioural changes toward more sustainable modes of production and consumption (Despeisse et al., 2017). Cerdas et al. (2017) addressed the need for knowledge to achieve behavioural changes, arguing that an inexperienced 3D printing user would produce significant waste, use more material, and require longer printing times. Training operators and designers can help reduce the manufacturing process's environmental impact and improve the process's quality (Gebler et al., 2014). As a result, educational systems and programmes must be revised to meet new knowledge demands (Gebler et al., 2014).

Martinsuo and Luomaranta (2018) emphasised that this approach requires a company to invest heavily in R&D, as granting resources to designers is vital to ensure learning and experimentation. Their findings also showed that companies must overcome their tolerance for the AM learning curve, which is sometimes considered expensive and time-consuming, especially for small- and medium-sized businesses.

3.2.4 Possibility (risk) of irresponsible or excessive consumption of three-dimensional printed products.

Specific barriers are those related to ReSOLVE dimensions Literature shows the possibility of AM inciting irresponsible or excessive consumption of 3D printed products, as it allows customers to co-design products that perfectly meet their demands and ambitions (Ghaffar et al., 2018). This freedom is a two-way street because while it allows the development of more circular products, it also opens up spaces for designing products that lead to waste. Furthermore, taking advantage of AM's design freedoms requires AM skills and competencies that individuals and organisations may lack or take time to establish (Ford & Despeisse, 2016).

AM technologies support shifting to a more consumer-centric business model (Bogers et al., 2016). Therefore, consumers have greater freedom to print with numerous materials and platforms with different specifications. Unfortunately, this means that the final product can pose a risk to people's safety and health (Bogers et al., 2016), which creates a significant barrier for a CE model.

Increased consumption of products can negatively impact environmental health. Ford and Despeisse (2016) emphasised that the growth of AM can lead to an alternative scenario in which less eco-efficient localised production, customer demands for customised goods, and a higher rate of product obsolescence are combined to increase resource consumption. Cerdas et al. (2017) highlighted the increase in general consumption, mainly in fashion products. It is highly likely that companies will aim to increase consumption by offering higher degrees of customisation in shorter times, and thus print more products and accordingly increase environmental impact. Unruh (2018) highlights a fact that corroborates this perspective. According to this author, in 2016, US toy maker Mattel announced a US$299 3D printer for children to make toys. This was considered wastage as potential plastic waste produced by thousands of children armed with a printer and an endless catalogue of downloadable toy designs (Unruh, 2018).

3.2.5 *Toxicological risks associated with the use of additive manufacturing impacting the environment and occupational health of workers.*

Literature describes the toxicological risks associated with this technology. These risks are not yet well known and should be the focus of future research (Kellens et al., 2017). However, it is known that 3D technology has some adverse effects, such as harmful emissions in the form of ultrafine particles and volatile organic compounds because thermoplastics are used as raw materials (Kim et al., 2015b; Rejeski et al., 2018). This is particularly worrying because most 3D printers are housed indoors (Behm et al., 2018). AM using metals also generates particulate matter owing to fine metal powders and high temperatures, thus negatively impacting the environment and human health (Chen et al., 2020). Acrylonitrile butadiene styrene (ABS) is the most widely used thermoplastic material. When this material was heated to approximately 170°C, the three major decomposition products were acrylonitrile, 1,3-butadiene, and styrene, all of which are toxic to humans (Chen et al., 2020). For CE, this risk must be investigated because the cradle-to-cradle approach promotes non-toxicity and purity of materials to obtain a safer use of resources (Chong et al., 2015).

3.2.6. Low printing/production pace with currently available additive manufacturing technology.

The literature on CE implementation describes the growth in efficiency and performance. However, most 3D machines are relatively slow and inefficient (Holmström & Gutowski, 2017;

Sanchez et al 2020), and require a longer production time. Although there have been constant advances in AM technologies, and many can already be fabricated rapidly, this is not the case for the most industrially used ones (such as material extrusion). In this case, the layer-by-layer process can take longer than some traditional manufacturing processes, such as CNC machining or injection molding, depending on the size and complexity of the part being produced (Fico et al., 2022). In addition to the layer-by-layer process, which requires a long time to complete a part for most machines, time is also required to prepare for the design of parts and post-processing (Fico et al., 2022). This includes preparing the 3D model for printing, optimizing the design for the specific printing process and material, and preparing the printer and materials for printing. After the printing is finished, post-processing is also necessary to remove support structures, clean the parts, and perform any finishing operations to achieve the desired surface quality and dimensional accuracy. These processes add to the overall lead time and can significantly reduce the productivity of the AM process, mainly when producing multiple parts (Strange & Zucchella, 2017). Consequently, adopting AM in production lines requires further development and consolidation (Ding et al., 2021; Strange & Zucchella, 2017). Thus, the economy associated with AM makes it more ideal for manufacturing products and components than for mass manufacturing, meaning that its main economic benefits are found in the personalised production of goods in single or small batches (Ford & Despeisse, 2016; Singh et al., 2017).

3.2.7 Lack of quality in items produced by additive manufacturing technologies.

The uncertain performance of products and components produced through AM is a widely discussed topic. (Ford & Despeisse, 2016). This is due to the quality issues that arise from using AM technologies. One of the reasons is the lack of technical standards in AM, which can result in lower quality of the printed object (Niaki & Nonino, 2017b). Another reason is the poor surface quality of 3D printed parts caused by the "staircase effect" in 3D printing technology, which negatively impacts the surface accuracy of the parts (Fico et al., 2022). The "staircase effect" is a visible, step-like pattern on the surface of a 3D-printed object caused by layering process used in FDM printing, where the edges of each layer can be slightly visible on the object's surface. Additionally, 3D printing processes of polymers via extrusion have a relatively low quality (Sanchez et al., 2020) as the material undergoes thermal degradation during the process (Depalma et al., 2020), negatively impacting its traction properties and mechanical strength of parts (Vidakis et al., 2020). These quality issues in 3D printing are primarily due to the immaturity of the manufacturing process (Zhou et al., 2022), and can make achieving circularity more challenging, as high material purity and dimensional accuracy are required to reduce rejection rates.

3.2.8 Limitation on the number of technical cycles of materials used in additive manufacturing.

Another topic discussed is the limitation on the technical cycles of recycling the materials used in AM. Several limitations in the raw materials used for 3D printing make it challenging to maintain technical recycling cycles. Ford and Despeisse (2016) highlighted that the multi-material goods produced by AM are not recyclable, and recycling of plastics is limited owing to losses in quality.

Polymeric materials are widely used in AM and are commonly processed using material extrusion, the most widely used AM technology (Mikula et al., 2020). In this technique, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are among the most used materials. However, using these thermoplastics presents a barrier for AM recycling, as the final quality is the main concern for mechanically recycled products (Sanchez et al., 2020). The main limitation related to reusing these materials is the problem of losing the properties after recycling several times (Mikula et al., 2020).

Fabbro et al. (2020) studied the effects of multiple ABS recycling systems in a closed circuit. Various closed-loop recycling processes were conducted in this study without any noticeable difficulty until the third AM process (two recycling cycles). In the third closed-loop recycling process, dimensional instability of the filament is observed during the extrusion process. DePalma et al. (2020) pointed out that ABS materials undergo significant thermal degradation during SLS (selective laser sintering) and FDM processing, making them difficult to reuse. Zhao et al. (2018) concluded that the repeated 3D printing process had only two cycles for PLA in FDM processing, as significant deteriorations in viscosity values were detected, making the material unsuitable for further reprocessing.

3.2.9 Limited availability of recycled additive manufacturing materials and limited efficiency of small-scale recycling technologies

Much has been discussed regarding the concept of recycling materials for 3D printing. Several studies have focused on using recycled plastics for 3D printing (Garmulewicz et al., 2018; Mikula et al., 2020; Sanchez et al., 2020), and several companies have already sold those. Despite this, Sun et al. (2020) argued that recycling 3D printed products and materials represents a challenge because there are several barriers to recycling. First, recycling potential is limited to certain materials (Ford & Despeisse, 2016), because not all 3D printed materials can be recycled (Garmulewicz et al., 2018); and even for materials that can be recycled, there are restrictions on the number of times this can be done because of quality and purity problems (Unruh, 2018; Vidakis et al., 2020; Zhao et al., 2018). Sun et al. (2020) also drew attention to the inefficiency of small-scale recycling because the supply chain structure for recycling is based on large, centralised processes, and AM requires small-scale recycling technologies. This creates barriers to recycling 3D printed waste.

3.2.10 Low acceptance of recycled raw materials for additive manufacturing.

The low acceptance or willingness to consume recycled material as raw material for AM has been discussed by some authors (DePalma et al., 2020; Zhao et al., 2018). Garmulewicz et al. (2018) argued that this limited demand among consumers might occur because of low recycling rates among consumers, who are generally not aware of the value of the materials contained in their waste. Zhong and Pearce (2018) highlighted the lack of acceptance of recycled materials over virgin materials by companies that use AM. These authors discovered a tendency to avoid using recycled materials because of quality issues and uncertainty regarding recycled filaments' consistency and mechanical properties. Sun et al. (2020) conducted an analytical and numerical study that showed that the quality of recycled materials significantly affects suppliers' decision-making for 3D printing. These authors argued that material suppliers prefer low-quality recycled materials to ensure that recycled material suppliers can survive in a market where virgin and recycled materials compete. Therefore, the quality of the recycled material must be below a specific limit compared to that of the virgin material. These authors found that material suppliers' profits decrease with an increase in the quality of recycled material, implying that suppliers may not be in favour of improving its quality.

3.2.11 Lack of sufficient match between novel or biodegradable materials and current three-dimensional printing technologies.

Some studies have mentioned a lack of a good match between novel materials and current 3D printing technologies. CE literature highlights the production and choice of new products and advanced and novel materials as leverage for their implementation. Lee et al. (2017) defined novel materials as a group of advanced materials that can be 3D printed for specific new applications. The authors emphasised that one challenge is ensuring the 3D printability of novel/advanced materials without compromising the original material properties. Novel AM materials are still limited to specific applications. Further development of novel materials is still required, as most printers work with a single material with limited industrial applicability (Ford and Despeisse, 2016; Lee, 2017). Recent works have highlighted the need for developing high-performance, compostable, or biodegradable materials for AM (Colorado et al., 2020; Faludi et al., 2019). As noted by Colorado et al. (2020), the current immaturity of materials in AM has been a barrier to developing innovative solutions. To address this, Ma et al. (2018) have emphasized the importance of investing in developing advanced AM material manufacturing technology. This will enable the production of high-performance materials and enhance both the industrial and consumer ability to create innovative products..

3.2.12 High raw material costs for additive manufacturing use.

The "exchange" action highlights that applying new technologies (citing, as an example, AM itself) is fundamental in implementing a CE. However, there are financial issues when using the technology itself. Ford and Despeisse (2016) and Weller et al. (2015) highlighted that high raw material prices are a barrier. Niaki and Nonino (2017b) argued that AM machines and materials are still expensive, but the cost will decrease as AM becomes a more commonly used production technique. In addition, most machines are patented, and this exclusivity hinders price reductions (Niaki & Nonino, 2017b). This economic aspect is also considered in CE because if circular AM activities are not economically viable, the AM's potential benefits will not materialise.

3.2.13 High unit cost of additive manufacturing.

The topic of unit cost in AM remains inconclusive (Franco et al., 2020). While some authors have found that the relationship between production quantity and unit cost is absent in AM (Atzeni and Salmi, 2012; Weller et al., 2015), others recent studies have argued that the average unit cost in AM depends on the manufactured quantity (Baumers and Holweg, 2019; Ding et al., 2021). Although AM's economics are fundamentally different from traditional manufacturing; economies of scale are still available in AM (Ding et al., 2021). Therefore, as larger production volumes become more economically feasible in the future, AM is expected to become more cost-effective (Ford & Despeisse, 2016). Currently, the unit cost of AM can be higher than traditional methods, as most applications that have been reported use AM to produce small-scale products (Baumers and Holweg, 2019). This remains an obstacle to realising the full potential of AM technology, as it can overshadow the potential positive benefits of increasing AM.

4. Discussion

The current study organised previous research into 15 benefits AM can provide to support the transition to a CE and 13 barriers preventing AM from meeting CE requirements. Given this, we propose a framework (Fig. 3) that organises, systematises, and formalises the ideas presented and the high volume of information retrieved from the literature. In addition, the proposed framework will assist in the development of future research.

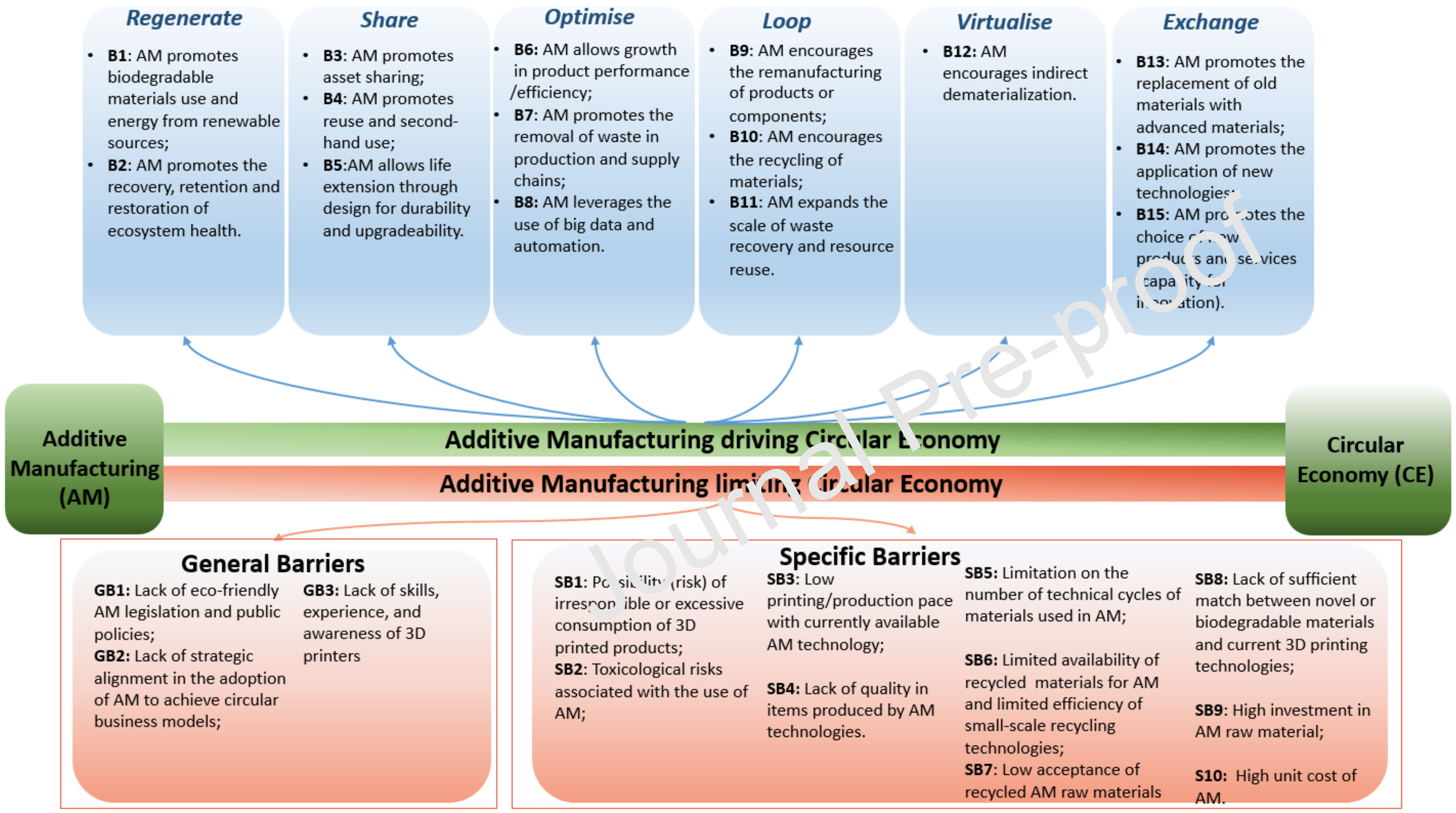

Fig. 3. Relationship between additive manufacturing and the circular economy (Legend: AM- Additive Manufacturing, CE- Circular Economy, 3D – three-dimensional).

Fig. 3 illustrates the relationship between AM and CE. In the upper part of the figure, there are 15 potential benefits of AM leading to CE related to each of the six ReSOLVE principles. At the bottom, barriers may restrict the potential for AM circulation. Barriers are classified as either general or specific.

Many benefits can be achieved directly by adopting AM technology. B5 benefits, for example, can be directly achieved with the use of AM because the variety in the design and manufacturing of complex geometries is an intrinsic feature of the technology. Thus, the ability to design durability and constant updates is a benefit that is directly achieved through technology. However, other benefits require effort to achieve, requiring some degree of intervention to realise such benefits. For example, the benefits linked to “loop” (B9, B10, and B11) are not so natural, since they need some stimuli to be perceived. Finally, some benefits can become barriers that limit circularity. Benefit B7, for example, can be directly achieved by AM adoption because it naturally shortens supply chains and reduces waste (Bogers et al., 2016; Ford & Despeisse, 2016). However, the slowness and inefficiency inherent in most current AM processes can cause wasted time in production or higher costs. Therefore, efforts are required to improve the printing speed (Tuan & Yin 2017).

It also provides a macro view of barriers limiting AM’s circularity. To this end, it was considered both intrinsic and extrinsic barriers to technology are considered. Intrinsic barriers are those provided by AM characteristics, while extrinsic barriers are those that limit the potential for AM circularity but are not related to its characteristics, instead of political, social, environmental, or educational characteristics of the context in which the technology is inserted. Barriers GB1, GB2, GB3, SB7, and SB9 could be considered extrinsic. Furthermore, many barriers can be influenced by the degree of technological maturity, which is relatively new. Therefore, it is expected that barriers

GB1, GB2, GB3, SB1, SB3, SB4, SB8, and SB9, which are somewhat influenced by the degree of technological maturity, will be mitigated as AM evolves and matures.

The highlighted barriers may indicate actions that need to be taken to reach a more significant potential for circularity. General barriers reveal some measures that need to be implemented so that AM can be instituted more environmentally friendly (i.e., eco-friendly), such as governance and educational measures.

Interviews with experts were essential for this study. This phase contributed significantly to revealing the barriers, which were almost completely restructured. In addition, new barriers were suggested, which were incorporated into the study by combining them with evidence from the literature. Thus, it was possible to obtain clarity of terms, enhanced understanding, and a broader and more systematised view of the barriers.

4.1. Overcoming barriers to achieve circularity: future research directions

Identifying the barriers that prevent AM from being more circular is crucial for developing a research agenda to mitigate or overcome them. This is especially important for AM companies interested in the benefits of a circular economy (CE). By understanding these barriers, AM companies can better leverage ReSOLVE actions to overcome them and reap the benefits of a CE. The agenda was summarised in figure 4.

4.1.1 Agenda for overcoming barriers through regenerate

To reach this regenerate, organizations must implement plans that focus on transitioning to renewable energy and materials, and restoring, preserving, and regenerating ecosystems (Ellen MacArthur Foundation, 2015). Adhering to these guidelines can help overcome many of the barriers identified, particularly SB1, SB2, SB8, and SB9.

For instance, by following guidelines for environmental health, stakeholders can develop safer practices to improve the purity of the work environment and reduce occupational health hazards caused by AM use, mitigating barrier SB2. Additionally, efforts to inform and educate AM operators and users would be effective in overcoming barrier SB1. In terms of materials used in AM, incentive policies are needed to encourage the selection of materials that support the CE, such as biodegradable materials. This would be effective in mitigating barrier GB1. Additionally, the use of alternative materials, such as novel materials or locally abundant materials, can help alleviate barriers SB8 and SB9, respectively.

In light of this, the following guidelines for future research were developed:

- How to support the use of materials in AM that promote CE, such as biodegradable materials?
- How to enhance the purity of work environment and overcome the risk of occupational health hazards caused by AM?

4.1.2 Agenda for overcoming barriers through share

To achieve share, it is essential to slow down the product life cycle and maximize the utilization of products by sharing them among multiple users. (Ellen MacArthur Foundation, 2015). Adhering to these sharing guidelines can help overcome many barriers. For example, sharing knowledge and open data between companies can help mitigate barrier GB3. Another guideline that aims at this goal is maximizing the use of AM products and machines. A machine rental service with assisted printing could be an effective way to achieve this while also reducing the misuse of 3D printers, thereby mitigating barrier SB1.

In view of this, the following guidelines for future research were developed:

- How to encourage the sharing of knowledge and open data between companies?
- How to maximize the use of AM products and machines?

4.1.3 Agenda for overcoming barriers through optimise

To optimize AM in the CE context, organizations must improve the performance and efficiency of products and processes, and eliminate waste in production and supply chain (Ellen MacArthur Foundation, 2015). Adhering to these optimization guidelines can help mitigate barriers SB3 and SB4. To address SB3, more research and development is needed to enhance process efficiency and increase the capacity and speed of machines, such as material extrusion machines which are typically slow (Fico et al., 2022). To address SB4, research and development in new quality control methods and material properties is necessary to minimize failure rates and reduce AM waste.

In addition, there are other opportunities for future research in optimization. For instance, redesigning components and products to simplify the supply chain and reduce waste has been explored, however, the design principles of AM products are not yet fully advanced, and it is crucial to understand how to encourage designers to create AM products with sustainable principles in mind.

Considering this, the following guidelines for future research emerge:

- How to enhance process efficiency, increasing the capacity and speed of AM machines?
- How to improve quality in AM products, minimizing failure?
- How to encourage and educate designers to minimize waste in AM?

4.1.4 Agenda for overcoming barriers through Loop

To achieve "loop", AM needs to be geared towards keeping components and materials in closed loops (Ellen MacArthur Foundation, 2015). Barriers such as SB5, SB6, and SB7 may prevent this from happening. To overcome this, the value chain must establish incentives for recycling, reusing, and remanufacturing. Additionally, research is needed to improve the quality of recycled materials.

Other opportunities have also been identified to achieve this goal. For example, there is limited knowledge on how to structure a recycling infrastructure to meet the demands of a decentralized AM market. Although recent studies have shown the economic and environmental feasibility of a distributed network in the supply chain (Santander et al., 2020), there are no studies that have considered the social and political aspects of this infrastructure

In the light of this, the following agenda for future research emerged:

- What incentives can be offered for promote recycling, reuse and remanufacturing in AM?
- How to develop the quality of recycled materials in AM?
- How to structure a recycling infrastructure to meet a decentralised AM market demand?

4.1.5 Agenda for overcoming barriers through virtualise

To achieve virtualise, virtual information regarding AM needs to be easily accessible so that consumers can use the technology more efficiently. In addition, developing new online platforms can help companies mitigate barrier GB3 by providing more knowledge to 3D printing workers. However, investing in new types of businesses must be beneficial for stakeholders. Therefore, it is important to conduct analyses to understand the actual need for this type of investment. One potential question to consider in this regard is: How to incentive the development of new online AM platforms?

4.1.6 Agenda for overcoming barriers through exchange

To achieve exchange, AM organizations must replace old with advanced materials, apply new technologies and choose new products/services (Ellen MacArthur Foundation, 2015). To accomplish this, barriers such as SB8, SB9, and SB10 may need to be overcome. Future guidelines for achieving this include research and development in novel AM materials to address barrier SB8, research and development in low-cost materials with improved properties to attenuate barriers SB9 and SB10.

In view of this, the following guidelines for future research emerge:

- How to encourage the development of novel AM materials?
- What new materials could be developed to ensure low-cost raw materials with superior properties?
- What new services can be created to assist the AM printing?

As in ReSOLVE each action reinforces and accelerates the performance of the other actions, it is natural that decision making at one level has a positive impact on the others. For example, guidelines to mitigate or overcome barriers in regeneration can also enhance overcoming barriers in exchange. For instance, mitigating barriers SB8 and SB9 leverages the advancement of both, regenerate and exchange, actions of ReSOLVE. Therefore, it is important to approach the ReSOLVE actions holistically and consider how actions taken in one level can positively impact the others. That is why the general barriers could also be addressed here. This holistic approach ensures that the organization's efforts in one level will not only achieve the goals of that level but also contribute to the overall success of the CE in AM.

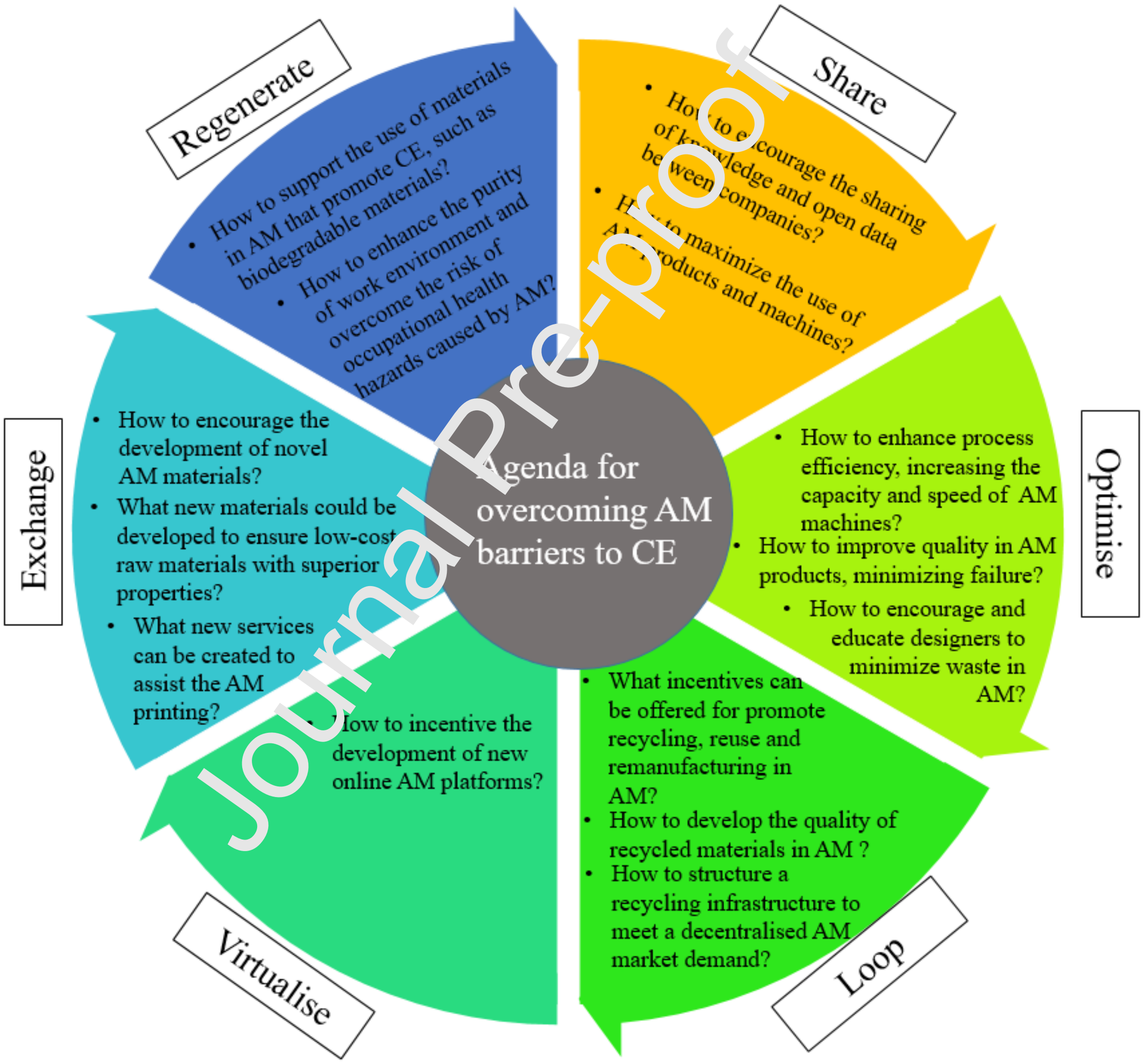

Fig 4. Agenda for overcoming additive manufacturing barriers for circular economy (Legend: AM- Additive Manufacturing, CE- Circular Economy).

4.2. Limitations

Most of the limitations were addressed while conducting this study. However, some problems still exist. First, some articles may have been excluded from the final literature review sample because of the choice of keywords. Thus, although the methodology allows for replicability, the choice of keywords may slightly alter the general results. Nevertheless, the conclusions are robust as they are supported by references and extensively described in the Results section, thus minimising possible qualitative research bias. Second, the judgement and contributions of experts are subject to their background and experience. These limitations can be further addressed in future works that: (i) conduct reviews and continuously update the framework as a "live" body of knowledge; and (ii) perform empirical data collection using either large samples of experts or adjusted quantitative methodologies to further validate the relevance and occurrence of barriers and benefits.

Finally, this paper has shown that the ReSOLVE framework can be a valuable tool for AM businesses to align with the principles of Circular Economy. However, it is possible that some AM solutions or barriers may not be fully captured by this framework. Although the use of the framework is justifiable, there may be other alternatives. Therefore, exploring AM solutions under the lens of other Circular Economy (EC) frameworks could be a path for future research.

5. Conclusions

This study identified the benefits and barriers of AM for CE through a multi-method approach. First, it was observed how AM supports the implementation of circularity using the ReSOLVE structure, created to assist organisations in implementing circular strategies. The literature reveals 15 benefits that AM can leverage in circularity. The next step was to survey the barriers that hinder AM in achieving the specific goals of the CE. These barriers are classified into two groups: general and specific barriers, which refer to the actions of the ReSOLVE structure. This resulted in a framework that organised and systematised the finds.

Most research on this topic has demonstrated the benefits of AM for CE in specific applications and contexts. However, the broader adoption of AM benefiting CE also depends on overcoming the barriers that have been raised. It is also essential to note that if circular activities in AM are not economically viable, the benefits of CE will not be fully seized by companies, governments, and society.

This study contributes to the literature in several ways. First, it systematises the barriers and benefits of AM concerning CE in a readily available and applicable framework. Second, it blends established knowledge in the academic literature on the topic with expert judgment, bringing a practical perspective to the approach. Third, using the ReSOLVE framework as the underlying structure encourages the direct and actionable use of the resulting framework by practitioners and policymakers, as the framework is widely known and used in CE practices among organisations and governments. Finally, section 4.2 provided an opportunity to critically analyse the barriers identified in the literature and propose a future agenda for overcoming them, intending to transform AM into a more circular technology. While this study has made valuable contributions, it is vital to keep in mind the limitations discussed in section 4.3 when evaluating the results.

Although this work has analysed the benefits and barriers regarding specific points, to address how AM technology meets CE goals, a more collective and integrated effort is required to ensure that production, consumption, and recovery cycles achieve a more circular model. Therefore, closer integration and deeper interdisciplinary collaboration are essential for advancing CE.

Because AM is a relatively immature technology, potential new AM applications with more comprehensive and significant CE benefits will soon be developed. Overall, analyses and classifications have made it possible to understand that studies addressing the relationship between AM and CE are still in their early stages. As a result, empirical evidence on how digital technologies are applied in practice to meet CE goals is still lacking. To meet these requirements, there is a need for a better understanding of how to support the active involvement of all actors in a supply chain throughout all phases of the circular life cycle. However, some aspects remain poorly studied and have been described in the literature. These gaps in the literature have revealed avenues for future studies.

In each of the ReSOLVE framework's actions, the study reveals the future agenda for a circular AM. And as was already said, interdisciplinary cooperation must underpin these actions. For instance, there is currently a chance to think about how circularity can affect policymakers' ability to impact AM development. For technology to adhere to CE principles, the AM governance structure is still not well defined. This governance aspect is of fundamental importance to align efforts in different dimensions: local, product-oriented initiatives and general regulations operating within and across countries and regions.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: