**UNIVERSIDADE FEDERAL DE SÃO CARLOS**

CENTRO DE CIÊNCIAS EXATAS E DE TECNOLOGIA

**PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO**

# AN ANALYSIS OF THE RELATIONSHIP BETWEEN ADDITIVE MANUFACTURING AND CIRCULAR ECONOMY

THAIS MOREIRA TAVARES

**DISSERTAÇÃO DE MESTRADO**

UNIVERSIDADE FEDERAL DE SÃO CARLOS
CENTRO DE CIÊNCIAS EXATAS E TECNOLOGIA

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO

THAIS MOREIRA TAVARES

# AN ANALYSIS OF THE RELATIONSHIP BETWEEN ADDITIVE MANUFACTURING AND CIRCULAR ECONOMY

Texto de Defesa apresentado ao Programa de Pós-Graduação em Engenharia de Produção da Universidade Federal de São Carlos (UFSCar), como parte dos requisitos para obtenção do título de mestre em Engenharia de Produção.

**Orientador:** Prof. Dr. Gilberto Miller Devós Ganga

**SÃO CARLOS-SP**
**2022**

**UNIVERSIDADE FEDERAL DE SÃO CARLOS**
CENTRO DE CIÊNCIAS EXATAS E DE TECNOLOGIA
**Programa de Pós-Graduação em Engenharia de Produção**

## Folha de Aprovação

Defesa de Dissertação de Mestrado da aluna Thais Moreira Tavares, realizada em 22/03/2022.

### Comissão Julgadora

Dr. Gilberto Miller Devós Ganga (UFSCar- PPGEP)
Dr. Moacir Godinho Filho (UFSCar- PPGEP)
Dr. Lauro Osiro (UFTM)
Dr. Luís Antônio de Santa-Eulalia (Université de Sherbrooke, Canadá)

Dr. Vinicius Picanço Rodrigues (INSPER)

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001.

O Relatório de Defesa assinado pelos membros da Comissão Julgadora encontra-se junto ao Programa de Pós-Graduação em Engenharia de Produção.

# DEDICATÓRIA

*Dedico este trabalho a minha família pelo importante apoio nessa caminhada.*

# AGRADECIMENTOS

Aos meus pais Maria Auristela e Tavares, que dedicaram suas vidas me auxiliando e incentivando aos estudos. A toda doação em forma de apoio emocional, intelectual e financeiro a que me dedicaram neste período de realização da pesquisa. Ao Thalis Henrique, por todo companheirismo, palavra de apoio e escuta compreensiva dos momentos de alegria aos desafiantes. Aos meus irmãos, Tales e Gisele, pelo companheirismo e troca nesta caminhada.

Em especial aos professores Dr. Gilberto Miller Devó Ganga e ao Dr. Moacir Godinho Filho, que em conjunto colaboraram com o desenvolvimento desta dissertação por meio de uma orientação pautada por um elevado nível científico.

Gostaria também de expressar minha gratidão à banca examinadora. Ao professor Dr. Vinicius Picanço Rodrigues, obrigada pelas valiosas contribuições, pela confiança, atenção,e apoio concedido no auxílio à pesquisa. Ao Professor Dr. Lauro Osiro, pela dedicação, apoio e disponibilidade em contribuir com o método de Pesquisa. Ao professor Dr. Luís Antonio de Santa- Eulalia, pelo valioso conhecimento em Manufatura Aditiva concedido à pesquisa.

À Universidade e aos professores do Departamento de Engenharia de Produção da UFscar, por proporcionarem conteúdos e ensinamentos. Aos colegas do Grupo de Pesquisa em Gestão de Operações & Cadeia de Suprimentos Digitais e Sustentáveis (GOSC), e os funcionários da Secretária da Pós-Graduação do Departamento deEngenharia de Produção da Universidade Federal de São Carlos.

Por fim, agradeço à Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), pela concessão da bolsa de estudo.

# RESUMO

Uma das tecnologias em destaque da Indústria 4.0 é a Manufatura Aditiva (MA), que permite a fabricação de objetos camada por camada de forma contínua ou incremental. A Economia Circular (EC) visa melhorar a eficiência dos recursos de modo a levar a uma mudança do atual modelo linear de extração, transformação e descarte para um modelo onde os recursos fluem de maneira circular. Alguns estudos iniciais apontam a Manufatura Aditiva como uma promessa de sustentabilidade e desenvolvimento de fluxos de materiais mais circulares. No entanto, ainda há incerteza sobre os impactos e benefícios da Manufatura Aditiva para a circularidade. A partir desse contexto, este trabalho visa primeiramente entender a relação entre Manufatura Aditiva e Economia Circular. Para atingir este objetivo, foi realizado um estudo multi-métodos para entender como a AM é benéfica ou desafiadora em um contexto de Economia Circular. Em segundo, este trabalho visa colaborar no desenvolvimento de estratégias de implementação da AM em um contexto de CE. Para tal, foi realizado um segundo estudo, que utilizou o método fuzzy DEMATEL, para levantar as relações de interdependência entre as barreiras levantadas no primeiro estudo. A análise dessas relações possibilitou a elaboração das estratégias de implementação de uma MA circular.  A pesquisa contribui para a prática e a teoria. Na teoria, elabora o estado da arte da intersecção entre os temas, evoluindo para um framework abordando benefícios e barreiras (validados por especialistas) que a AM traz para a EC. O estudo contribui para a prática ao mostrar quais desenvolvimentos e estratégias precisam ocorrer para facilitar o caminho para um AM circular.

**Palavras-Chave:** Manufatura Aditiva. Impressão 3D. Economia Circular. Sustentabilidade.

# ABSTRACT

Additive Manufacturing (AM) is an important technology of Industry 4.0. It allows the fabrication of objects layer by layer in a continuous or incremental way. Circular Economy (CE) aims to improve resource efficiency in order to lead to a shift from the current linear model of receiving, transforming and disposing to a model where resources flow in a circular manner. Some early studies refer to Additive Manufacturing as a promise of sustainability and development of more circular material flows. However, there is still uncertainty about the impacts and benefits of Additive Manufacturing for circularity. From this context, this work aims firstly to understand the relationship between additive manufacturing and circular economy. To achieve this goal, a multi-method study was carried out to understand how AM is beneficial or challenging in a Circular Economy context. Second, it aims to collaborate in the implementation of AM strategies in an EC context. To coordinate the elaboration of the strategies, a second multi-method study was carried out, using a fuzzy DEMATEL method. This method was used to understand the interdependence relationships between the barriers raised in the first study. The study of these relationships is essential in the elaboration of strategies for implementing a more circular AM. The research contributes to practice and theory. In theory, it elaborates the state of the art of the intersection between the themes, evolving into a framework addressing benefits and barriers (validated by experts) that AM brings to CE. The study also contributes to practice by showing to organizations what developments and strategies need to take place to smooth the way for a circular AM.

**Keywords:** Additive Manufacturing. 3D printing. Circular Economy. Sustainability.

# LISTA DE FIGURAS

# LISTA DE TABELAS

# LISTA DE ABREVISTURAS E SIGLAS

**3D** – Três dimensões ou tridimensional

**AI** – *Artificial Inteligence*

**ANP** – *Analytic Network Process*

**ASTM** – *American Society for Testing and Materials*

**BDA** – *Big Data and Analytics*

**C2C** – *Cradle to Cradle*

**CAD** – *Computer Aided Desing*

**$CO_2$** – Dióxido de Carbono

**CPS** – Cyber Physical System

**DEMATEL** – *Decision Making Trial and Evaluation Laborato*ry

**DM** – *Data Mining*

**EC**– Economia Circular

**FANP** - *Fuzzy Analytic Network Process*

**FDM** – Fused Depositon Modeling

**FST**- *Fuzzy Set Theory*

**IoS** – *Internet of Service*

**IoT** – *Internet of things*

**MA** – Manufatura Aditiva

**PLA** – *Polylactic Acid*

**RESOLVE** – *Regenerate, share, optmise, loop, virtualize, Exchange*

**RSL** – Revisão Sistemática da Literatura

**SLA** – *Steliography*

**SLT** – *Stendart Triangle Language*

## SUMÁRIO

# 1 INTRODUCTION

This chapter will explain what will be conducted throughout this dissertation. It contains the contextualization, the objectives, the methodological release and the structure of the work.

## 1.1 CONTEXTUALIZATION

The recently emerged concept of smart manufacturing refers to the ability that the industry quickly adjusts its structure and physical and organizational facilities to changes in technology as the manufacturing becomes faster and more responsive (WANG et al., 2017). Industrial production is constantly changing, and the term ‘‘revolution’’ is used to describe a powerful change. The production paradigm has changed three times and is now undergoing the fourth shift.

The first Industrial Revolution became known as the age of mechanization. The second stood out for its intensive electricity use, and the third for its widespread digitalization. More recently, the conciliation of internet technologies and future-oriented technologies in the field of “smart” objects (machines and products) seems to result in a paradigm shift in industrial production. In this future expectation, the term “Industry 4.0” was created based on a fourth industrial revolution (LASI et al., 2014).

Industry 4.0 is made up of emerging technologies that are disruptive, representing new ways to create value for organizations and citizens. Over time, these technologies promise to transform all known systems, from how goods and services are produced and transported to the means of communication and interaction with the surrounding world (SCHWAB, 2018). Thus, Industry 4.0 is composed of continuous innovation and technological development. It encompasses several information technologies such as Additive Manufacturing (AM), Cyber Physical Systems (CPS), Internet of Things (IoT), Cloud Computing, mobile devices, Big Data and others (ALMADA-LOBO, 2015). In this work, we will focus on one of the leading technologies of Industry 4.0, Additive Manufacturing (AM).

Additive Manufacturing (AM) is not a new technology, and until recently, it was used almost exclusively for prototyping. However, large companies have already taken their first steps towards small-scale production and mass production with 3D printing, which is the basic unit of MA (3D HUBS, 2019). Thus, many predict this technology will be a breakthrough that will drastically change current business models (IVAN; YIN, 2017; PETSIUK; PEARCE, 2020).

Another concept that has aroused the interest of many researchers is the Circular Economy (CE), which, despite being a recent concept, goes back to different schools of thought. There are records of the ecological economist Boulding (1966) describing the economy as a circular system being a prerequisite for maintaining the sustainability of human life on earth. In the present day, the concept has evolved. In general, CE aims to improve the efficiency of society's resources, eliminating the concept of waste and moving away from the dominant linear take-make-waste model, which goes from extraction to disposal in landfills, to a circular model where resources are kept looping into the economy (GHISELLINI; CIALANI; ULGIATI, 2016).

This new scenario of new technologies and concepts leads to one uncertainty: whether the new technologies in growth meet the requirements of a more Circular Economy. First, there is a doubt if the adoption of the new emerging technologies is beneficial for the Circular Economy. Second, there is still a lack of empirical evidence on how the key enabling technologies of Industry 4.0 are applied in practice by companies to achieve specific CE requirements (CENTOBELLI et al., 2020). Regarding AM technology itself, there are recent studies that discuss the implications of AM for sustainability, but there are uncertainties about whether the adoption of AM is capable of creating more circular material flows or not. It is still unclear whether the new technology allows for a more circular use of resources and to what extent it is truly sustainable, facilitating the Circular Economy (DESPEISSE et al., 2017; UNRUH, 2018).

According to Tang, Mak and Zhao (2016) and Peng et al. (2018), many studies are being conducted to address the crucial issues of AM such as reliable and consistent quality, comprehensive material selection, improved productivity and efficiency. However, the issue of sustainability remains largely unexplored. Evans (2009) argues that this clarity requires a better understanding of information flows and relationships between stakeholders throughout the product life cycle.

Therefore, the present work aims to fill this gap, approaching the existing relationship between Additive Manufacturing and Circular Economy. Therefore, this work aims to answer the following research question: How are Additive Manufacturing and Circular Economy related?

## 1.2 RESEARCH PURPOSE

Based on the previously stated research question, this work has its central objective to understand the relationship between Additive Manufacturing and Circular Economy. To achieve it, three specific objectives were determined:

- Specific Objective 1: Understand how Additive Manufacturing contributes to the Circular Economy;
- Specific Objective 2: Raise the potential barriers that prevent Additive Technology from meeting the requirements of the Circular Economy;
- Specific objective 3: Analyze the dependency relationships of the barriers raised to establish mitigation strategies that allow an AM with more significant circular potential;

Specific objectives 1 and 2 were achieved through a multi-method approach (secondary data analysis, systematic literature review and expert opinions), composing the first article of this dissertation. To achieve specific objective 3, empirical research was carried out using the multicriteria decision-making method, the Fuzzy DEMATEL, composing the second article of this dissertation.

This dissertation adopted a structure that favours the production of scientific articles to be submitted in high-impact journals with selective editorial policy. Therefore, despite our struggle to avoid redundancy, repetition may sometimes appear on the text to facilitate the understanding of the two articles separately. Below we describe a synthesis of the methodological procedures used in the research.

## 1.3 AN OVERVIEW OF THIS DISSERTATION RESEARCH METHODO

The present study is classified as a mixed-methods research, a term used to represent research that integrates quantitative and qualitative techniques in the same research design (CRESWELL; PLANO CLARK, 2011).

This section presents the methodological release, through which general and specific objectives will be achieved. As the organization of the dissertation follows the structure of articles, it is opportune to define a research method for each article, as highlighted in Table 1.1

**Table 1.1** - Summary of Research Methods

| Specific Objectives | Research Method | Dissertation chapter |
|---|---|---|
| 1. Understand how Additive Manufacturing contributes to the Circular Economy<br>2. Raise the potential barriers that prevent Additive Technology from meeting the requirements of the Circular Economy | Mixed methods research (Secondary data analysis; Systematic Review of Literature; Validation with experts) | 3 - The benefits and barriers of Additive Manufacturing for Circular Economy: a framework proposal |
| 3. Analyze the dependency relationships of the barriers raised to establish mitigation strategies that allow an AM with greater circular potential | Mixed methods research (Systematic Review of Literature; Validation with experts; Fuzzy DEMATEL) | 4 - Additive Manufacturing in the Circular Economy context: understanding the interaction of critical barriers |

**Source:** Author.

Chapter 3 corresponds to the first article produced, a multi-method research. The first method to be planned and developed was analysing secondary data (SON et al., 2016) to find a model that would guide us in structuring the conceptual model to be created. Therefore, after researching several reports, the RESOLVE Framework, proposed by the Ellen MacArthur Foundation, was adopted. RESOLVE comprises six action areas for companies and countries that want to move towards the circular economy. The second method used was the systematic literature review (DENYER; TRANFIELD, 2009) to understand the state of the art of research relating Additive Manufacturing and Circular Economy. Finally, we carried out an exploratory search in the databases in order to help us define the general scope of the review to be carried out. Through this review, we seek to answer the following research questions :

Q1: How does AM support the implementation of CE?

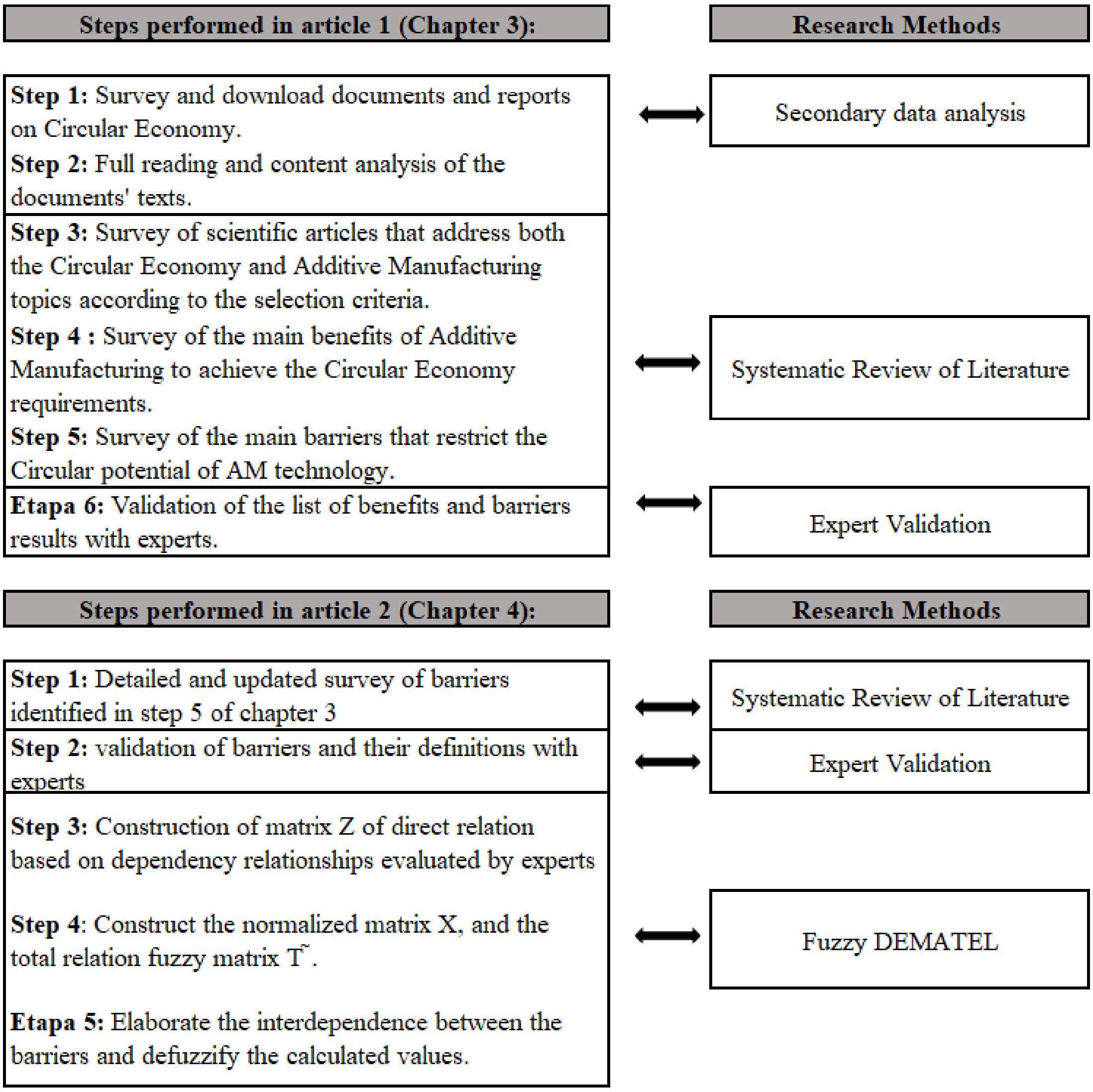
Q2: In what ways does AM prevent greater circularity from being achieved?

The technical procedures of the systematic literature review are described in detail in Chapter 3. As a result of the RSL, a conceptual framework was proposed to describe the relationships between additive manufacturing and the circular economy, highlighting the potential benefits of AM to CE and AM's barriers for circularity. Subsequently, the framework model was validated in the light of experts in additive manufacturing and circular economy.

Chapter 4 corresponds to the second article produced for this dissertation. In this article, we analyze the dependency relationship between the barriers that restrict the circularity potential of AM technology. With this, it was possible to develop mitigation strategies so that the use of AM reaches a more significant potential for circularity. In order to do so, we used a multi-method approach, consisting first of updating the systematic review of the literature presented in Chapter 3, and using the conceptual model as an input of variables – the barriers- to structure the application of multi-criteria decision-making methods; and second it was used the Fuzzy DEMATEL method to analyze the dependency relationship between the barriers. DEMATEL is a method used to extract quantitative interrelationships between multiple factors to solve a problem (FALATOONITOOSI et al., 2013; GHARAKHANI et al., 2014; PANAHIFAR, 2015). Furthermore, the inclusion of the fuzzy approach makes the human uncertainty of decision-makers to be considered, resulting in a more accurate and effective method.

The steps of each chapter (article) mentioned above were briefly detailed in Figure 1.1.

**Figure 1.1** - Summary of the research methodological flow



**Steps performed in article 1 (Chapter 3):**

**Research Methods**

**Step 1:** Survey and download documents and reports on Circular Economy.

**Step 2:** Full reading and content analysis of the documents' texts.

Secondary data analysis

**Step 3:** Survey of scientific articles that address both the Circular Economy and Additive Manufacturing topics according to the selection criteria.

**Step 4 :** Survey of the main benefits of Additive Manufacturing to achieve the Circular Economy requirements.

**Step 5:** Survey of the main barriers that restrict the Circular potential of AM technology.

Systematic Review of Literature

**Etapa 6:** Validation of the list of benefits and barriers results with experts.

Expert Validation

**Steps performed in article 2 (Chapter 4):**

**Research Methods**

**Step 1:** Detailed and updated survey of barriers identified in step 5 of chapter 3

Systematic Review of Literature

**Step 2:** validation of barriers and their definitions with experts

Expert Validation

**Step 3:** Construction of matrix Z of direct relation based on dependency relationships evaluated by experts

**Step 4**: Construct the normalized matrix X, and the total relation fuzzy matrix $\tilde{T}$.

**Etapa 5:** Elaborate the interdependence between the barriers and defuzzify the calculated values.

Fuzzy DEMATEL

**Source:** Authors.

## 1.4 WORK STRUCTURE

Chapter 1 contains the introduction, clarifying the context, objectives, and research methods. In Chapter 2, a literature review defines and deepens the content of the two primary constructs of the dissertation: Additive Manufacturing and Circular Economy. Chapter 3 presents a multi-method article on how Additive Manufacturing influences the Circular Economy. Chapter 4 presents the second multi-method article covering the dependency relationships between the barriers that limit AM from being a more circular technology. Finally, Chapter 6 will present the conclusions of this research.

## REFERENCES

3D HUBS. **3D Printing Trends Q1/20183D Printing Trends Q1 2019**. [s.l: s.n.]. Disponível em: <https://f.3dhubs.com/tpeFNMnNBD83pKJYnSHpne.pdf>

ALMADA-LOBO, F. The Industry 4 . 0 revolution and the future of Manufacturing Execution Systems (MES) Cyber-physical Systems. v. 4, p. 16–21, 2015.

CENTOBELLI, Piera et al. Designing business models in circular economy: A systematic literature review and research agenda. **Business Strategy and the Environment**, v. 29, n. 4, p. 1734-1749, 2020.

CRESWELL, John W.; PLANO CLARK, Vicki L. Choosing a mixed methods design. **Designing and conducting mixed methods research**, v. 2, p. 53-106, 2011.

DENYER, David; TRANFIELD, David. **Producing a systematic review**. 2009.

DESPEISSE, M. et al. Unlocking value for a circular economy through 3D printing: A research agenda. **Technological Forecasting and Social Change**, v. 115, p. 75–84, 2017.

EVANS, Steve et al. **Towards a sustainable industrial system: With recommendations for education, research, industry and policy**. University of Cambridge, Institute for Manufacturing, 2009.

FALATOONITOOSI, E. et al. Decision-Making Trial and Evaluation Laboratory. **Research Journal of Applied Sciences, Engineering and Technology**, v. 5, n. 13, p. 3476–3480, 2013.

GHISELLINI, P.; CIALANI, C.; ULGIATI, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. **Journal of Cleaner Production**, v. 114, p. 11–32, 2016.

GHARAKHANI, D. et al. Fuzzy AHP and Fuzzy DEMATEL Methods for Supplier Selection Criteria. 2014.

IVAN, Sobolev; YIN, Yong. Additive manufacturing impact for supply chain—Two cases. In: **2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)**. IEEE, 2017. p. 450-454.

LASI, H. et al. Industry 4.0. **Business and Information Systems Engineering**, v. 6, n.4, p.239–242, 2014.

PANAHIFAR, F. Partner Selection Factors for Successful CPFR Implementation Using Fuzzy DEMATEL. **Journal of Economics, Business and Management**, v. 3, n. 12, p. 1138–1145, 2015.

PENG, Tao et al. Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. **Additive Manufacturing**, v. 21, p. 694-704, 2018.

PETSIUK, A. L.; PEARCE, J. M. Open source computer vision-based layer-wise 3D printing analysis. **Additive Manufacturing**, v. 36, n. March, p. 101473, 2020.

SCHWAB, Klaus et al. The global competitiveness report 2018. In: **World Economic Forum**. 2018.

SON, B. et al. Int . J . Production Economics Supply chain information in analyst reports on publicly traded companies. **Intern. Journal of Production Economics**, v. 171, p. 350–360, 2016.

TANG, Y.; MAK, K.; ZHAO, Y. F. A framework to reduce product environmental impact through design optimization for additive manufacturing. **Journal of Cleaner Production**, v. 137, p. 1560–1572, 2016.

UNRUH, G. Circular Economy, 3D Printing, and the Biosphere Rules. **California Management Review**, v. 60, n. 3, p. 95–111, 2018.

# 2 LITERATURE REVIEW

This chapter presents the definitions of Industry 4.0, Additive Manufacturing and Circular Economy. The objective is to capture important information about the themes, raise information relevant to the research, and define concepts to develop a Systematic Review.

## 2.1 THE INDUSTRY 4.0

Manufacturing processes are understood at different times since the beginning of the industrial process, which took place in England in the 18th century. Since that period, technology has advanced. So, its evolution is divided into phases, called industrial revolutions.

The first Industrial Revolution can be defined as the era of mechanization at the end of the 18th century. It was characterized by the use of water and steam energy to industrialize mechanical production. From the end of the 19th century and the beginning of the 20th century, the second combined the use of electric energy and new production methods, standing out for the application of mass production technologies powered by electricity through the division of labor. The third wave automated production through digital and computing technologies (LASI, 2014; PARK, 2018). Recently, based on advanced digitization within factories, the conciliation of internet technologies and future-oriented technologies in the field of “smart” objects (machines and products) seems to result in a paradigm shift in industrial production. In this future expectation, the term “Industry 4.0” was created based on a fourth industrial revolution (LASI et al., 2014), which began in the 21st century with Artificial Intelligence, Big Data, Internet of Things and robot technologies (PARK, 2018). Several governments have driven this paradigm shift under different names (such as The Industry of the Future in France, Smart Industry in the United States, Industry 4.0 in Germany, Made in China 2025 in China), the idea is to allow manufacturing companies to make a big change (ROSIN et al., 2019).

The term Fourth Industrial Revolution became widely known at the Hannover Fair in 2011, which referred to Industry 4.0 as part of the High Tech Strategy 2020 in Germany. It aimed to establish Germany as an integrated industry leader and market supplier (PARK, 2018). the time elapsed since the aforementioned eventevent mentioned above, research shows that few professionals can provide a concrete definition of Industry 4.0 (HENG, 2014).

Wang et al. (2017), based on a literature review, provide a summary of the general definition of Industry 4.0. They claim that, as a collective term, Industry 4.0 involves value chain organization and technology. Cyber-physical systems (CPSs) monitor physical processes, connect the virtual world to the physical world, and make decentralized decisions in the smart factories of Industry 4.0. In addition, the Internet of Things (IoT) enables real-time collaboration and communication between the CPS. Decision-making processes are supported by Data Mining (DM), which can discover knowledge from multiple sources.

In this context, participants use inter-organizational and internal services through the IoT. In general, Industry 4.0 has four components, and its general definition is based on them: (1) CPS, (2) mobile and cloud computing and IoT, (3) Big Data and DM, and (4) Internet of Service (IoS). Based on connectivity and computing power, the main idea behind smart Industry 4.0 products is that they incorporate self-management capabilities (ALAMADA-LOBO, 2015). In this concept, CPSs, IoT and IoS will collectively have a significant impact on all aspects of manufacturing companies (ALAMADA-LOBO, 2015). There are many technology enablers for Industry 4.0, including mobile, cloud, big data analytics, machine-to-machine, 3D printing, robotics, etc. While these are the disruptive technologies that trigger the transformation, the Industry 4.0 revolution goes far beyond that (ALAMADA-LOBO 2015).

Industry 4.0 has a meaningful long-term strategic impact on global industrial development (XU; XU; LI, 2018). Its implications are broad and complex for companies, governments, civil society organizations and individuals. They range from practical to ethical considerations and from monetary to social consequences (PARK, 2018). However, the Fourth Industrial Revolution does not only generate positive aspects, such as improving the quality of life. It also generates negative aspects, such as income inequality risks (BALOGH, 2017). With more automated production using smart machines, providing human labor has diminished the low cost advantage. This means that jobs can become increasingly restricted, which hurts economies based on labour-intensive production (PARK, 2018).

Like previous industrial revolutions, the Fourth Industrial Revolution will also come in waves of technological innovations, creating new opportunities for manufacturing and becoming increasingly complex. This shift will integrate the impacts of the Fourth Industrial Revolution and stand out in a wide range of changes. Faced with this, business and government leaders in the public and private sectors, and civil society leaders, must assess their market positioning and their flexibility for disruptions. Consequently, a better understanding of the dynamics of broader change is vital, especially for manufacturing companies to maintain their competitiveness and seize new opportunities (WEF, 2016).

## 2.2 ADDITIVE MANUFACTURING

This subsection presents a brief history of the emergence of Additive Manufacturing, its definition, process categories and process steps.

### 2.2.1 Brief history and definition

One of the core technologies of Industry 4.0 is Additive Manufacturing (AM), which has increasingly attracted the attention of the industrial world (SUN et al., 2020). The first records of the use of three-dimensional technologies for the construction of objects date back to the second half of the 19th century, around 1860, when François Willème conducted initial trials in the creation of 3D replicas of objects, a French artist who was developing photosculpture. The artist used the techniques of newly invented photography and combined it with the principles of optics and sculpture to create three-dimensional replicas of objects (BOURELL; ROSEN; LEU, 2014; ZHAI; LADOS; LAGOY, 2014).

From there, other techniques were developed until, in the late 1980s, 3D technology was finally patented and commercialized by companies such as 3D System, Stratasys and EOS. In the late 2000s, 3D printing was absorbed into the open-source and do-it-yourself movements, fueling more interest in the new technology. Since then, consultants and experts have labelled 3D printing a disruptive technological innovation since the technology has brought innovations to manufacturing in many industries, including medical devices, apparel, automotive, distribution, spare parts, and others. Despite this growing development, even today, the use of 3D printing is strongly limited to some industrial niches. Most of AM's current and potential industrial applications come from the fields of aviation and the automotive sector (KUNOVJANEK; REINER, 2019).

3D Printing is often used synonymously with Additive Manufacturing, although the latter term constitutes a broader reality. AM's key feature is not a single technology, but a set of several (at different stages of development), allowing the use of various materials and different levels of output quality (FORD; MORTARA; MINSHALL, 2016; GARMULEWICZ et al., 2018). A broad definition is that AM employs the 3D printing process to join materials, in which products are built, layer upon layer, on a base, through a series of cross-sections, from data from a 3D model (ASTM, 2013).

Currently, AM is still under development globally, but with the promise of tremendous growth in the future. Several countries are already moving in this direction. Several industrial countries propose manufacturing development plans, such as the Advanced Manufacturing Plan, proposed by the United States; the German Industry 4.0, the co-existing man-machine factories of the future introduced by Japan; and the thirteenth five-year development plan proposed by China. All these countries show that smart manufacturing will be the core development of modern manufacturing, and automated equipment such as 3D printing and robots play a crucial role in this development (HUANG, 2018).

### 2.2.2 AM process categories

In 2012, the American Society for Testing and Materials (ASTM) formulated a set of standards (ASTM 2012) organizing the range of available AM processes into seven process categories: material extrusion, directed energy deposition, material blasting, powder bed melting, VAT polymerization, binder jetting and sheet lamination.

Each method has its advantages and disadvantages (see Table 2.1). The most used category of processes is material extrusion, which builds the object by extruding material through a nozzle. The process uses molten plastics (fused deposition modelling - FDM) or gelatinous materials, generally followed by a drying step. In the second group, directed energy deposition, metals are melted using different sources of high energy, or electron beams. In the third category of processes, material blasting, droplets of a liquid (photopolymer or wax) are deposited and hardened with ultraviolet light in technologies such as inkjet or polyjet printing. In the fourth group, powder bed fusion, the object is built by sintering or fusing powder materials thanks to a high energy source, such as a laser, as in Selective Laser Sintering and Selective Laser or a beam of electrons, as in Electron Beam Fusion. In the fifth group, VAT polymerization, the solidification of a liquid material occurs through polymerization of plastic or resin using a light source, such as lasers in stereolithography technology. In the sixth group, binder jet, the object is obtained by bonding with chemicals in indirect inkjet printing. In the last category of processes, sheet lamination, the object is constructed by cutting and assembling solid materials by compaction (manufacturing laminated objects) (ARRIETA-ESCOBAR et al., 2020). Some technologies still require a post-processing step, such as drying or polishing.

**Table 2.1 -** Advantages e disadvantages of each AM process

| Process | Advantages | Disadvantages |
|---|---|---|
| **Binder Jetting** | Large number of potential materials | Rough or grainy appearance |
| | Able to create ceramic molds for metal casting | Poor strength |
| | Support structures are included automatically in layer fabrication | Post-processing required to remove moisture or improve strength |
| | Low-imaging specific energy | |
| **Direct Energy Deposition** | High material deposition rate and high material utilization | Low to medium part complexity |
| | High efficiency for repair and add-on features | Poor surface finish and resolution |
| | Mainly metal and suitable for large components | Poor dimensional accuracy |
| | Deposition of thin layers wear resistant metals on components | Limited materials for production purposes |
| **Material Extrusion** | Low cost of the entry-level machines | Low level of precision and long build time |
| | A variety of raw materials are available | Unable to build sharp external corners |
| | Versatile and easy to customize | Anisotropic nature of a printed part |
| **Material Jetting** | No waste of model material | Post-processing may damage thin and small features |
| | High resolution and accuracy | Support materials cannot by recycled thus wasted |
| | Multiple materials and multiple colors | |
| **Powder Bed Fusion** | Support is not required for polymer powder | Rough surface finish for polymer |
| | Both polymer and metal powder can be recycled | Relatively slow build rate |
| | High part complexity and wide range of materials | Small to medium parts only |
| | Good accuracy and resolution for metals | Expensive machines |
| **Sheet Lamination** | High fabrication speed | High material waste |
| | No support structures are needed | Difficult to remove support trapped in internal cavities |
| | Low warping and internal stress | Thermal cutting produces noxious fumes |
| | Multi-materials and multi-colors are possible | Possible warpage of lamination as a result of heat of laser |
| **Vat Photopolymerization** | High-resolution and accuracy, good surface finish | Require support |
| | High fabrication speed | Require post processing to remove support |
| | Low-imaging specific energy | Require post curing for enhanced strength |
| | Wide range of materials | |

**Source**: LEE et al. (2017).

### 2.2.3 Process steps

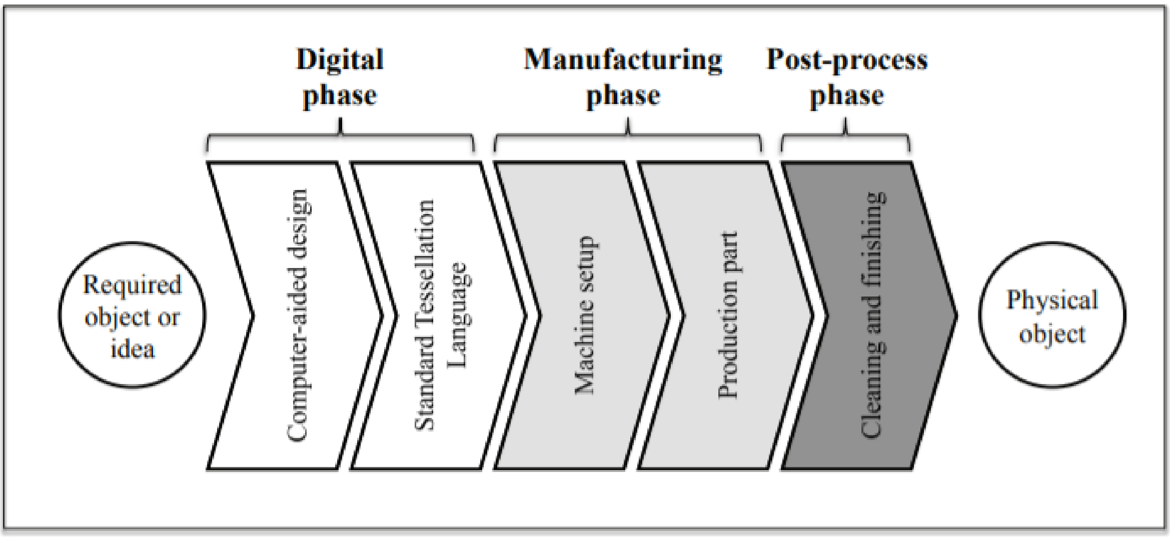
While the joining details and forming equipment of AM vary depending on the process type, they share the same fundamental forming principle, where all parts are built along a single laydown direction (bottom to top or top to bottom), with a layer-by-layer bond. AM mimics biological processes, creating products layer by layer, which is inherently less expensive than traditional subtractive production methods (FORD; DESPEISSE, 2016). The three-dimensional printing process has common steps in all its variants. Its starting point is a virtual model of a part to be materialized, regardless of the machine used to build the model. The AM process steps explained below are digital or design, manufacturing or printing and post-process (KIETZMANN; PITT; BERTHON, 2015; MA et al., 2018).

The digital or design stage focuses on the planning and design of the product architecture and comprises two phases, Computer-Aided Design (CAD) and the Standard Triangle Language (STL). ). Therefore, the user creates his project in 3D design by computer in the CAD phase and in the next phase, he exports the project to the STL file extension, which is a readable form of 3D printing (KIETZMANN; PITT; BERTHON, 2015). AM stage 2 is manufacturing or printing, responsible for manufacturing products or components using designed CAD model file, selected materials and pre-determined AM process in stage 1. This stage also involves the upstream process, which includes the procedures (e.g. material mining, machine setup) that are used to support the MA process (MA et al., 2018). Stage 3 is the post-process. In this step, separate post-processing is done to create the final object. Thus, some operations require surface treatment or other fabrication procedures to improve printed objects' shape (KIETZMANN; PITT; BERTHON, 2015). Figure 2.1 presents the above-mentioned steps.

Due to these characteristics and manufacturing steps, AM is inherently suitable for building parts with complex geometry and structure in relatively small volumes. Due to its characteristics and dependence on information technology, technology has come to be seen as a hallmark of advanced manufacturing, capable of sustaining a future of mass customization and flexible production (GIURCO, 2014).

Due to the numerous advantages, the use of AM for industrial applications has increased substantially in the last two decades. While the advantages of reducing the amount of matter are clear, economic sustainability discusses AM's economic performance using the main indicator: cost. MA is an intuitively expensive manufacturing approach. (MA et al., 2018). However, Additive Manufacturing is a critical disruptive technology that is transforming business. While the scale of this transformation and its speed are subject to debate, there is a growing consensus that technology is changing manufacturing in many industries. Moreover, these changes are essential to identify new leverage points for the transition to a circular economy (GARMULEWICZ et al., 2018).

**Figure 2.1** – AM processes steps



**Source** : ROMERO-TORRES; VIEIRA, 2016.

## 2.3 CIRCULAR ECONOMY

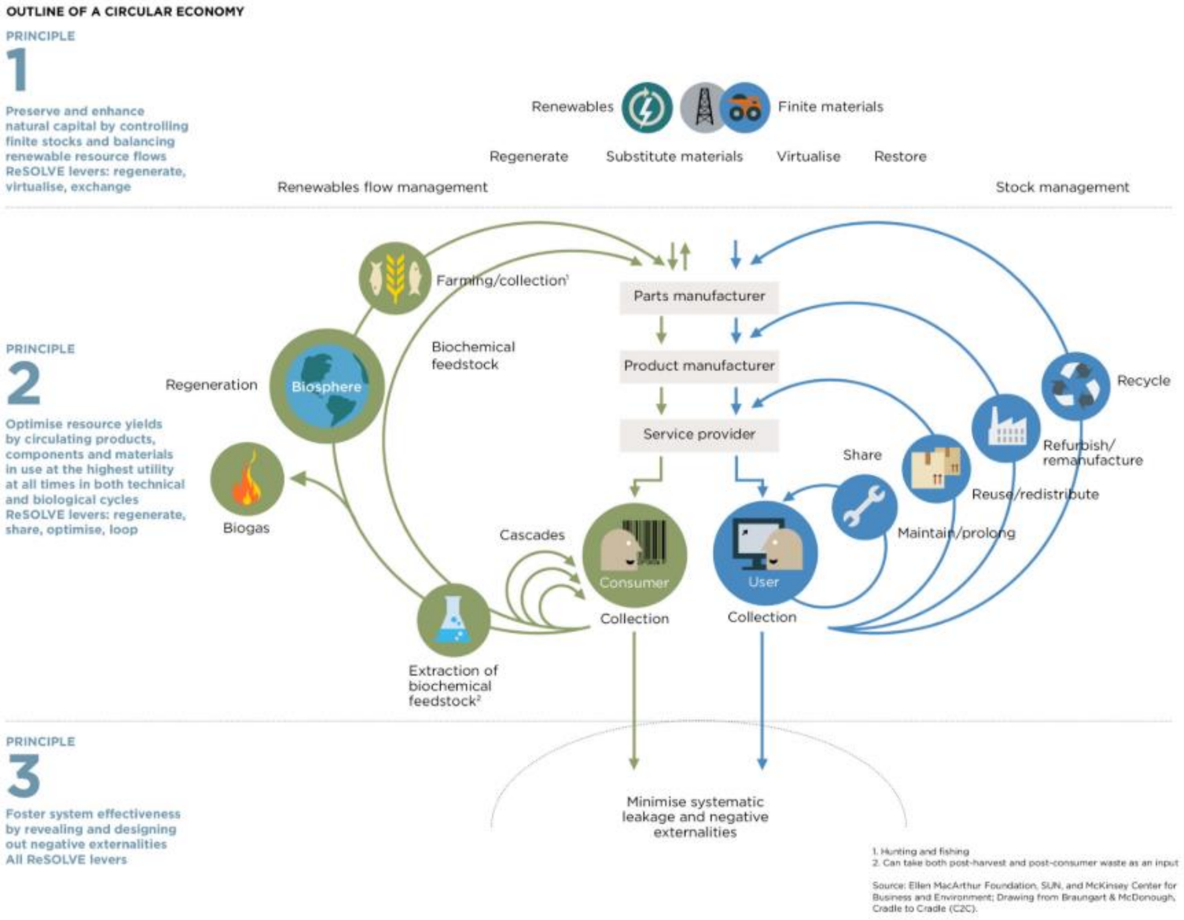
Natural resources are essential to sustain society. However, the large and growing human population (estimated to increase to over 9 billion by 2050) are depleting many of the world's natural resources. As a result, competition for land, water and energy may intensify as the harmful effects of climate change may become increasingly apparent (BSI, 2017). Consequently, it is natural that one needs to completely rethink current patterns and volumes of production and consumption to ensure the availability of resources in the future. The transition to a circular economy could significantly solve emerging resource and climate problems and create opportunities for shared value (BSI, 2017).

Although there are hundreds of different definitions of circular economy (KIRCHHERR; REIK; HEKKERT, 2017), It generally refers to an economy that operates with closed material loops, creating circular flows of resources in the economy. In its broadest elaboration, a CE is seen as a comprehensive transformation of the linear production models, the linear model “take, make and dispose”, associated with the accumulation of waste and the creation of landfills (UNRUH, 2018). CE is framed as an economic imperative rather than an environmental imperative, where production and consumption systems are conducted in a closed loop, and waste is designated as a valuable resource (GARMULEWICZ et al., 2018; GIURCO et al., 2014).

The circular economy concept has deeply rooted origins in China (MATHEWS, 2011). However, its practical applications to modern economic systems and industrial processes have gained traction since the 1970s by a small number of academics, thinkers, and businesses. The expression "Cradle to Cradle" (C2C), conceived by Stahel in the late 1970s, indicates the development of a "closed-loop" approach to production processes (MACARTHUR, 2013).

The Ellen Macarthur Foundation's report (2013) highlights four sources of value creation for business models, where "closing the loop" initiatives of products can be very profitable: maintenance, redistribution, remanufacturing and recycling. A general illustration of the circular economy concept is given in Figure 2.2.

**Figure 2.2 –** Circular economy concept



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

**Source:** ELLEN MACARTHUR FOUNDATION, 2013

The waterfall representation in Figure 2.2 illustrates that smaller loops (closer to the user) generally have less impact. This report argues that to complete the basic principles of a restorative Circular Economy, a push is needed to change the material composition from technical to biological nutrients and have them propagate in different applications before extracting valuable raw material and ultimately reintroducing their nutrients into the biosphere. Figure 2.2 further illustrates how nutrient-based technological and biological products and materials circulate in the economic system, each with its own set of characteristics (ELLEN MACARTHUR FOUNDATION, 2013).

The circular economy principles offer a description of how it should work as a whole and provide an outline of specific sources of the core potential for economic value creation. For example, the comparative economics and attractiveness of different circular configurations (eg reuse versus remanufacturing versus recycling) can differ significantly for different products, components or material types (ELLEN MACARTHUR FOUNDATION, 2013). However, there are four simple principles of value creation, which will be presented below:

a) Inner circles: in general, the smaller the circles, the more significant the savings in costs embedded in material, labour, energy. Tighter circles will benefit from a comparatively larger virgin material substitution effect given the inefficiencies along the linear supply chain. Whenever the costs of collecting, reprocessing and returning the product, component or material to the economy are less than the linear alternative (including the avoidance of end-of-life treatment costs), establishing circular systems can make economic sense;

b) Longer cycles: A second potential for creating fundamental value is keeping products, components and materials in use longer within the circular economy. This prolongation of use will replace the inflows of virgin material to contain the dissipation of material outside the economy;

c) Cascading Uses: In cascades, the potential for arbitrage value creation is rooted in the lower marginal costs of reusing the cascading material as a substitute for inflows of virgin material and its built-in costs (labour, energy, material), as well as externalities against the marginal costs of bringing the material back to reuse;

d) Pure, non-toxic inputs: The fourth lever enhances value creation potential. To generate maximum value, each of the above levers requires a certain purity of material and quality of products and components. These

> improvements in the product and reverse cycle process translate into further reductions in comparative reverse cycle costs, keeping nutrients, especially technical ones, in higher quality throughout cycles, increasing material longevity. In addition to reverse cycle performance, keeping toxic materials out of product design can have other significant benefits.

Older theories such as regenerative design, performance economics, cradle to cradle, Biomimicry, Blue Economy, Natural Capitalism and Industrial Ecology have made an important contribution to the refinement and development of the circular economy concept (ELLEN MACARTHUR FOUNDATION, 2013). Due to the combination of different principles from these founding schools of thought, CE cannot easily be reduced to a simple definition. Furthermore, the idea of the circular economy proposes a fundamental paradigm shift and a different way of thinking about the economy. This promotes the existence of multiple interpretations of the idea in organizations, increasing the complexity of the concept and making it difficult for organizations to improve the way they manage resources (BSI, 2017). To manage these resources correctly, Levänen, Lyytinen and Gatica (2018) highlight that the interaction between policymakers and companies is critical to enable the transition at the company level, as they can facilitate or hinder the development of circular business models, intervening directly in the sectors through rules and regulations.

While it is essential for CE to manage resources within an organization, the transition comes from the involvement of all actors in society and the ability to link and create appropriate patterns of collaboration and exchange. Furthermore, some success stories indicate that there has to be an economic return on investment to adequately motivate companies and investors (GHISELLINI; CIALANI; ULGIATI, 2016). The involvement of all actors ensures that the functioning of a CE-based society has all its resources flowing circularly, whether in the biocycle (biomass) or technocycle (inorganic materials) (DESPEISSE et al., 2017). Ghisellini, Cianlani and Ulgiati (2016) highlight that the development of the circular economy in cities, provinces or regions involves the integration and redesign of four systems: the industrial system (for example, the gradual elimination of heavy polluting companies in favor of economic activities light, such as related to high-tech industries), the infrastructure system that provides services (transport and communication systems, water recycling systems, etc.), the cultural structure, and the social system.

According to the Ellen Macarthur Foundation report (2015), the circular economy is based on three fundamental principles. The first talks about preserving and enhancing natural capital, controlling finite stocks and balancing flows of renewable resources – for example, replacing fossil fuels with renewable energy. The second principle concerns optimizing the production of resources by circulating products, components and materials at all times, both in technical and biological cycles. This can be done by sharing or looping products and extending the product's life. Finally, the third principle promotes system effectiveness by revealing and projecting negative externalities such as water, air, soil and noise pollution; of Climate Change; toxins; congestion; and adverse health effects related to resource use. These three CE principles can be translated into a set of six business actions: Regenerate, Share, Optimize, Loop, Virtualize and Exchange, which together forms the ReSOLVE structure.

### 2.3.1 ReSOLVE framework

To assist organizations in implementing circular strategies, structures and practices have been developed. One of the most used frameworks is ReSOLVE, proposed by the Ellen MacArthur Foundation, a leading global institution in establishing the Circular Economy position on the agenda of decision-makers in business, government and academia. Each of the six actions represents a significant circular business opportunity. In different ways, they all increase the utilization of physical assets, prolong their lives, and shift resources from finite sources to renewable sources. Moreover, each action reinforces and accelerates the performance of the other actions. The structure is detailed below (ELLEN MACARTHUR FOUNDATION, 2015):

Regenerate: Refers to a set of actions that maintain and enhance the Earth's biological capacity, which includes the shift to renewable energy and materials. It also covers the recovery, retention and regeneration of ecosystem health and the return of recovered resources to the biosphere;

Share: It is essential to keep the loop speed of the product low in order to maximize its utilization. One way to do this is from a sharing economy: goods and assets are shared between individuals. In this way, ownership is not required to harness the value of a product. As a consequence, products must be designed to last longer, allowing for reuse and extended shelf life. Another way is to reuse products throughout their useful technical life (second hand) or even extend their useful life through maintenance, repair and design for more excellent durability;

Optimise: Refers to improvements in the efficiency and performance of a product. It also highlights the removal of waste in the production and supply chain. Digital manufacturing technologies such as sensors, automation, radio frequency identification (RFID), big data and remote steering are used to leverage CE. All these actions must be implemented without changes to the actual product or technology;

Loop: Maintenance of biological and technical components in closed loops is considered. As an example of biological cycles, anaerobic digestion is important for recovering organic waste's value. Technical cycles can restore the value of products by promoting remanufacturing, recycling, reuse and repair. The aim is to avoid landfill or incineration as much as possible, boosting the return of waste to the economy;

Virtualise: It is a strategy that focuses on the dematerialization of resources, replacing physical products with virtual products (direct dematerialization), for example books, CDs, DVDs. Dematerialization also happens indirectly in the form of online purchases, vehicles self-employed or virtual offices, for example;

Exchange: New technologies are adopted, improving society's production of goods and services. There is the substitution of old materials for more advanced ones and the choice of new products or services;

Each of the six actions represents a significant circular business opportunity and, in different ways, increases the use of physical assets, extends their life and shifts the use of resources from finite sources to renewable sources. Thus, each action reinforces and accelerates the performance of the other actions (ELLEN MACARTHUR FOUNDATION, 2015).

## REFERENCES

ALMADA-LOBO, F. The Industry 4 . 0 revolution and the future of Manufacturing Execution Systems (MES) Cyber-physical Systems. v. 4, p. 16–21, 2015.

ARRIETA-ESCOBAR, J. A. et al. Geoderma 3D printing : An emerging opportunity for soil science. v. 378, n. May, 2020.

ASTM. **Standard Terminology for Additive Manufacturing Technologies**. [s.l.] American Society for Testing and Materials - ASTM, 2013.

ASTM., STANDARD F2792. 2012. **Standard terminology for additive manufacturing technologies.** ASTM F2792-10e1, 2012.

BOURELL, David L.; ROSEN, David W.; LEU, Ming C. The roadmap for additive manufacturing and its impact. **3D Printing and Additive Manufacturing**, v. 1, n. 1, p. 6-9, 2014.

DESPEISSE, M. et al. Unlocking value for a circular economy through 3D printing: A research agenda. **Technological Forecasting and Social Change**, v. 115, p. 75–84, 2017.

ELLEN MACARTHUR FOUNDATION. **Delivering the circular economy: A toolkit for policymakers**. Ellen MacArthur Foundation, 2015.

ELLEN MACARTHUR FOUNDATION. Towards the circular economy. **Journal of Industrial Ecology**, v. 2, p. 23-44, 2013.

FORD, SIMON; DESPEISSE, M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. **Journal of Cleaner Production**, v. 137, p. 1573–1587, 2016.

FORD, Simon; MORTARA, Letizia; MINSHALL, Tim. The emergence of additive manufacturing: introduction to the special issue. 2016.

GARMULEWICZ, A. et al. Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold? **California Management Review**, v. 60, n. 3, p. 112–132, 2018.

GHISELLINI, P.; CIALANI, C.; ULGIATI, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. **Journal of Cleaner Production**, v. 114, p. 11–32, 2016.

GIURCO, D. et al. Circular Economy: Questions for Responsible Minerals, Additive Manufacturing and Recycling of Metals. **Resources**, v. 3, n. 2, p. 432–453, 2014.

HENG, Stefan. Industry 4.0: upgrading of Germany's industrial capabilities on the horizon. **Available at SSRN 2656608**, 2014.

HUANG, C.-H. Continued evolution of automated manufacturing - Cloud-enabled digital manufacturing. **International Journal of Automation and Smart Technology**, v. 5, n. 1, p. 2–5, 2015.

KIETZMANN, Jan; PITT, Leyland; BERTHON, Pierre. Disruptions, decisions, and destinations: Enter the age of 3-D printing and additive manufacturing. **Business Horizons**, v. 58, n. 2, p. 209-215, 2015.

KIRCHHERR, Julian; REIKE, Denise; HEKKERT, Marko. Conceptualizing the circular economy: An analysis of 114 definitions. **Resources, conservation and recycling**, v. 127, p. 221-232, 2017.

KUNOVJANEK, M.; REINER, G. How will the diffusion of additive manufacturing impact the raw material supply chain process ? How will the diffusion of additive manufacturing impact the raw material supply chain process ? **International Journal of Production Research**, v. 0, n. 0, p. 1–15, 2019.

LASI, H. et al. Industry 4.0. **Business and Information Systems Engineering**, v. 6, n.4, p.239–242, 2014.

LEE, Jian-Yuan; AN, Jia; CHUA, Chee Kai. Fundamentals and applications of 3D printing for novel materials. **Applied materials today**, v. 7, p. 120-133, 2017.

LEVÄNEN, Jarkko; LYYTINEN, Tatu; GATICA, Sebastian. Modelling the interplay between institutions and circular economy business models: A case study of battery recycling in Finland and Chile. **Ecological Economics**, v. 154, p. 373-382, 2018.

MA, J. et al. An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment. **Journal of Cleaner Production**, v. 192, p. 55–70, 2018.

MACARTHUR, Ellen et al. Towards the circular economy. **Journal of Industrial Ecology**, v. 2, p. 23-44, 2013.

MATHEWS, John A.; TAN, Hao. Progress toward a circular economy in China: The drivers (and inhibitors) of eco-industrial initiative. **Journal of industrial ecology**, v. 15, n. 3, p. 435-457, 2011

PARK, S. C. The Fourth Industrial Revolution and implications for innovative cluster policies. **AI & SOCIETY**, v. 0, n. 0, p. 0, 2018.

PETSIUK, A. L.; PEARCE, J. M. Open source computer vision-based layer-wise 3D printing analysis. **Additive Manufacturing**, v. 36, n. March, p. 101473, 2020.

ROMERO-TORRES, A.; VIERA, D. R. Is 3D printing transforming the project management in the aerospace industry? **Journal of Modern Project Management**, v. 4, n. 1, p. 113–119, 2016.

ROSIN, F. et al. Impacts of Industry 4.0 technologies on Lean principles. v. 7543, 2020.

SUN, L. et al. Resources , Conservation & Recycling Virgin or recycled ? Optimal pricing of 3D printing platform and material suppliers in a closed-loop competitive circular supply chain. **Resources, Conservation & Recycling**, v. 162, n. December 2019, p. 105035, 2020.

TANG, Y.; MAK, K.; ZHAO, Y. F. A framework to reduce product environmental impact through design optimization for additive manufacturing. **Journal of Cleaner Production**, v. 137, p. 1560–1572, 2016.

UNRUH, G. Circular Economy, 3D Printing, and the Biosphere Rules. **California Management Review**, v. 60, n. 3, p. 95–111, 2018.

WANG, Yi et al. Industry 4.0: a way from mass customization to mass personalization production. **Advances in Manufacturing**, v. 5, n. 4, p. 311-320, 2017.

WORLD ECONOMIC FORUM. The future of jobs: Employment, skills and workforce strategy for the fourth industrial revolution. In: **Global challenge insight report. Geneva: World Economic Forum. 2016**.

XU, L. DA; XU, E. L.; LI, L. Industry 4 . 0 : state of the art and future trends. v. 7543, p. 0–22, 2018

ZHAI, Yuwei; LADOS, Diana A.; LAGOY, Jane L. Additive manufacturing: making imagination the major limitation. **Jom**, v. 66, n. 5, p. 808-816, 2014.

# 3 THE BENEFITS AND BARRIERS OF ADDITIVE MANUFACTURING FOR CIRCULAR ECONOMY: A FRAMEWORK PROPOSAL

## 3.1 INTRODUCTION

Additive manufacturing (AM), one of the cornerstones of Industry 4.0, has recently gained increasing popularity (Petsuik and Pearce, 2020). The intensification of competitiveness, combined with the challenge of increasing the complexity of manufactured products, has required companies and their designers to make substantial changes to the product development process. Thus, AM advancements have emerged as a solution as it allows companies to customize products to meet the client's intricate requirements (Sun et al., 2020).

Over the last decade, AM, also known as 3D printing, has been used almost exclusively for prototyping. However, recently, its use has been extended to industrial applications (Hassani, 2020), and large companies are taking their first steps toward small-scale production and mass production with 3D printing (3D HUBS, 2019). Garmulewicz et al. (2018) argue that AM is one of the leading disruptive technologies that can transform businesses, add new resources, and change the underlying economy in many manufacturing sectors. This technology is particularly relevant for the aerospace and automotive industries (Stentoft et al., 2020), driving significant innovations in medicine, manufacturing, engineering, and customised production (Arrieta-Escobar et al., 2020). In this context, AM has received increasing attention from the industrial world, with a growing interest in its processes (3D HUBS, 2019).

Numerous studies have discussed the potential benefits of AM, including the enablement of product and process innovation; support for flexible manufacturing and product customisation; complexity reduction of supply chains; faster delivery; generation of less waste across the production chain; ability to create complex geometries and lightweight components; reduction of material consumption in manufacturing; reduction of energy consumption; reduction in transport required in the supply chain; reduction in transport costs; and reduction in wasted inventory, and a reduction in warehouse spaces (Ford and Despeisse, 2016; Martinsuo and Luomaranta, 2018; Stentoft et al., 2020).

Various factors can influence a company's decision of adopting AM technology. For example, one of the factors to consider is the speed of delivery. If a company has this criterion as a competitive priority, production in AM could lead to short-term manufacturing of products, allowing the company to bring manufacturing closer to demand points, thereby shortening, or even eliminating, delivery times (Berman, 2012). Economic benefits have also been emphasised, mainly due to the decrease in inventory turnover resulting from manufacturing on-demand, flexible use of manufacturing equipment, and energy-saving (Niaki and Nonino, 2017a). AM can also offer new possibilities for product and process innovation (Niaki and Nonino, 2017a), helping the company win new customers and create products that cannot be manufactured with conventional manufacturing technology. Another factor could be a competitive advantage acquired if the company is inserted in an uncertain market that requires a wide variety of products and adaptability to the diverse demands of customers (Weller et al., 2015).

Thus, given the high range of factors that can encourage the adoption of AM, the pace of diffusion of this technology depends on how different companies use AM and how much it makes it marketable (Martinsuo and Luomaranta, 2018). In addition to economic issues, technical issues are also considered during the adoption of AM. So, changes in strategic production plans are also likely to be necessary. Thus, the decision to adopt AM technologies requires manufacturing companies to consider the general effects of technology on their supply chains, processes, and management (Martinsuo and Luomaranta, 2018).

Petsiuk and Pearce (2020) predicted that AM would rapidly grow due to the numerous advantages and adoption factors. This growth will have a significant social and economic impact. According to a report released by 3D hubs (3D HUBS, 2019), the world's largest network of additive manufacturing services, the expected average annual growth of the 3D printing market for the next five years is 23.5%. Given these growth forecasts, concerns regarding the impact of AM on the circular economy (CE) context have emerged recently (Sun et al., 2020). With the growth of technology, efforts to implement and adopt sustainability in AM in companies have also been accelerated (Majeed et al., 2021). Consequently, substantial progress has been made in this area, with an increasing number of works and publications covering AM sustainable aspects. With this, the link between AM and CE also began to be related in some works recently (Despeisse et al, 2017; Garmulewicz et al., 2018). The Circular Economy power to add value while keeping the resource looping back into the economy began to be seen as an essential competitive advantage. Also, when the concerning about the environment began influencing companies and industries, they have started giving attention to these essential themes (Colorado, Velasquez, and Monteiro, 2020), so the need for more circular business models also started to grow, with emphasis on the new smart factories, including the  AM industry (Centobelli et al., 2020).

However, as a not fully developed technology, the future trajectory of AM remains to be determined. There are several uncertainties regarding the aligning this technology with the system redesign preconised by CE. Although the critical concept of the CE is the circular flow of materials (Kirchherr, Reik, and Hekkert, 2017; Yuan, Bi, and Moriguichi, 2006), AM still cannot allow a more circular use of resources (Despeisse et al., 2017). 3D printing often uses virgin plastics derived from fossil fuels, which can exist in the environment for centuries after disposal and can be toxic to aquatic organisms (Behm et al., 2018). Also, AM can stimulate higher levels of consumerism, immediate gratification, and a disposable society due to its intrinsic characteristics (Unruh, 2018). This can negatively impact the environment (Rejeski, Zhao, and Huang, 2018). Despite all this, there is a growing need for companies to ensure greater environmental compliance without compromising their economic viability.

In this context, there is much doubt as to whether the current path of adoption of AM creates more circular material flows or leads to a less eco-efficient alternative scenario (Despeisse et al., 2017). Under these conditions, how the phenomenon of AM adoption meets the requirements of a CE needs to be better understood. The present work aims to fill this gap by exploring, through a multi-method study, how AM technology brings companies or society closer or pushes them further away from the CE. The multi-method approach combines secondary data collection, systematic literature review, and interviews with experts.

The following research questions will be answered:

Q1: How does AM support the implementation of CE?

Q2: In what ways does AM prevent greater circularity from being achieved?

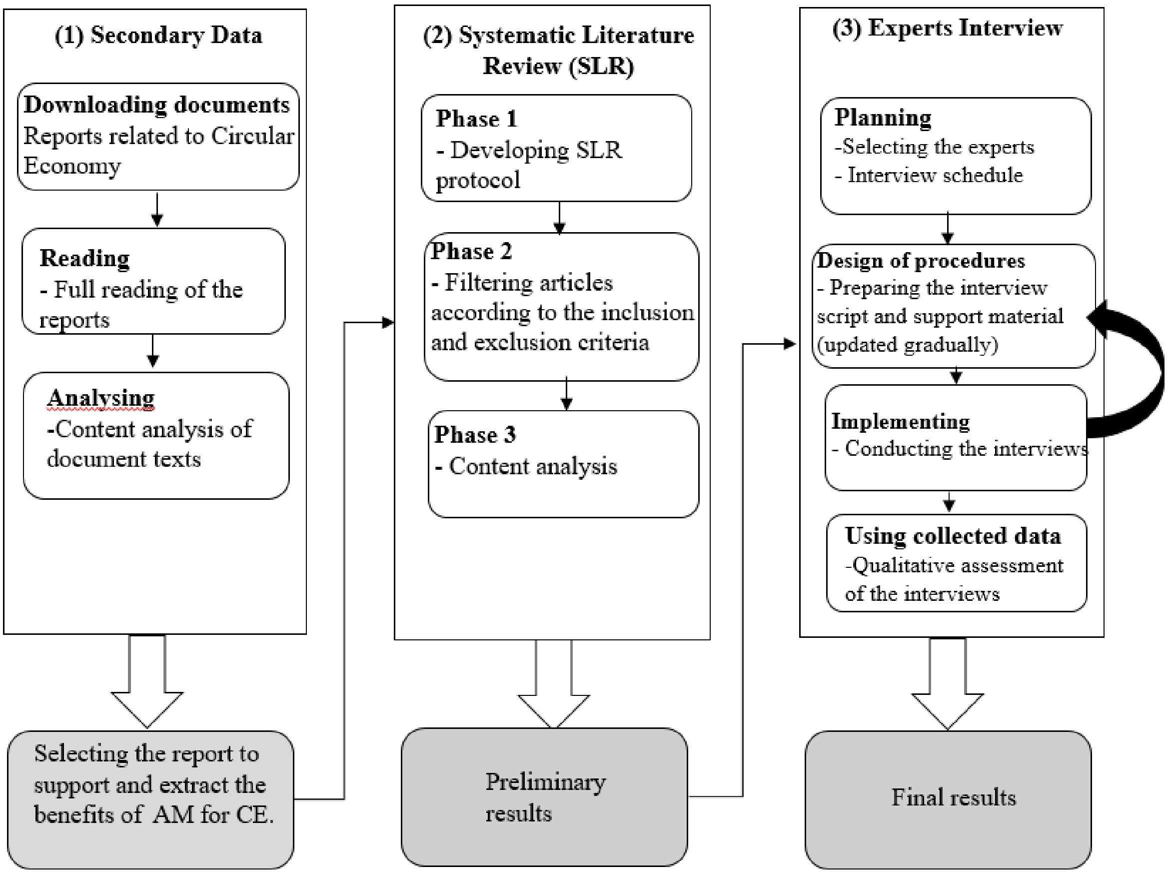
First, we used secondary data on the circular economy to select documents for theoretical support. Then, we performed a systematic literature review to understand state of the art on how AM meets the CE requirements. Finally, a set of interviews with experts was conducted to evaluate the results obtained in the study. Following these steps we proposed a framework which give us a great glimpse of the benefits and barriers of AM to CE.

The study is structured as follows: First, the theme is briefly contextualised and justified. In Section 2, the methodological procedures are presented, and the research steps are described in detail. Section 3 presents the results. Section 4 shows the discussion of these results. Section 5 outlines the conclusions, the main future research avenues and the study limitations.

## 3.2 RESEARCH METHOD

The research method used in the present research involved the combination of (i) consultation of secondary qualitative data (reports on CE); (ii) a systematic literature review (SLR), following Denyer and Tranfield (2009), and (iii) interviews with experts. The logical structure of the combination of these methods is presented in Figure 3.1.

**Figure 3.1 -** Research method followed in this study



### 3.2.1 Secondary data

Secondary data were used based on the method described by Son et al. (2016), which allows for the replication of research results. The content of reports was analysed to understand the characteristics, principles, and implementation of CE. The reports were downloaded without time restrictions because CE is a recent topic. We opted for a sample of documents that included manuals and reports by typing a “circular economy report” on Google. Thirty-seven documents on CE were downloaded and read in full.

After reading the various documents in full, the principles and characteristics of the CE were understood and analysed. Then, Ellen Macarthur Foundation's “Delivering the circular economy, a toolkit for policymakers’ report, was selected. This report describes a methodology for the formulation of CE policies through ReSOLVE framework. The framework identifies six areas of action for companies and countries that wish to move toward a CE and serves as a practical approach to help organisations implement CE principles. Thus, this structure was chosen because it represents a crucial tool for analysing the implementation of a CE propositioned by the Ellen MacArthur Foundation (2015). Then, to understand how AM adoption meets the implementation requirements of the CE, the framework was used to generate a more efficient way of communicating the results of the SLR.

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

This study intends to involve all the ReSOLVE levers proposed by Ellen Macarthur Foundation (2015) for a CE implementation. For this, we developed a Systematic Review of Literature (SRL) to raise the benefits and barriers that AM technology imposes on CE.

### 3.2.2 Systematic Literature Review (SLR)

An SLR approach was used to analyse and understand how the phenomenon of AM adoption meets or does not meet the requirements of a CE. The systematic review ensured that no critical research was neglected and minimised bias, allowing neutral data collection and analysis (Denyer and Tranfield, 2009; Bryman, 2006). This approach is suitable for gaining more insights and understanding quantitative and qualitative problems, rather than automatic filtering. According to Denyer and Tranfield (2009) guidelines, this systematic literature review (SLR) was conducted in three phases based on the two proposed research questions.

In Phase 1, the SLR protocol was developed to provide an explicit description of the activities to be performed (Tranfield, Denyer, and Smart, 2003). The keywords were chosen to focus on the two primary constructs of the research: AM and CE. The material search phase was carried out until March 2021, using keywords and Boolean operators OR and AND, as follows: “circular economy” OR “zero waste” OR “closed-loop” AND “Additive Manufactur *” OR “3D print *”. Using these words, 305 articles were extracted from the Scopus database. The search string was formulated from these by adding the new ones found in the 305 articles to these keywords.

Finally, 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 databases with comprehensive coverage in scientific disciplines (Chadegani et al., 2013). The engineering village base was also considered to have many journals and international scope in the research area. In addition, the review was limited to articles published in peer-reviewed journals to ensure the high quality of this article (Denyer and Tranfield, 2009), excluding conference proceedings and book chapters. Articles that met the inclusion and exclusion criteria were considered in the RSL, thus guaranteeing the quality of the selected papers (Tranfield, Denyer, and Smart, 2003).

In the second phase, the search string returned 5,335 articles from the three databases, of which 1,083 were duplicate articles. After that, papers were filtered in two stages to ensure that relevant works were included according to the pre-stipulated inclusion and exclusion criteria, as described in Table 3.1.

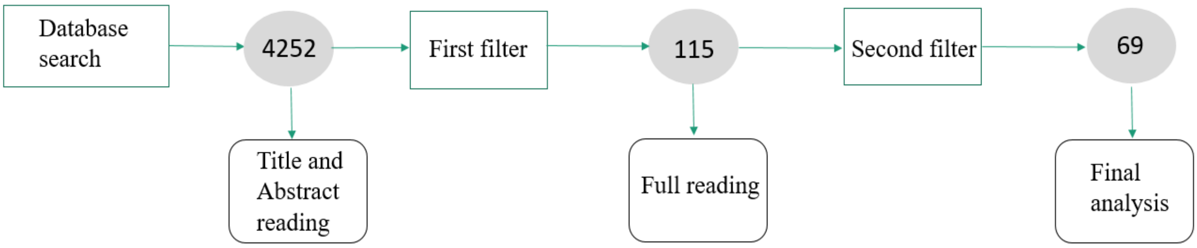
**Table 3.1 -** SRL inclusion and exclusion criteria

| Criteria | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| **Focus** | Dealing with Additive Manufacturing related to Circular Economy or some construct of ReSOLVE framework | Refer to Additive Manufacturing without relating it to the Circular Economy or any construct of framework ReSOLVE |

| Criteria | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| **Access** | Papers written in English. | Do not have access to the paper or it is not written in English |
| **Quality** | Scientific periodical with peer review | Scientific periodical without peer review, business newspapers, current magazines, conferences, books and websites. |
| **Analysis Unit** | Papers that address Additive Manufacturing and Circular Economy | Papers that do not address the relationship of Additive Manufacturing and Circular Economy |
| **Theoretical framework** | Concepts of Additive Manufacturing and Circular Economy ( or ReSOLVE constructs) in a context of operations management, sustainability, environment, supply chain management as the focus of the paper | Concepts related to psychology, physiology and health as the focus of the paper |

After filtering according to the inclusion and exclusion criteria, 64 articles were selected for further analysis. Figure 3.2 illustrates the filtering process.

**Figure 3.2 -** Research Summary



Phase 3 of the review was dedicated to analysing and synthesising the aforementioned research questions. We adopted the content analysis procedure proposed by Bringer et al. (2006) and Krippendorff (2018). Thus, after reading the full texts, the chosen articles were loaded into NVivo Software (2019) for further analysis. NVivo allows the gathering and analysis of all data in a meaningful and reliable way, in addition to efficiently organising, storing, and retrieving data, optimising time, and making a rigorous backup of discoveries with evidence. It is also possible to import data from almost any source (text, audio, video, e-mails, images, spreadsheets, online surveys, and web content). Thus, NVivo allows complex relationships to be established from the data and provides excellent research reliability (N Vivo, 2019).

According to the requirements described by Krippendorff (2018), categories were then created with the available data. This allowed us to identify relationships and connections between the other authors who represented the same constructs. Thus, specific codes were created for each research question, seeking to answer them according to the research analysed. For question 1, six codes were made for each of the ReSOLVE actions and 15 subcodes, referring to the 15 benefits of AM to CE. Benefits were sought within each article analysed. Furthermore, for question 2, the factors were first codified and subdivided into general and specific factors. Subsequently, subcodes were created for each of the two source codes. The following sections of this review aim to analyse the results and answer SLR questions.

### 3.2.3 Interviews with experts

At the end of the systematic review, experts made refinements to evaluate the benefits and barriers of applying AM to CE found in the literature. The results were evaluated through a semi-structured interview process of a group of academic experts in AM and CE to achieve sufficient robustness. This step was essential to adjust the lists, add items, and readjust the phrases.

To establish a systematic procedure for collecting, analysing, and synthesising the data of the interviews, we adopted the procedures recommended by Silveira et al. (2017). This approach is summarised using four primary characteristics: entry points, procedures, project management, and participation. The 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 the interviews. The procedure has four steps (planning, design of procedures, implementation, and use of data) and is explained below.

In the procedure, general planning was performed in the first phase, where the experts to be invited were selected. This selection was based mainly on the experience of experts in AM or CE. Thus, six experts were selected. Studies using methodologies based on a panel of similar experts have proven that the number of experts chosen was a good number for our research (Adebanjo, Laosirihongthong, and Samaranayake, 2016). The sequence of interviews was random and based on the availability of experts. The general schedule of the interviews was based on the individual availability of experts.

The interviewer guide was updated gradually according to the refinements promoted by the expert until saturation was reached. The third step, the implementation, was at the stage of the interviews. The interviews lasted an average of one hour and were carried out as follows: first, the objective of the interview was explained; second, the preliminary list of benefits, followed by the barriers. The respondents were asked about their general perceptions and whether they agreed with the preliminary results for each item. This question would launch a discussion that would or would not change the results. This interactive process could arise:

(i) the list of benefits and their definitions (as defined by the expert), and

(ii) the list of barriers and their definitions, as defined by the expert.

In addition, a final section was included with some general critical reflections or insights from the researcher. This procedure helped deepen the qualitative analysis of the study.

## 3.3 RESULTS

After collecting secondary data and a SLR, the preliminary results in Tables 3.2 and 3.3 were obtained. Sections 3.3.1 and 3.3.2 answer the first and second questions of the research and demonstrate the final results after expert evaluation.

**Table 3.2** – Preliminary results of benefits

| **Category** | **Code** | **Benefit** |
|---|---|---|
| ***Regenerate*** | **B1** | AM promotes the use of materials and energy from renewable sources and biodegradable materials |
| | **B2** | AM promotes the recovery, retention, and restoration of ecosystem health |
| ***Share*** | **B3** | AM promotes asset sharing |
| | **B4** | AM promotes reuse/second hand use |
| | **B5** | AM alows product life extension |
| ***Optimize*** | **B6** | AM allows product performance/efficiency growth |
| | **B7** | AM promotes the removal of production waste in the supply chain |

| | | |
|---|---|---|
| | **B8** | AM leverages the use of big data, automation, remote sensing, and steering |
| ***Loop*** | **B9** | AM encourages remanufacturing of products or components |
| | **B10** | AM encourages recycling of materials |
| | **B11** | AM expands the scale of waste recovery and resource reuse |
| ***Virtualize*** | **B12** | AM encourages dematerializing indirectly |
| ***Exchange*** | **B13** | AM promotes the replacement of old with advanced materials |
| | **B14** | AM promotes the application of new technologies |
| | **B15** | AM promotes the choice of new products and services |

**Source:** authors

**Table 3.3** - Preliminary results from the list of barriers

| Category | Code | Barrier |
|---|---|---|
| **General Barriers** | **GB1** | Lack of eco-friendly AM policies and laws |
| | **GB2** | Lack of strategic planning for AM to achieve circularity |
| | **GB3** | Lack of skills and knowledge about AM |
| **Specific Barriers** | **SB1** | Wasteful habits and behaviors in the use of AM might harm ecosystems health |
| | **SB3** | Toxicological risks |
| | **SB3** | Low speed AM generates waste in the supply chain |
| | **SB4** | Limited number of suitable materials for AM |
| | **SB5** | Lack of acceptance of recycled materials over virgin materials for AM |
| | **SB5** | AM processes cause uncertainty in material properties |

### 3.3.1 AM boosting the CE

AM boosts CE in the most diverse aspects. According to our content analysis, in the CE approach, studies including one or more of the six actions of the ReSOLVE framework were considered. Table 3.4 shows the 15 benefits (coded from B1 to B15) and the authors of the articles that show in specific points how AM supports the CE approach. The following results are presented from section 3.3.1.1 to section 3.3.1.6.

**Table 3.4** – AM benefits for circularity

| 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; Corker; Fan, 2018; Sauerwein; Doubrovski, 2018; Strack, 2019; Tang; Mak; Zhao, 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; Uiterkamp; Visser, 2014; Peng et al., 2018; Tang; Mak; Zhao, 2016. |
| **Share** | B3 | AM promotes asset sharing | Bogers; Hadar; Bilberg, 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 growth in product performance/efficiency | Jin; Du; He, 2017; Laverne et al., 2019; Ma et al., 2018; Majeed; Lv; Peng, 2019; Wang et al., 2019; Yang et al., 2019. |
|  | B7 | AM promotes the removal of waste in production and supply chain | Ahsan; Habib; Khoda, 2015; Bogers; Hadar; Bilberg, 2016; Cerdas et al., 2017; Ford, Despeisse, 2016; Ghaffar; Corker; Fan, 2018; Jiang, 2020; Jin; Du; He, 2017; Kellens et al., 2017; Kunovjanek; Reiner, 2019; Laverne et al., 2019; Peng et al., 2018; Tang; Mak; Zhao, 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; Lv; Peng, 2019; Nascimento et al., 2019; Wang et al., 2019. |
| **Loop** | B9 | AM encourages the remanufacturing of products or components | Kellens et al., 2017; Le; Paris; Mandil, 2018; Matsumoto et al., 2016; Saboori et al, 2019; Tian et al., 2017. |

| Action | Code | Benefit | References |
|---|---|---|---|
| | B10 | AM encourages the recycling of materials | Behm et al., 2018; Chong et al., 2015; Clemon; Zohdi, 2018; Colorado; Veslásquez; Monteiro, 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; Gebler; Uiterkamp; Visser, 2014; Nascimento et al., 2019; Sauerwein; Doubrovski, 2018; Sauerwein et al., 2019; Unruh, 2018. |
| **Virtualise** | B12 | AM encourages indirect dematerialization | Bogers; Hadar; Bilberg, 2016; Cappa et al., 2016; Ford; Despeisse, 2016; Garmulewicz et al., 2018; Gabler; Uiterkamp; Visser, 2014; Huang, 2015; Majeed; Lv; Peng, 2019; Millard et al., 2018; Tziantopoulos et al., 2019; Unruh, 2018; Wang et al., 2019. |
| **Exchange** | B13 | AM promotes the replacement of old materials with advanced materials | Bloomfield; Borstrock, 2018; Ghaffar; Corker; Fan, 2018. |
| | B14 | AM promotes the application of new technologies | Kim et al., 2015a; Majeed et al., 2021; Majeed; Lv; Peng, 2019; 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. |

#### 3.3.1.1 Additive Manufacturing contributing to Regenerate

Some papers contributed to “regenerate,” focusing on how AM encourages the use of materials and energy from renewable sources and the use of biodegradable materials. Some authors have studied the use of biodegradable materials produced from 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 up of 70% plastic and 30% recycled wood fibre were as durable as models made up of 100% virgin plastic. Ghaffar, Corker, and Fan (2018) addressed the use of biodegradable materials in the construction sector. They presented new pathways for future propositions in the CE context and the role that AM can play in achieving circularity in the construction sector. It was concluded that the modern construction industry is going through a period of policy change in which it is more environmentally oriented; therefore, it is highlighted that raw materials destined for AM must be carefully selected for this technology to demonstrate its impact. This is 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, in AM materials. Thus, the printing of this material results in a ceramic-like material. Yadav et al. (2020) studied the biocompatibility of orthopaedic implant biomaterials, leading to selecting materials compatible with human anatomy. They identified the classes of biomaterials based on their 3D printability to make their processing more oriented toward a CE. The study shows that 3D printed biomaterials require less material to manufacture with less waste and can be made with precision that matches human anatomy. Regarding the use of renewable energy sources, Strack (2019) reviewed recent AM approaches for generating biological energy in the form of microbial fuel cells. The objective was to provide an overview of the AM approaches to biological energy generation and describe the existing research tactics.

The health of ecosystems is of paramount importance in CE. Some studies have pointed out how AM contributes to the recovery, retention, or restoration of the environment's health. Tang, Mak, and Zhao (2016) proposed a general methodology to accurately assess the environmental impact of a product manufactured by the AM process. The results showed AM process could save energy and reduce environmental impacts. Peng et al. (2018) focused on the energy and environmental impacts of AM. Statistical analysis of the data that provides an overview of the environmental impact predictions is presented. They discussed energy and material reduction opportunities in AM through design, material preparation, fabrication, use, and end-of-life treatment. Faludi et al. (2015) compared the environmental impacts of two 3D printers with a traditional computer-controlled milling machine to determine which method is the most sustainable. It was found that the sustainability of AM versus that of conventional machining depends mainly on the percentage of use of each machine. In both 3D printers, electricity is always the dominant impact. However, for a Computer Numerical Command machine at maximum utilization, material waste becomes dominant, and the cutting fluid is approximately at the same level as electricity usage.

There is still a discussion regarding CO2 emissions with the use of AM. Its ability to move from a centralised manufacturing system to a more decentralised system may imply transport reduction, with a consequent reduction in CO2 emissions in this stage of the product cycle life (Ford and Despeisse, 2016). Garmulewicz et al. (2018) pointed out two immediate and measurable benefits of using plastic waste for locally distributed manufacturing using 3D printing: reducing landfills and road cargo transportation. Gebler, Uiterkamp, and Visser (2014) proposed a qualitative assessment method of the sustainability implications induced by AM and globally quantified the changes in life cycle costs, energy emissions, and CO2 by 2025. The authors conclude that AM represents a manufacturing technology with great sustainability potential, mainly if it is applied to mass production markets and if social impacts are fully addressed.

#### 3.3.1.2 Additive Manufacturing contributing to Share

The flexibility of products allows products to be quickly adapted, ensuring utility for more than one user, whether through sharing or reuse. It also enables modular and efficient manufacturing systems, allowing the manufacture of differentiated products in batches of only one product or spare parts, and making products more adaptable for reuse. Bloomfield and Borstrock (2018) presented a flexible 3D printed textile product that combines advanced manufacturing technologies. This ensured adaptability and usability of clothing by different users. In this study, the practice of reuse is encouraged by the new modular technology since a garment can be reused by creating new clothes, accessories, toys, or other applications. In addition, practices related to the repair, reuse, and reuse of the material life cycle can be extended and adapted to meet new requirements. Sitotaw et al. (2020) conducted a review of the state of the art of AM on textiles. In agreement with Bloomfield and Borstrock (2018), the study highlights the advantages of rapid adaptability and customisation and the sustainability of textiles.

Sharing in the context of AM can also occur in digital projects and files over the internet. Bogers, Hadar, and Bilberg (2016) studied how a consumer goods manufacturer organises operations by migrating from a manufacturer-centred value logic to consumer-centred value logic using AM. One of the main changes that occurred was the transformation of centralised to decentralised supply chains, in which the consumer effectively takes over the manufacturer's production activities. This change leads to design freedom, allowing personalised shapes, digital interaction with consumers, and direct manufacturing. This also allows copying and sharing digital projects and files on the internet.

Millard et al. (2018) addressed the issue of digital sharing. According to the authors, sharing occurs at the virtual level when the right skills and equipment can produce digital content composed of virtual bits and make it available instantly worldwide. For the authors, access to 3D printers and the freedom that this technology brings is part of the creative movement, contributing to a 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 the CE.

#### 3.3.1.3 Additive Manufacturing contributing to Optimise

Current additive technologies are relatively slow and inefficient, requiring a longer production time (Holmström and Gutowski, 2017) since the layer-by-layer process takes a long time to manufacture a part completely. However, the increase in AM applications encourages researchers to improve AM processes to optimise and reduce waste in the production phase and along the supply chain. Jiang (2020) planned an AM process to save manufacturing time. The strategy consisted of a five-step process that involves multilayer-to-multilayer manufacturing, instead of a layer-upon-layer manufacturing. The results showed that the new strategy saves 1039 s of time for manufacturing a part compared to the conventional layer-by-layer method.

AM allows the production of complex and optimised components because of the freedom of form and geometry. Also, it makes possible simplicity of assemblies, which include fewer parts and fewer different materials. These technology characteristics allow the reduction of waste in production (Ghaffar, Corker, and Fan, 2018). The design freedom allowed by AM enables improvements in sustainability (without compromising functional performance) that can be achieved by redesigning components, products, and the process itself (Ford and Despeisse, 2016; Tang, Mak, and Zhao, 2016). This process/product redesign enhances the manufacturing of more specific products, with fewer components, materials, stages, and interactions (Ford and Despeisse, 2016).

Numerous studies have addressed the issue of waste reduction stimulated in process planning from product design (Ahsan, Habib, and Khoda 2015; Jin, Du, and He, 2017; Kellens et al., 2017; Peng et al., 2018). Jin, Du, and He (2017) assessed 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 materials forming the surface boundary. Therefore, this material can be saved based on acceptable geometric precision and mechanical strength. Thus, this work 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 manufacturing stamping tools and turbine blades. Ahsan, Habib, and Khoda (2015) also developed an AM process planning approach that minimises the use of resources. The proposed optimisation methodology offers an ideal manufacturing direction that minimises the consumption of resources and the total manufacturing time, reduces the plurality of the contour, and improves the surface quality manufacturing complexity and surface quality.

The optimisation can also refer to the actions taken to remove waste along AM-based supply chains. An expected effect of AM is the short supply chains, as the need for centralised tools and manufacturing is reduced. Thus, chains become reconfigured, with less centralised production and more innovative distribution models, with less need for transport and a shorter production cycle (Bogers, Hadar, and Bilberg, 2016; Turner et al., 2019; Tziantopoulos et al. 2019). Turner et al. (2019) explored the feasibility of a redistributed business model to manufacturers that employ AM as part of a circular production and consumption system. The study showed that the reduction in transport and the increase in customer involvement (due to the decrease in the chain) are the main benefits that would occur if a redistributed model was implemented in a given sector.

Inventory is another advantage in terms of waste reduction. Although centralised AM can reduce inventory maintenance requirements, decentralised AM can avoid the need for stock retention (Kellens et al., 2017). The adoption of AM can reduce the need to maintain extensive inventories of each component used to create a single product, reducing or eliminating waste inventory, including unsold and obsolete goods (Despeisse et al., 2017). Kunovjanek and Reiner (2019) verified that AM could directly reduce raw material stocks.

Some studies have shown how AM increases product performance or efficiency (Jin, Du, and He, 2017; Laverne et al., 2019; Ma et al., 2018; Majeed, Lv, and Peng., 2019; Wang et al., 2019; Yang et al., 2019). Laverne et al. (2019) provided AM designers with guidelines to help printers efficiently use AM to obtain optimal product models, considering their environmental impact. Thus, they provided insights into improving product performance by reducing the scale of material flows. MA et al. (2018) developed an approach to assess the sustainability of the product life cycle produced by AM. As a result, it was possible to obtain a fundamental understanding of the sustainability performance of an AM product's life cycle. Finally, Yang et al. (2019) provided a new perspective for selecting a more sustainable assembly project. The study investigated the consolidation of parts made by AM, and the results were weight reduction, extended life expectancy, and improved functional performance of the product (accelerator pedal set).

Other studies have shown another benefit of “optimise”: the tendency to leverage the use of technologies associated with AM, such as the internet of things, sensors, big data, and cloud computing, to promote the reliability and efficiency of processes (Huang, 2015; Kim et al., 2015a; Majeed et al., 2021; Majeed, Lv, and Peng, 2019; Nascimento et al., 2019; Wang et al., 2019). Majeed, Lv, and Peng (2019) proposed a framework to design high-quality AM products using big data analytics (BDA). By analysing each AM process and essentially inspecting all elements, big data analysis can determine when imperfections occur, preventing future problems from arising. BDA 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 intelligent manufacturing of high-value products. Nascimento et al. (2019) used the technology of a mobile application to generate a map of the location of waste for disposal. When combined with specialised software to optimise collection routes based on geographic data and real-time traffic conditions, it is possible to decide the type of vehicle needed to collect waste for use in 3D printing. Wang et al. (2019) developed a new architecture for a cloud-based AM platform. Artificial intelligence and cyber-physical system technologies are used in the Internet of Things (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 will allow the verification and validation of AM information across the digital spectrum.

#### 3.3.1.4 Additive Manufacturing contributing to Loop

To this action, the benefits were concentrated on those describing technical cycles. So, the paper shows how AM encourages reuse, remanufacture, and recycling of products and components. Many authors suggest AM products must be designed to encourage reuse, remanufacturing, and recycling, boosting the return of waste to the economy. However, for AM to support the “loop,” it is essential to integrate the supply chain through a handling, transportation, and storage policy that supports the reverse flow.

Several studies have shown how recycling, reuse and remanufacturing can be encouraged in the context of AM (Table 3.4.1)

**Table 3.4.1-** How AM can enhance recycling, reuse of materials, and remanufacturing

| Activities | Summary of Results | Main References |
|---|---|---|
| **Recycling** | Many papers have shown that in the context of AM, plastic is the most recycled material because it is also the most used material. Despite this, some research has been dedicated to studying the recycling of metals in the context of AM. These are the most suitable for an optimal CE due to their high recyclability. | Clemon; Zohdi, 2018; Colorado; veslásquez; Monteiro, 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; Woern; Pearce, 2017; Zhao et al., 2018; Zhong; Pearce, 2018. |
| **Reuse** | To leverage this activity, some papers have shown 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 of repairs and upgrades. This is due to AM characteristics such as digital production and adaptability. | Chong et al., 2015; Depalma et al., 2020; Ford; Despeisse, 2016; Nascimento et al., 2019; Sauerwein et al., 2019. |
| **Remanufacturing** | Many papers have shown many benefits in remanufacturing for AM due the technology capability of add new material to existing surfaces to repair and remanufacture used and worn parts. | Kellens et al., 2017; Le; Paris; Mandil, 2018; Matsumoto et al., 2016; Saboori et al., 2019; Tian et al., 2017. |

“Loop” emphasizes the product design to achieve greater circularity of resources. It means 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, to ensure longevity and the resource loop, product design should guarantee the ease of repair, remanufacturing, recycling, and reuse of resources. In this field, Sauerwein et al. (2019) conducted a series of interviews with designers about their 3D printed design projects. They discovered that AM supports circular design strategies, creating opportunities to extend a product's life, 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 the design of AM allows digital projects to be developed to produce spare parts on demand when repair and remanufacturing are required. However, companies are still beginning to discover the implications of using AM technologies to extend the product life cycle and close the cycle.

Nascimento et al. (2019) exemplified the reuse of resources by recommending a circular model to reuse electronic scrap devices, integrating web technologies, reverse logistics, and AM to support EC practices. DePalma et al. (2020) investigated the potential of two prevalent industrial polymer 3D printing technologies, Selective laser sintering (SLS) and fused deposition modelling (FDM), to provide a CE solution for plastic waste based on the reuse of that material. The results showed that available industrial 3D printing technologies could help reduce plastic waste in manufacturing, although a full 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 speeding up the recycling and reuse of materials for improved infrastructure materials. Plastics are among the most commonly reviewed materials in material recycling because of their greater use in AM (Colorado, Velasquez, and Monteiro, 2020). Cunico et al. (2018) presented and characterised the post-processing of 3D printing surface finish from recycled plastic waste. As the main result of this work, the proposed recycling process was confirmed to improve the object's properties. Polylactic acid (PLA) is one of the most commonly used plastic materials. Zhao et al. (2018) conducted research related to the mechanical properties of recycled PLA, which was obtained from printed parts of virgin PLA that were subsequently re-extruded by FDM in filaments suitable for 3DP use. Recent research and initiatives to propose a new approach based on distributed plastic recycling for AM technologies were also analysed to reduce plastic waste and support CE. Woern and Pearce (2017) proved that using recycled plastic instead of virgin plastic for AM could save 98% material cost. Santander et al. (2020) demonstrated the economic and environmental feasibility of a network distributed in a closed-loop supply chain for recycling plastic using 3D printing technologies. The results showed positive economic and environmental benefits with the realisation of a new recycling method. Despeisse et al. (2017) pointed out that a more distributed material market may encourage lower concentrations of natural resources. In addition, it is highlighted that the local markets for more flexible materials may be more suitable for recycling highly distributed sources of waste by avoiding loss of information due to large-scale recycling (Despeisse et al., 2017). Sanchez et al. (2020) show how AM rapid technical evolution allows a new path to a circular economy using thermoplastic recycling and distributed production. For this, a systematic literature review was performed, and a framework was proposed using 6 main stages (recovery, preparation, composition, raw material, printing, quality) to identify the global value chain of distributed recycling via the AM approach. Based on the results, they proposed different future research paths at the micro, meso and macro level to better understand the connections between circular economy and distributing recycling to reach the full potential and improve recycling closed and open loop.

The metals are the most suitable material for an optimal CE because of their high recyclability (Colorado, Velasquez, and Monteiro, 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.

Tian et al. (2017) demonstrated remanufacturing in AM in a process that uses filaments impregnated with recycled carbon fibre and pure PLA as a raw material. This study proposed a recycling and remanufacturing process of thermoplastic reinforced with continuous 3D-printed fiber fibre, providing fully recyclable composite materials with mechanical properties even more significant than the original ones. This allows manufacturing a green-looking compound based on 3D printing without considering carbon fibress. In addition to Tian et al. (2017), remanufacturing for 3D printing has been cited or researched by other authors. Kellens et al. (2017) emphasised that AM can be used to repair or remanufacture damaged components and avoid producing new components. Le, Paris and Mandil (2017) combined traditional or subtractive manufacturing technology techniques with additive technology techniques to propose an alternative remanufacturing strategy. This strategy allowed end-of-life parts to be reused directly to manufacture new parts. Matsumoto et al. (2016) described trends, factors, and barriers to remanufacturing, with AM for remanufacturing being a topic discussed. According to the authors, the benefit of AM may be mainly the ability to add new material to existing surfaces to repair and remanufacture used and worn parts. Saboori et al. (2019) presented an overview of a flexible type of AM, targeted energy deposition, and its role in repairing metal components. The results confirmed the significant capacity of this type of process in repairing and remanufacturing complex geometries for industries such as automotive and aerospace.

#### 3.3.1.5 Additive Manufacturing contributing to Virtualise

For “virtualise,” we sought to identify research that addressed indirect dematerialisation in the context of AM. The emphasis on indirect dematerialisation is because direct dematerialisation is not possible in AM. After all, this technology directly materialises resources. So, we will study Virtualise in AM in a point of view of developing

product services and online markets.

Gebler, Uiterkamp, and Visser (2014) predict that supply chains, combined with online platforms, will become more dynamic and be digitized as the pre-chains move to digital information processing, while physical pre-chains will be eliminated. Ford and Despeisse (2016) emphasised that digital information processing will lead digital projects to be kept on file; the ability to reproduce these files as spare parts for repair and remanufacturing will extend product's 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. Wang et al. (2019) explored how the cloud platform can help customers use AM more efficiently, providing sufficient information and support throughout the product development process. For this purpose, a cloud-based additive manufacturing platform was proposed, enabling the IoT. Cappa et al. (2016) studied an integrated approach based on collaborative production combined with 3D production. Individuals collaborate with researchers via the web to develop a new product in the approach used. The sustainability improvements achieved with the process involve a significant reduction in total costs and purchase price and a reduction in energy consumption and pollutant emissions.

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

In addition to all the transformations brought about by dematerialisation in supply chains, business models, and production systems, dematerialisation in the context of AM has direct consequences for logistics; 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 3D manufacturing. This shortens the production and logistics time (Tziantopoulos et al., 2019). Other changes were highlighted by Millard et al. (2018), who pointed out that manufacturing distributed on a large scale can profoundly impact the future of manufacturing and our physical world and work, behaviour, and local and city development, along with politics globally.

#### 3.3.1.6 Additive Manufacturing contributing to Exchange

New production technologies will be required to be applied and combined with AM on the principle of "Exchange" or "exchange" (Kim et al., 2015a; Majeed et al., 2021; Majeed, Lv and Peng, 2019; Wang et al., 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, Lv and Peng (2019) reported that this new trend, from the viewpoint of the CE, may allow BDA to guide more innovative and circular products. AM combined with BDA can reduce manufacturing defects and energy consumption and save time and money, thus benefiting customers, manufacturers, and the environment. Wang et al. (2019) reinforced 3D printing with IoT. The advantage was that the IoT provides new features for a cloud-based platform, allowing customers to remotely control and monitor the printing process. In this way, local printers can communicate with the cloud platform automatically. Kim et al. (2015a) proposed integrating the AM of federated architecture technology for information systems. The proposed that a federated information system architecture provides a platform that allows for the verification and validation of 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 such a combination of technologies applied at the beginning of the product's life stage in the AM process. The results showed that the framework supports AM companies and produces energy-efficient products, which is helpful for intelligent and sustainable manufacturing, reducing emissions, and clean production.

Other studies have focused on highlighting the use of AM to substitute old materials for advanced materials (Bloomfield and Borstrock, 2018; Ghaffar, Corker, and Fan, 2018) in the construction sector (Ghaffar, Corker, and Fan, 2018) and in the textile sector (Bloomfield and Borstrock, 2018). The choice of new innovative products or services in the context of AM was also addressed (Behm et al., 2018; Bloomfield and Borstrock, 2018; Candi and Beltagui, 2019). Candi and Beltagui (2019) analysed survey data collected from 177 US companies that use AM for innovation. The results showed that AM in innovation is more effective for companies facing more significant turbulence in their operating environments. This is because the main benefits of AM are derived from its ability to allow flexible responses to uncertainty.

### 3.3.2 Additive Manufacturing limiting the CE

Some barriers that limit AM from meeting the CE requirements are identified in this section. This analysis classified the barriers into general (GB) and specific (SB), as shown in Table 3.5.

**Table 3.5** – AM barriers for circularity

| Berriers | Code | Barriers | References |
|---|---|---|---|
| **General Barriers** | GB1 | Lack of eco-friendly AM legislation and public policies. | Ford and Despeisse, 2016; Garmulewicz et al., 2018; Unruh, 2018. |
| | GB2 | Lack of strategic alignment in the adoption of AM to achieve circular business models. | Bogers, Hadar and Bilberg, 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; Uiterkamp; Visser, 2014; Martinsuo Luomaranta, 2018; Shukla; Todorov; Kapletia, 2018. |
| **Specifics Barriers** | SB1 | Possibility (risk) of irresponsible or excessive consumption of 3D printed products. | Bogers, Hadar and Bilberg, 2016; Cerdas et al., 2017; Ford and Despeisse, 2016; Ghaffar, corker and fan, 2018. Giurco et al., 2014; Unruh, 2018. |
| | SB2 | Toxicological risks associated with the use of AM impact 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 and Despeisse, 2016; Holmstrom and Gutowski, 2017; Singh, Ramakrishna and Gupta, 2017; Strange and Zucchella, 2017. |
| | SB4 | Lack of standardization of materials and quality control of items produced by AM technologies. | Depalma et al., 2020; Despeisse et al., 2017; Ford and Despeisse, 2016; Niaki and Nonino, 2017b; Vidakis et al., 2020. |

| Berriers | Code | Barriers | References |
|---|---|---|---|
| | SB5 | Limitation on the number of Technical cycles of materials used in AM | Depalma et al., 2020; Dal Fabbro et al., 2020; Ford and Despeisse, 2016; Garmulewicz et al., 2018; 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 and Despeisse, 2016; Garmulewicz et al., 2018; Sauerweinet al., 2019; Sun et al., 2020. |
| | SB7 | Low acceptance of recycled raw materials for MA. | Depalma et al., 2020; Sun et al., 2020; ZHAO et al., 2018; ZHONG; PEARCE, 2018. |
| | SB8 | Lack of sufficient match between novel materials and current 3D printing technologies | Ford and Despeisse, 2016; Lee et al., 2017; Ma et al., 2018. |
| | SB9 | High raw material costs for use AM. | Ford and Despeisse, 2016; Niaki and Nonino, 2017b; Weller et al., 2015. |
| | SB10 | High unit cost of manufacturing AM | Ford and Despeisse, 2016; Weller et al., 2015. |

#### 3.3.2.2 General barriers

An identified barrier that inhibits circularity, in general, is the lack of legislation and/or public policies that regulate the environmental impact generated by the use of AM. For example, there are situations in which the use of AM can cause wastage. The literature does not mention specific laws or standards that provide, for example, the reuse or recycling of this waste. Thus, these technical cycles face a series of barriers to achieving CE's expected benefits. According to Garmulewicz et al. (2018), there is a lack of distributed circular business models to organise recycling materials for use in AM. Ford and Despeisse (2016) highlighted the lack of standards in the repair and remanufacturing processes in the context of AM. Thus, circular regulations and standards in this area and others are welcome so that additive manufacturing could drive CE.

In addition, this technology requires regulations related to toxicology. There is scientific evidence that 3D technology generates negative environmental impacts, such as harmful emissions in ultrafine particles and volatile organic compounds in some options of materials used. However, there are no laws that describe the choice of material with possible toxicological effects that can be generated. Therefore, policymakers should consider the toxicological implications of 3D printing material options and encourage choices of 3D printing materials that support the emergence of a sustainable CE (Unruh, 2018).

The lack of strategic alignment between AM and circular business models is another barrier that restricts the circularity potential of this technology. New business models must be developed because of the new emerging AM technologies. The development of this business model implies managing organisational changes and openness to external sources (Boger, Hadar, and Bilberg, 2016).

Martinsuo and Luomatanta (2018) emphasised 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 to circular materials at the early stage of AM diffusion. However, this impulse depends on intensive strategies, such as systematic choices beyond new additive technologies.

However, the existing literature does not explain how companies design their business models according to the CE principles. There is fertile ground for research at the intersection between the CE and the field of strategic management (Centobelli, 2020). 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 (Jabbour et al., 2018). This will require a better understanding of how these technologies can adequately support the chain of actors (customers, suppliers, and institutions) involved in a circular business model, allowing and supporting the active involvement of external actors throughout all phases of a circular life cycle (Centobelli, 2020).

A third general barrier identified was the lack of skills, experience, and awareness regarding the use of AM. Although this fact 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 (Garmulewicz et al., 2018; Martinsuo and Luomaranta 2018; Shukla, Todorov, and Kapletia, 2018).

To play a positive role in circularity, AM needs to be aligned with users' awareness of the impact of manufacturing. Democratising manufacturing, making technology available to individual entrepreneurs or the general public requires a change in mentality and behavioural changes to 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 and unconscious 3D printing user would produce more significant waste, use more material, and require longer printing times. Training operators and designers would thus help reduce the environmental impact of the manufacturing process and improve the quality of the process. Therefore, educational systems and programmes need to be adjusted to meet the new demands for knowledge (Gebler, Uiterkamp, and Visser, 2014).

Martinsuo and Luomaranta (2018) emphasised that this approach requires a company to invest heavily in R&D. In addition, granting resources to designers is vital for ensuring learning and experimentation. The research findings also showed that companies must overcome the hurdle regarding the strengths of traditional manufacturing performance and tolerate the AM learning curve, which is sometimes considered expensive and time-consuming, especially for small- and medium-sized businesses.

#### 3.3.2.1 Specific Barriers

Specific barriers limit the AM circularity potential in specific points of the ReSOLVE actions.

The literature shows that there is a possibility that AM incites the irresponsible or excessive consumption of 3D printed products, posing a risk to the health of ecosystems. AM allows customers to co-design products that perfectly meet their demands and ambitions (Ghaffar, Corker, and Fan, 2018). However, this freedom is a two-way street because, as it allows the development of more circular products, it also opens up spaces for the design of products that lead to waste. Moreover, taking advantage of AM's design freedoms requires AM skills and competencies that individuals and organisations may lack and take time to establish (Ford and Despeisse, 2016).

AM technologies support the shift to a more consumer-centric business model (Bogers, Hadar, and Bilberg, 2016; Ford and Despisse, 2016). Consumers can have greater freedom to print with numerous materials and platforms with different specifications. This would mean that the final product will be dependent on the platform, which can pose a risk to people's safety and life (Bogers, Hadar, and Bilberg, 2016), which creates a significant risk for a CE model.

The possible increased consumption of products is another factor that 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, as it is very likely that companies can aim to increase consumption by offering higher degrees of customisation in shorter times, placing the product just a click away from the point of sale and thus print more products, multiplying the environmental impact. Unruh (2018) highlights a fact that corroborates this perspective. According to the author, in 2016, the American toy maker Mattel announced a $299 3D printer for children to make toys. This was considered wastage as potential plastic waste would be produced by thousands of children armed with a printer and an endless catalogue of downloadable toy designs (Unruh, 2018). Thus, this increase in consumption and production would lead to several issues that would need to be analysed.

Another AM barrier that poses risks to environmental health is the existence of toxicological risks associated with the use of technology. These risks are not well known yet and should be focused by 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 of the use of thermoplastics as a raw material (Kim et al., 2015b; Rejeski; Zhao; Huang, 2018), which is particularly worrying because most 3D printers are housed indoors (Behm et al., 2018). In addition to thermoplastics, AM of metals also generates particulate matter due to fine metal powders and high temperatures, negatively impacting the environment and human health (Chen et al., 2020). Furthermore, acrylonitrile-butadiene-styrene (ABS) is the most widely used thermoplastic material. When this material is heated to approximately 170 C, three major decomposition products are acrylonitrile, 1,3-butadiene, and styrene. All are toxic to humans (Chen et al., 2020). For CE, this is a risk that 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).

The literature on CE describes its implementation's growth in efficiency and performance. However, most 3D machines are relatively slow and inefficient (Holmström and Gutowski, 2017), requiring a longer production time. Although there is a constant advance in AM technologies and many already can fabricate rapidly, this is not the case for the most industrial used ones (such as material extrusion). In addition to the layer-by-layer process, which takes a long time to complete a part for most machines, time is also required to prepare for printing, design the parts, and post-processing. Thus, productivity is low. Moreover, the adoption of AM in production lines requires further development and consolidation (Strange and Zucchella, 2017). In this way, the economy associated with AM makes it more ideal for manufacturing products and components to order than for mass manufacturing, making its main economic benefits to be found in the personalised production of goods in single or small batches (Ford and Despeisse, 2016; Singh, Ramakrishna, and Gupta, 2017).

Another barrier of AM that compromises circularity is the uncertain performance of products and components produced (Ford and Depeisse, 2016) because of the limitation in the quality of the items developed by AM technologies. Due to the lack of technical standards (Niaki and Nionino, 2017b), printing an object through AM can result in lower quality. An example is the 3D printing processes of polymers via extrusion, which have a relatively low quality (Despeisse et al., 2017), as the material undergoes thermal degradation (Depalma et al., 2020), which negatively affects the traction properties of the material (Vidakis et al., 2020). This uncertainty in quality remains a significant problem for 3D printing, which constitutes a barrier to reaching the CE.

Another barrier highlighted by many authors is the limitation in the technical cycles of recycling materials used in AM. This is because several limitations in the raw materials of 3D printing make it challenging to maintain technical recycling cycles. Much has been discussed regarding the idea of recycling materials for 3D printing. The production of raw materials from plastic waste, for example, reduces costs and reduces environmental impacts (Garmulewicz et al., 2018; Giurco et al., 2014; Tian et al., 2017; Unruh, 2018; Zhong and Pearce, 2018). Several studies have focused on using recycled plastics for 3D printing, and several companies have already sold recycled filaments (Garmulewicz et al., 2018). Despite this, Sun et al. (2020) argue that recycling 3D printed products and materials represents a challenge, as there are several barriers to recycling. First, the recycling potential is limited to certain materials (Ford and 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 due to 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 since the supply chain structure for recycling is based on large centralized processes and AM requires small-scale recycling technologies. These create barriers to recycling 3D printed waste.

Ford and Depeisse (2016) highlight that the multi-material goods produced by AM are not recyclable, and the recycling of plastics is limited due to losses in quality. Dal Fabbro et al. (2020) studied the effects of multiple ABS recycling in a closed circuit. Various closed-loop recycling processes were conducted in the 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 was observed during the extrusion process. DePalma et al. (2020) pointed out that PA 12 and ABS materials undergo significant thermal degradation during SLS and FDM processing, making it difficult to reuse. Zhao et al. (2018) concluded that the repeated 3D printing process only required two cycles for PLA in FDM processing, as significant deteriorations in viscosity values were detected, making the material unsuitable for further reprocessing.

Regarding recycling, another barrier was a low acceptance or willingness to consume recycled material as a raw material for AM (DePalma et al., 2020; Garmulewicz et al., 2018; Sun et al., 2020; Zhao et al., 2018; Zhong and Pearce, 2018). Garmulewicz et al. (2018) argued that this limited demand among consumers might occur due to low recycling rates, who are generally not aware of the value of the materials contained in their waste. Zhong and Pearce (2018) highlight the lack of acceptance of recycled materials over virgin materials in companies that use AM. The authors discovered a tendency to avoid using recycled material because of concerns regarding the degradation of the quality and the uncertainty regarding the consistency of the diameter and the mechanical properties of the recycled filaments. Sun et al. (2020) carried out analytical and numerical studies that showed that the recycled material's quality significantly affects the suppliers' decision-making for 3D printing. The authors argue that material suppliers prefer low-quality recycled material to ensure that recycled material suppliers can survive in the market where virgin and recycled materials compete. Therefore, the quality of the recycled material must be below a specific limit for the virgin material. They found that the profits of material suppliers decrease with an increase in the quality of the recycled material, which implies that the suppliers may not be in favour of improving its quality.

Another AM barrier restricting circularity is the lack of sufficient match between novel materials and current 3D printing technologies. Circular Economy literature highlights the production and choice of new products and advanced materials as leverage for their implementation. Lee et al., 2017 define novel materials as a group of advanced materials that can be 3D printed for specific new applications. The authors emphasize one challenge is to solve the 3D printability of the novel/advanced materials without comprising original material properties. Further development of novel materials is still required, since most printers still work with a single material with limited industrial applicability (Lee, 2017). Ford and Despeisse (2016) argue that the technology's relative immaturity indicates that there are currently few materials for developing new processing techniques. This inhibits innovative solutions in diverse materials and material combinations. Ma et al. (2018) argue that it is necessary to increase the development of AM material manufacturing technology to improve industrial products and the ability of consumers to innovate products.

“Exchange” action highlights that applying new technologies (citing as an example the AM itself) is fundamental in the implementation of a CE. However, there is a financial issue in using the technology itself. Ford and Despeisse (2016) and Weller et al. (2015) highlight that one of the barriers to this is the high raw materials prices. Niaki and Nonino (2017b) argue that machines and materials for AM are still expensive but the cost will decrease as AM becomes a more commonly used production technique. In addition, most of the machines are still patented, and this exclusiveness hinders price reduction (Niaki and Nonino, 2017b). This economic aspect is also considered in Circular Economy since if circular AM activities are not economically viable, the benefits AM brings to CE will not happen.

Finally, many authors found that AM tends to increase costs, while others reported reducing costs. However, a significant AM barrier reported is that the unit manufacturing cost is still higher than the unit cost in traditional manufacturing (Ford and Despeisse, 2016; Weller et al., 2015). This remains an obstacle to realizing the full potential of AM technology as it can overshadow the potential positive benefits of increasing AM.

## 3.4 DISCUSSION

The present research categorised previous studies into 15 benefits that AM can provide to the transition toward a CE. Barriers that prevent AM from meeting CE requirements have also been identified. Given the results obtained, we propose a framework (Figure 3.3) that organises, systematises, and formalises the ideas presented and the high volume of information retrieved from the literature. In addition, the present framework assists in the development of future research.

**Figure 3.3** – Relationship between AM and CE

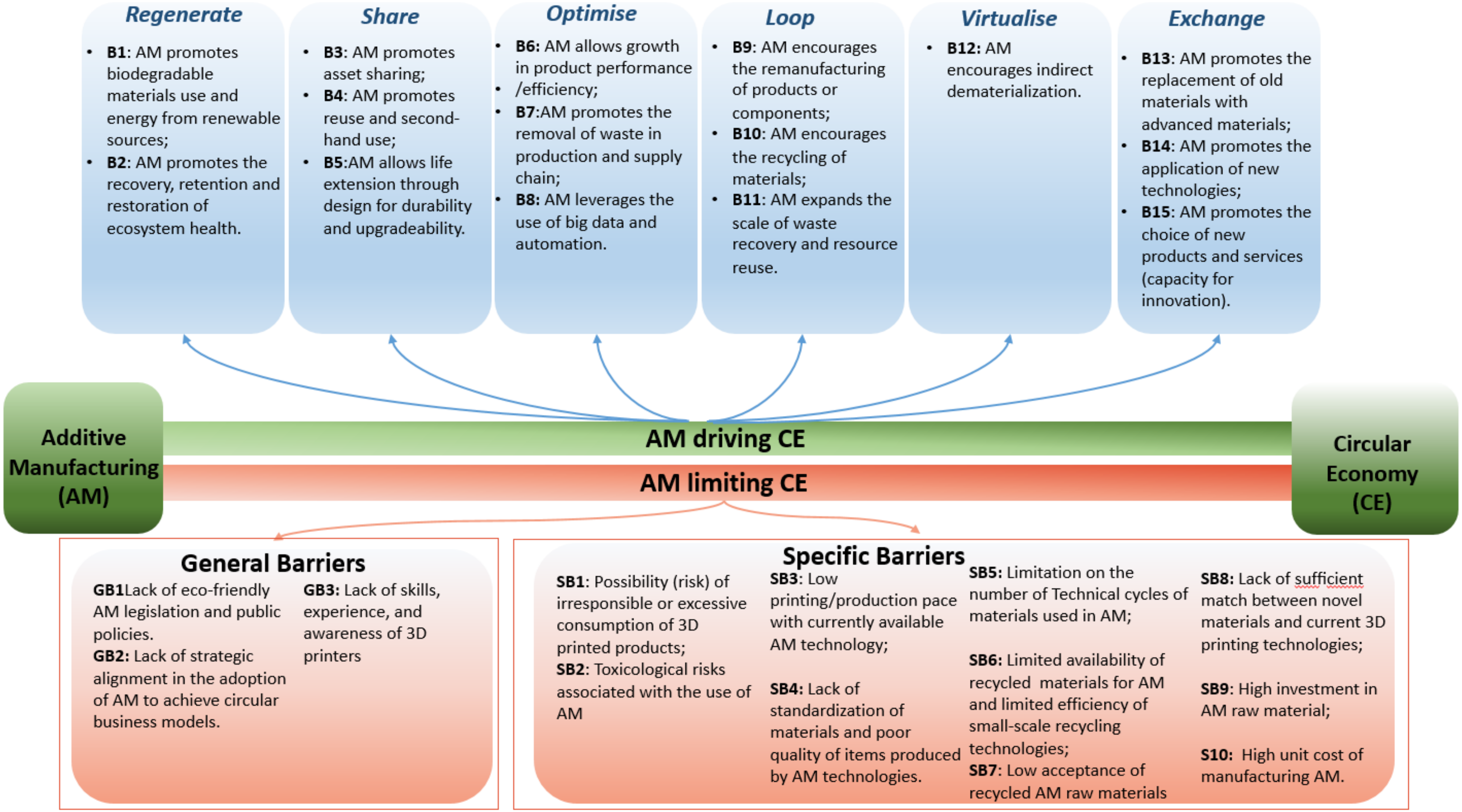


Figure 3.3 manages to portray the relationship between AM and CE. In the upper part of the figure, there are 15 potential benefits that AM leads to CE in each of the six ReSOLVE principles. At the bottom are barriers that, according to the literature, restrict the potential of AM circularity. As presented in the results section, these barriers were classified as general and specific.

Notably, numerous benefits presented are achieved naturally only by adopting AM technology. The B5 benefit, for example, can naturally be achieved with the use of AM since the variety of design and manufacturing of complex geometries is an intrinsic feature of the technology. Thus, the ability to design for durability and constant update is a directly achieved benefit through technology. However, other benefits require efforts to be achieved, and some degree of intervention is required to realise such benefits. The benefits linked to the "Loop" (B9, B10, and B11), for example, are not such natural benefits in the context of AM since they need some stimuli to be perceived.

Recycling, remanufacturing, and reusing materials offer some challenges, such as the limitation of accepting non-virgin products or the difficulty of recycling on small-scale. Despite this, many researchers have evaluated the positive effects of the resource loop in the context of AM. Finally, some benefits can also become a barrier that limits circularity. Benefit B7, for example, can be directly achieved by AM adoption since it naturally shortens supply chains and reduces waste (Bogers, Hadar, and Bilberg 2016; Ford and Despeisse 2016); however, at the same time, 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 printing speed by making many new commercial technologies emerge every day (Ivan and Yin 2017).

We advance a significant theoretical contribution by providing a macro view of what limits AM's circularity potential, as we considered both intrinsic and not intrinsic barriers to the technology. The intrinsic barriers are those provided by AM characteristics, and non-intrinsic barriers are those that limit the potential of circularity of the technology but are not related to its characteristics. For example, we can consider barriers GB1, GB2, GB3, SB7, and SB9 not intrinsic to AM, as they limit the potential for circularity but are not related to its characteristics, but rather to political, social, environmental or educational characteristics in which the use of technology is inserted. Furthermore, many existing barriers are influenced by the degree of maturity of the technology, which is relatively new. It is expected that the barriers GB1, GB2, GB3, SB1, SB3, SB4, SB8 and SB9, which are somehow influenced by the degree of technology maturity, will be mitigated as AM evolves and matures.

In reality, the barriers raised may indicate the actions that need to occur to reach a more significant potential for circularity. The general barriers show us some measures need to be implemented so that AM is instituted on a more environmentally friendly basis—i.e., on an eco-friendly basis—such as governance measures and educational measures.

Interviews with experts were essential for the study. The input data presented for evaluation are presented in Tables 3.2 and 3.3, and the final results are presented in Tables 3.4 and 3.5. This particular phase contributed significantly to obtaining the barriers, which were almost completely rewritten and restructured. In addition, five new barriers were suggested, which were incorporated into the work by combining them with evidence in the literature. Thus, it was possible to obtain clarity of terms, enhanced understanding, and a broader and more systematised view of the barriers.

To add, we identified some gaps for future research. In “optimise,” much was discussed about the changes in the redesigning of components and products so that there are fewer manufacturing subcomponents and a consequent simplification in the supply chain, with less waste. However, the design characteristics of AM products are not yet fully advanced, and it is necessary to understand how to encourage designers to project AM products considering sustainable principles.

A gap point in the “loop” is how the waste infrastructure must be redesigned to meet production in a distributed AM chain. In a decentralised supply chain, incentives for the adequate circulation of material flows may increase (Despeisse et al., 2017). However, little is known regarding how a recycling infrastructure will be structured to meet a decentralised AM market demand. Although some recent studies have already demonstrated the economic and environmental feasibility of a network distributed in the supply chain, such as Santander et al. (2020), there are still no studies that consider social and political aspects of this infrastructure.

Finally, there are still uncertainties regarding ways of educating and developing AM skills in people and designers to facilitate CE regarding general barriers that limit circularity. Likewise, there is still no clear definition of the structure of AM governance for the technology to be more sustainable or for it to comply with CE principles. 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.

## 3.5 CONCLUSIONS

This study identified the benefits of AM for a CE through a multi-method approach. Systematically, it was observed how AM supports the implementation of circularity using the ReSOLVE structure, created to assist organisations in implementing circular strategies. Within each ReSOLVE action, the literature revealed benefits AM can leverage in circularity (15 in total). The next step was to survey the barriers that limit AM to achieve the specific goals of the CE. The barriers were classified into two groups: general barriers and specific barriers, which more explicitly refer to the actions of the ReSOLVE structure.

Most works on this topic have shown the benefits of AM to CE in specific applications and contexts. However, the broader adoption of AM and the positive impact of such adoption to CE also depends on overcoming barriers raised in this study. Also, it is essential to note that if circular activities in the AM are not economically viable, the benefits for the CE will not be fully seized by companies, governments, and society.

### 3.5.1 Theoretical and practical contributions

This study contributes to the literature in several ways. First, it systematizes the barriers and benefits of AM to CE in a readily available and applicable framework. Second, it blends the established knowledge guarded by 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 direct and actionable use of the resulting framework by practitioners and policymakers, as the framework is widely known and used in the practice of CE in organisations and governments.

Because AM is a relatively immature technology, which is continuously evolving and changing, likely, new AM applications with more comprehensive and more significant benefits for CE will soon be created. Thus, numerous studies are being conducted to address AM issues such as reliable quality, more comprehensive material selection, optimised productivity, and efficiency, which improve the relationship with CE. Although the present work has analysed these benefits at specific points, addressing how the AM technology meets CE goals, a more collective and integrated effort is required to ensure that the production, consumption, and recovery cycles achieve a more circular model. Therefore, closer integration and deeper interdisciplinary collaboration are essential in advancing towards CE.

In general, the analyses and classifications made it possible to understand that studies addressing the relationship between AM and CE are still in their initial stages. In general, there is still a lack of empirical evidence on how digital technologies are applied in practice to meet CE goals. For AM to meet these requirements, there is a need for a better understanding of how it would 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 described in the literature. Therefore, some gaps identified in the literature will shed light on proposals for future work.

### 3.5.2 Limitations and future directions

We strove to address as many limitations as possible during the conduction of the study. However, there are limitations to this study. First, some articles might have been excluded from our final sample due to our keywords choice. Thus, even though our methodology allows for full replicability of results, the choice of keywords might slightly alter the general results. Nevertheless, our conclusions are believed to be robust. Second, the judgement and contributions made by experts are subject to their particular background and experience. These limitations can be further addressed in future works aimed at (i) conducting complementary reviews and continuously updating the framework as a “live” body of knowledge and (ii) performing empirical data collection with either large samples of experts or adjusted quantitative methodologies further to validate the relevance and occurrence of barriers and benefits.

## REFERENCES

3D HUBS, 2019. 3D Printing Trends Q1/20183D Printing Trends Q1. https://downloads.hubs.com/3D_Printing_Trends_Q1_2019.pdf (accessed 13 March 2021).

Dotun. Adebanjo, Tritos Laosirihongthong, Premaratne Samaranayake, 2016. The Management of Operations Prioritizing lean supply chain management initiatives in healthcare service operations : a fuzzy AHP approach Prioritizing lean supply chain management initiatives in healthcare service operations : a fuzzy AHP approach. Production Planning & Control 7287, 1–14. https://doi.org/10.1080/09537287.2016.1164909

Chadegani, Aghaei, Arezoo, Salehi, H., Yunus, M., Farhadi, H., Fooladi, M., Farhadi, M., & Ale Ebrahim, N., 2013. A comparison between two main academic literature collections: Web of Science and Scopus databases. Asian Social Science 9(5), 18-26. http://dx.doi.org/10.5539/ass.v9n5p18

Amm Nazmul, Ahsan, Habib Md Ahasan, Khoda Bashir, 2015. Resource based process planning for additive manufacturing. Computer-Aided Design 69, 112-125. https://doi.org/10.1016/j.cad.2015.03.006

Arrieta-Escobar, Javier A. Derrien, Delphine, Ouvrard, Stéphanie, Asadollahi-Yazdi, Elnaz, Hassan, Alaa, Boly, Vincent, Tinet, Anne-Julie, Dignac, Marie-France 2020, 3D printing : An emerging opportunity for soil science. Geoderma 378, 114588. https://doi.org/10.1016/j.geoderma.2020.114588

Behm, Jocelyn E, Waite, B. R., Hsieh, S. T., & Helmus, M. R., 2018. Benefits and limitations of three-dimensional printing technology for ecological research. BMC Ecology 18(1), 1-13. https://doi.org/10.1186/s12898-018-0190-z

Berman, Barry, 2012. 3-D printing: The new industrial revolution. Business Horizons 55(2), 155-162. https://doi.org/10.1016/j.bushor.2011.11.003

Bloomfield, Mark, and Shaun Borstrock, 2018. Modeclix. The additively manufactured adaptable textile. Materials Today Communications 16, 212–216. http://dx.doi.org/10.1016/j.mtcomm.2018.04.002

Bogers, Marcel, Ronen Hadar, Arne Bilberg, 2016. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. Technological Forecasting and Social Change 102, 225–239. https://doi.org/10.1016/j.techfore.2015.07.024

Bringer, Joy D, Lynne Halley Johnston, Celia H. Brackenridge, 2006. Using computer-assisted qualitative data analysis software to develop a grounded theory project. Field Methods 18(3), 245-266. https://doi.org/10.1177/1525822X06287602

Bryman, Alan, 2006. Integrating quantitative and qualitative research: how is it done?.Qualitative Research 6(1), 97-113. https://doi.org/10.1177/1468794106058877

Candi, Marina, and Ahmad Beltagui, 2019. Effective use of 3D printing in the innovation process. Technovation 80, 63-73. https://doi.org/10.1016/j.technovation.2018.05.002

Cappa, Francesco. Del Sette, F., Hayes, D., & Rosso, F., 2016. How to Deliver Open Sustainable Innovation: An Integrated Approach for a Sustainable Marketable Product. Sustainability 8(12), 1341. https://doi.org/10.3390/su812134

Centobelli, Piera, Cerchione, R., Chiaroni, D., Del Vecchio, P., & Urbinati, A., 2020. Designing business models in circular economy: A systematic literature review and research agenda. Business Strategy and the Environment 29(4), 1734-1749. https://doi.org/10.1002/bse.2466

Cerdas, Felipe, Juraschek, M., Thiede, S., & Herrmann, C., 2017. Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System. Journal of Industrial Ecology 21(1), S80–S93. https://doi.org/10.1111/jiec.1261

Chen, Rui, Yin, H., Cole, I. S., Shen, S., Zhou, X., Wang, Y., & Tang, S., 2020. Exposure, assessment and health hazards of particulate matter in metal additive manufacturing: A review. Chemosphere 259, 127452. https://doi.org/10.1016/j.chemosphere.2020.127452

Chong, Siewhui, Chiub, H. L., Liaob, Y. C., Hungc, S. T., & Pand, G. T., 2015. Cradle to Cradle®design for 3D printing. Chemical Engineering Transactions 45, 1669–1674. https://doi.org/10.3303/CET1545279

Clemon, L. M., and T. I. Zohdi, 2018. On the tolerable limits of granulated recycled material additives to maintain structural integrity. Construction and Building Materials 167, 846–852. https://doi.org/10.1016/j.conbuildmat.2018.02.099

Colorado, Henry A., Elkin I. Gutiérrez Velásquez, Sergio Neves Monteiro, 2020. Sustainability of additive manufacturing: the circular economy of materials and environmental perspectives. Journal of Materials Research and Technology 9(4), 8221-8234. https://doi.org/10.1016/j.jmrt.2020.04.062

Cunico, Marlon Wesley Machado Cavalheiro, P. M., & de Carvalho, J., 2019. Development and characterisation of 3D printing finishing process applying recycled plastic waste. Virtual and Physical Prototyping 14(1), 37-52. https://doi.org/10.1080/17452759.2018.1521248

Dal Fabbro, Pierandrea, La Gala, A., Van De Steene, W., D'hooge, D. R., Lucchetta, G., Cardon, L., & Fiorio, R., 2020. Influence of machine type and consecutive closed-loop recycling on macroscopic properties for fused filament fabrication of acrylonitrile-butadiene-styrene parts. Rapid Prototyping Journal 27(2), 268-277 https://doi.org/10.1108/RPJ-03-2020-0060

Denyer, David, David Tranfield, 2009. Producing a systematic review. The Sage handbook of organizational research methods. Sage Publications Ltd 671–689.

Depalma, K. Walluk, M. R., Murtaugh, A., Hilton, J., McConky, S., & Hilton, B., 2020. Assessment of 3D printing using fused deposition modeling and selective laser sintering for a circular economy. Journal of Cleaner Production 264, 121567. https://doi.org/10.1016/j.jclepro.2020.121567

De Sousa Jabbour, Ana Beatriz Lopes, Jabbour, C. J. C., Godinho Filho, M., & Roubaud, D., 2018. Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. Annals of Operations Research 270(1), 273-286. https://doi.org/10.1007/s10479-018-2772-8

Despeisse, Mélanie, Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S, Minshall, T.H.W., Mortara, L., Reed-Tsochas, F.P. & Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: A research agenda. Technological Forecasting and Social Change 115, 75-84. https://doi.org/10.1016/j.techfore.2016.09.021

Ellen Macarthur Foundation, 2015. Delivering the circular economy: A toolkit for policymakers.

Faludi, Jeremy, Bayley, C., Bhogal, S., & Iribarne, M., 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. Rapid Prototyping Journal 21(1), 14–33. https://doi.org/10.1108/RPJ-07-2013-0067

Ford, Simon, and Mélanie Despeisse, 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. Journal of Cleaner Production 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Garmulewicz, Alysia., Holweg, M., Veldhuis, H., & Yang, A., 2018. Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold? California Management Review 60(3), 112–132. https://doi.org/10.1177/0008125617752695

Gebler, Malte, Anton J. M. Schoot Uiterkamp, Cindy Visser, 2014. A global sustainability perspective on 3D printing technologies. Energy Policy 74, 158–167. https://doi.org/10.1016/j.enpol.2014.08.033

Ghaffar, Seyed Hamidreza, Jorge Corker, Mizi Fan, 2018. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. Automation in Construction 93, 1–11. https://doi.org/10.1016/j.autcon.2018.05.005

Giurco, Damien., Littleboy, A., Boyle, T., Fyfe, J., & White, S., 2014. Circular Economy: Questions for Responsible Minerals, Additive Manufacturing and Recycling of Metals. Resources 3(2), 432–453. https://doi.org/10.3390/resources3020432

Hassani, Vahid, 2020. An investigation of additive manufacturing technologies for development of end-use components : A case study. International Journal of Pressure Vessels and Piping 187, 104171. https://doi.org/10.1016/j.ijpvp.2020.104171

Holmström, Jan, and Timothy Gutowski, 2017. Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? Journal of Industrial Ecology 21, S21–S24. https://doi.org/10.1111/jiec.12580

Huang, Chung-Hung, 2015. Continued evolution of automated manufacturing - Cloud-enabled digital manufacturing. International Journal of Automation and Smart Technology 5(1), 2–5. https://doi.org/10.5875/ausmt.v5i1.861

Ivan, Sobolev, and Yong Yin, 2017. Additive manufacturing impact for supply chain—Two cases. In: 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). p. 450-454. https://doi.org/10.1109/IEEM.2017.8289931

Jiang, Jingchao, 2020. A novel fabrication strategy for additive manufacturing processes. Journal of Cleaner Production 272, 122916. https://doi.org/10.1016/j.jclepro.2020.122916

Jin, Yuan, Jianke Du, Yong He, 2017. Optimization of process planning for reducing material consumption in additive manufacturing. Journal of Manufacturing Systems 44(1), 65–78. https://doi.org/10.1016/j.jmsy.2017.05.003

Kellens, Karel, Baumers, M., Gutowski, T. G., Flanagan, W., Lifset, R., & Duflou, J. R., 2017. Environmental Dimensions of Additive Manufacturing Mapping Application Domains and Their Environmental Implications. Journal of Industrial Ecology 21(1), S49–S68. https://doi.org/10.1111/jiec.12629

Khorram Niaki, M. and Nonino, F., 2017b. Impact of additive manufacturing on business competitiveness: a multiple case study. Journal of Manufacturing Technology Management, (28)1, 56-74. https://doi-org.ez31.periodicos.capes.gov.br/10.1108/JMTM-01-2016-0001

Kim, Yuna, Yoon, C., Ham, S., Park, J., Kim, S., Kwon, O., & Tsai, P. J. (2015b). Emissions of nanoparticles and gaseous material from 3D printer operation. Environmental Science & Technology 49(20). 12044-12053. https://doi.org/10.1021/acs.est.5b02805

Kim, Duck Bong, Witherell, P., Lipman, R., & Feng, S. C., (2015a). Streamlining the additive manufacturing digital spectrum : A systems approach. Additive Manufacturing 5, 20–30. https://doi.org/10.1016/j.addma.2014.10.004

Krippendorff, Klaus, 2018. Content analysis: An introduction to its methodology. Sage Publications.

Kunovjanek, Maximilian, and Gerald Reiner, 2019. How will the diffusion of additive manufacturing impact the raw material supply chain process ? International Journal of Production Research 58(5), 1540–1554. https://doi.org/10.1080/00207543.2019.1661537

Laverne, Floriane, Marquardt, R., Segonds, F., Koutiri, I., & Perry, N., 2019. Improving resources consumption of additive manufacturing use during early design stages: a case study. International Journal of Sustainable Engineering. 12(6), 365-375. https://doi.org/10.1080/19397038.2019.1620897

Le, Van Thao, Henri Paris, Guillaume Mandil, 2018. Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies. International Journal on Interactive Design and Manufacturing 12(2), 525–536. https://doi.org/10.1007/s12008-017-0395-y

Lee, Jian-Yuan, Jia An, and Chee Kai Chua, 2017. Fundamentals and applications of 3D printing for novel materials. Applied materials today 7, 120-133. https://doi.org/10.1016/j.apmt.2017.02.004

Ma, Junfeng. Harstvedt, J. D., Dunaway, D., Bian, L., & Jaradat, R., 2018. An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment. Journal of Cleaner Production 192, 55–70. https://doi.org/10.1016/j.jclepro.2018.04.249

Majeed, Arfan, Zhang, Y., Ren, S., Lv, J., Peng, T., Waqar, S., & Yin, E., 2021. A big data-driven framework for sustainable and smart additive manufacturing. Robotics and Computer-Integrated Manufacturing 67, 102026. https://doi.org/10.1016/j.rcim.2020.102026

Majeed, Arfan, Jingxinang Lv, Tao Peng, 2019. A framework for big data driven process analysis and optimization for additive manufacturing. Rapid Prototyping Journal 25(2), 308–321. https://doi.org/10.1108/RPJ-04-2017-0075

Martinsuo, Miia, and Toni Luomaranta, 2018. Adopting additive manufacturing in SMEs: exploring the challenges and solutions. Journal of Manufacturing Technology Management 29(6), 937–957. https://doi.org/10.1108/JMTM-02-2018-0030

Matsumoto, Mitsutaka, Yang, S., Martinsen, K., & Kainuma, Y., 2016. Trends and research challenges in remanufacturing. International Journal of Precision Engineering and Manufacturing - Green Technology 3(1), 129–142. https://doi.org/10.1007/s40684-016-0016-4

Millard, Jeremy. Sorivelle, M. N., Deljanin, S., Unterfrauner, E., & Voigt, C., 2018. Is the maker movement contributing to sustainability? Sustainability (Switzerland) 10(7). 1-29. https://doi.org/10.3390/su10072212

Nascimento, Daniel Luiz Mattos, Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., & Tortorella, G., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. Journal of Manufacturing Technology Management 30(3), 607–627. https://doi.org/10.1108/JMTM-03-2018-0071

Niaki, Mojtaba, and Fabio Nonino, 2017a. Additive manufacturing management: a review and future research agenda. International Journal of Production Research 55(5), 1419-1439. https://doi.org/10.1080/00207543.2016.1229064

Peng, Tao, Kellens, K., Tang, R., Chen, C., & Chen, G., 2018. Sustainability of additive manufacturing : An overview on its energy demand and environmental impact. Additive Manufacturing 21, 694–704. https://doi.org/10.1016/j.addma.2018.04.022

Rejeski, David, Fu Zhao, Yong Huang, 2018. Research needs and recommendations on environmental implications of additive manufacturing. Additive Manufacturing 19, 21–28. https://doi.org/10.1016/j.addma.2017.10.019

Saboori, Abdollah, Aversa, A., Marchese, G., Biamino, S., Lombardi, M., & Fino, P., 2019. Application of directed energy deposition-based additive manufacturing in repair. Applied Sciences 9(16), 3316. https://doi.org/10.3390/app9163316

Sanchez, Fabio A. Cruz, Boudaoud, H., Camargo, M., & Pearce, J. M., 2020. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. Journal of Cleaner Production, 264, 121602. https://doi.org/10.1016/j.jclepro.2020.121602

Santander, Pavlo Sanchez, F. A. C., Boudaoud, H., & Camargo, M., 2020. Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. Resources, Conservation and Recycling 154, 104531. https://doi.org/10.1016/j.resconrec.2019.104531

Sauerwein, Mariet, and E. L. Doubrovski, 2018. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications 15, 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028

Sauerwein, Mariet, Doubrovski, E., Balkenende, R., & Bakker, C., 2019. Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production 226, 1138-1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Shukla, Manish, Ivan Todorov, and Dharm Kapletia, 2018. Application of additive manufacturing for mass customisation: understanding the interaction of critical barriers. Production Planning and Control 29(10), 814–825. https://doi.org/10.1080/09537287.2018.1474395

Giordani da Silveira, Willian, W., Pinheiro de Lima, E., Gouvea da Costa, S. E., & Deschamps, F., 2017. Guidelines for Hoshin Kanri implementation: Development and discussion. Production Planning and Control 28(10), 843–859. https://doi.org/10.1080/09537287.2017.1325020

Singh, Sunpreet, Seeram Ramakrishna, Munish Kumar Gupta, 2017. Towards zero waste manufacturing: A multidisciplinary review. Journal of Cleaner Production 168, 1230–1243. https://doi.org/10.1016/j.jclepro.2017.09.108

Sitotaw, Dereje, Berihun Ahrendt, D., Kyosev, Y., & Kabish, A. K., 2020. Additive Manufacturing and Textiles—State-of-the-Art. Applied Sciences 10(15), 5033. https://doi.org/10.3390/app10155033

Son, Byung-Gak Sodhi, M., Kocabasoglu-Hillmer, C., & Lee, T. H., 2016. Production Economics Supply chain information in analyst reports on publicly traded companies. International Journal of Production Economics 171, 350–360. https://doi.org/10.1016/j.ijpe.2015.10.011

Stentoft, Jan Philipsen, K., Haug, A., & Wickstrøm, K. A., 2020. Motivations and challenges with the diffusion of additive manufacturing through a non-profit association. Journal of Manufacturing Technology Management. 32(4), 841-861. https://doi.org/10.1108/JMTM-04-2020-0125

Strack, Guinevere, 2019. Additive manufacturing approaches for biological power generation. Current Opinion in Electrochemistry 17, 167–173. https://doi.org/10.1016/j.coelec.2019.06.002

Strange, Roger, and Antonella Zucchella, 2017. value chains and international business. Multinational Business Review 25(3), 174–184. https://doi.org/10.1108/MBR-05-2017-0028

Sun, Luoyi Wang, Y., Hua, G., Cheng, T. C. E., & Dong, J., 2020. Virgin or recycled ? Optimal pricing of 3D printing platform and material suppliers in a closed-loop competitive circular supply chain. Resources, Conservation & Recycling 162, 105035. https://doi.org/10.1016/j.resconrec.2020.105035

Tang, Yunlong, Kieran Mak, and Yaoyao Fiona Zhao, 2016. A framework to reduce product environmental impact through design optimization for additive manufacturing. Journal of Cleaner Production 137, 1560–1572. https://doi.org/10.1016/j.jclepro.2016.06.037

Tian, Xiaoyong, Liu, T., Wang, Q., Dilmurat, A., Li, D., & Ziegmann, G., 2017. Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. Journal of Cleaner Production 142, 1609–1618. https://doi.org/10.1016/j.jclepro.2016.11.139

Tranfield, David, David Denyer, Palminder Smart., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British Journal of Management 14(3), 207-222. https://doi.org/10.1111/1467-8551.00375

Turner, Chris Moreno, M., Mondini, L., Salonitis, K., Charnley, F., Tiwari, A., & Hutabarat, W, 2019. Sustainable production in a circular economy: A business model for re-distributed manufacturing. Sustainability 11(16), 4291. https://doi.org/10.3390/su11164291

Tziantopoulos, Konstantinos Tsolakis, N., Vlachos, D., & Tsironis, L., 2019. Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era. Production Planning and Control 30(7), 510–521. https://doi.org/10.1080/09537287.2018.1540052

Unruh, Gregory, 2018. Circular Economy, 3D Printing, and the Biosphere Rules. California Management Review 60(3), 95–111. https://doi.org/10.1177/0008125618759684

Vidakis, Nectarios Petousis M, Tzounis L, Maniadi A, Velidakis E, Mountakis N, Papageorgiou D, Liebscher M, Mechtcherine V., 2020. Sustainable Additive Manufacturing: Mechanical Response of Polypropylene over Multiple Recycling Processes. Sustainability 13(1), 159. https://doi.org/10.3390/su13010159

Wang, Yuanbin Lin, Y., Zhong, R. Y., & Xu, X., 2019. IoT-enabled cloud-based additive manufacturing platform to support rapid product development. International Journal of Production Research 57(12), 3975–3991. https://doi.org/10.1080/00207543.2018.1516905

Weller, Christian, Robin Kleer, Frank T Piller, 2015. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. International Journal of Production Economics 164, 43-56. https://doi.org/10.1016/j.ijpe.2015.02.020

What is NVivo? Purpose-built for qualitative and mixed-methods research. QSR International, 2019. https://www.qsrinternational.com/nvivo/what-is-nvivo (accessed 21 may 2020)

Woern, Aubrey L., and Joshua M. Pearce, 2017. Distributed manufacturing of flexible products: Technical feasibility and economic viability. Technologies, 5(4), 71. https://doi.org/10.3390/technologies5040071

Yadav, Dinesh Garg, R. K., Ahlawat, A., & Chhabra, D., 2020. 3D printable biomaterials for orthopedic implants: Solution for sustainable and circular economy. Resources Policy 68, 101767. https://doi.org/10.1016/j.resourpol.2020.101767

Yang, Sheng, Min, W., Ghibaudo, J., & Zhao, Y. F., 2019. Understanding the sustainability potential of part consolidation design supported by additive manufacturing. Journal of Cleaner Production 232, 722–738. https://doi.org/10.1016/j.jclepro.2019.05.380

Zhao, Peng, Rao, C., Gu, F., Sharmin, N., & Fu, J., 2018. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. Journal of Cleaner Production 197, 1046-1055. https://doi.org/10.1016/j.jclepro.2018.06.275

Zhong, Shan, and Joshua M. Pearce, 2018. Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. Resources, Conservation and Recycling 128, 48–58. https://doi.org/10.1016/j.resconrec.2017.09.023

# 4 ADDITIVE MANUFACTURING IN THE CIRCULAR ECONOMY CONTEXT: UNDERSTANDING THE INTERACTION BETWEEN CRITICAL BARRIERS.

## 4.1 INTRODUCTION

At the beginning of the 1980s, additive manufacturing (AM) technology, also known as 3D printing, was used almost exclusively for prototyping. However, today, a large number of technologies have been developed for 3D printing, so it is being used for a large number of applications, from industry to medicine (Arrieta-Escobar et al. 2020). Moreover, despite being a new technology, there has been remarkable growth in recent years (3D Hubs 2019). Therefore, it is already possible to find some of its established benefits in the literature, including, for example: the elimination of the need for moulds, which has enabled flexible manufacturing; support for customisation; the ability to produce products with complex designs (Niaki and Nonino 2017); the enablement of product and process innovation; the reduction of the complexity of supply chains; the generation of less waste across the production chain; the reduction of material consumption in manufacturing (Ford and Despeisse 2016; Stentoft et al. 2020); the reduction in transportation required in the supply chain; and the reduction both in wasted inventory and required warehouse space due to the ability to manufacture spare parts on-demand (Martinsuo and Luomaranta 2018).

For companies to adopt AM, it is necessary to identify the applications for which the benefits can best be converted into additional value for producers and customers (Weller 2015). With increasing concern for environmental issues, one of the AM benefits that can be converted into a competitive advantage for companies is sustainable manufacturing (Evans et al. 2017). Therefore, firms are focusing on business models inspired by sustainability principles. The execution of these business plans has offered advantages to producers in relation to accomplishing development plans to decrease resource consumption and pollution along the entire product life cycle (Ren et al. 2019).

A promising approach concerning sustainable operations management intended for sustainable use of resources is the circular economy (CE) (Dev et al. 2020). This approach is currently an essential issue in the manufacturing industry, and interest has grown among companies and academicians (Dev et al. 2020). In a CE environment, products and materials are kept at their highest value for as long as possible by looping them back into the economy (Ellen MacArthur Foundation 2013).

Several authors have argued that AM could provide new design solutions with opportunities for product life extension, as it allows reuse, recovery, and recycling due to its capacity for adjusting products to changing needs and contexts (Sauerwein et al. 2019). In addition, AM could avoid the waste of subtractive models in process fabrication (Ford and Despeisse 2016). However, despite this circular potential of AM, some barriers prevent AM from achieving the principles of the CE. Accordingly, there are several uncertainties regarding AM's alignment with the system redesign preconised by the CE.

There is still little literature that links AM and CE approaches. Some studies have been conducted regarding the sustainability of AM. Earlier studies compared the environmental impacts of the new technology (AM) with conventional manufacturing (Cerdas et al. 2015; Faludi et al. 2015). Subsequently, other studies emerged discussing the environmental impacts and sustainability of the technology (Gebler et al. 2014; Kellens et al. 2017; Rejeski et al. 2018; Tang et al. 2016).

Franco et al. (2020) pointed out that the literature concerning AM's effect on sustainability indicators remains inconclusive. Some authors have demonstrated that AM adoption reduces negative environmental impacts. Gebler et al. (2014) showed that industrial manufacturing's energy and CO2 emission intensities are reducible by up to 5% through AM by 2025. Further, other authors have asserted that AM can lead to material and energy savings (Despeisse et al. 2017; Niaki and Nonino 2017). Ford and Despeisse (2016) argued that the environmental impact of logistics can be reduced by implementing basic materials in AM. They concluded that AM could contribute to the transition toward more sustainable manufacturing. However, other results suggest a possible negative environmental impact of AM. For example, the ease and freedom of 3D printing may encourage increased consumption (Ford and Despeisse 2016). Thus, AM growth could lead to an alternative scenario of instant gratification and wastage. Cerdas et al. (2017) highlighted the increase in general consumption, mainly in fashion products, as companies can increase consumption by offering higher degrees of customisation. Further, AM often uses virgin plastics derived from fossil fuels (Behm et al. 2018) and the suitable materials for AM are mostly non-biodegradable (Arrieta-Escobar et al. 2020). Finally, many authors have identified the potential toxicity of some materials utilised in 3D printing (Chen et al. 2020; Rejeski, Zhao, and Huang 2018). Therefore, the environmental impact caused by AM has some crucial issues that need to be solved before AM can become a cleaner technology. Therefore, for AM to meet CE requirements, it needs to overcome such barriers.

Implementing a CE goes beyond only focusing on environmental or sustainable impacts, as the sustainability of AM does not automatically lead to products that work well in a CE (Sauerwein et al. 2019). Retaining the value of resources at the end of their life cycle is necessary to capitalise on the circular process (Ghisellini et al. 2016). However, studies linking AM and CE are in their early stage of development. Some recent studies have begun to explore this relationship (Despeisse et al. 2017; Ponis et al. 2021; Sanchez et al. 2020; Sauerwein et al. 2020).

Most studies linking the themes, however, have only addressed one or a few levers of the CE implementation methodology. For example, the recycling aspect of a CE has often been highlighted in works focusing on AM. Garmulewicz et al. (2018) provided a significant contribution by studying the locally distributed AM production of new products from recycled materials. These authors elaborated on many recycling barriers that the technology faces. Zhong and Pearce (2018) studied recycled plastic waste in 3D printing filaments. Sanchez et al. (2020) studied the opportunities that recycled plastic used in AM bring to the CE. Vidakis et al. (2020) studied the mechanical response of a material in multiple recycling processes used in 3D printing. Notably, no empirical studies have addressed the implementation of circular AM considering the wide levers of a CE context.

To guide CE implementation, the Ellen Macarthur Foundation (2015) published the widely used report "Delivering the circular economy, a toolkit for policymakers". This report describes a methodology for formulating CE policies through the ReSOLVE framework. The framework identifies six areas of action for companies that wish to move toward a CE and serves as a practical approach to help organisations implement CE principles. The six actions to implant CE are: regenerate; share; optimise; loop; virtualise; and exchange (Ellen MacArthur Foundation 2015). Our study intends to fill this literature gap by involving all the ReSOLVE actions proposed by the Ellen MacArthur Foundation (2015) for the implementation of AM in a CE context.

To achieve the proposed goals, our study uses a systematic literature review (SLR) to reveal the barriers that AM technology imposes on a CE, and a combination of the fuzzy logic with a multi-criteria decision making (MCDM) approach and the DEMATEL (DEcision MAking Trial and Evaluation Laboratory) method to examine the interdependency between the barriers. Through the analysis of such dependencies, we propose a framework to guide stakeholders to overcome these barriers, making AM a more circular technology.

To achieve this aim, the following research questions (RQs) are posed:

RQ1: Which barriers hinder circular AM?

RQ2: What are the relationships between such barriers?

RQ3: What can the main stakeholders do to overcome such barriers?

In this article, we consider both intrinsic and extrinsic barriers to the technology to obtain a macro view of what limits AM's circularity potential. We consider as intrinsic barriers all those provided by AM characteristics, and extrinsic barriers as those that limit the potential of the technology's circularity but that are not related to its characteristics. These barriers are related to political, social, environmental, or educational characteristics in which technology is inserted. Furthermore, we also identify barriers influenced by the degree of maturity of the technology, which is relatively new.

Some previous works have already highlighted some AM barriers. Stentoft et al. (2020) identified several AM barriers and showed how they can be reduced. Ford and Despeisse (2016) included the sustainability aspect and studied the advantages and challenges of AM for sustainability. Although previous studies have reported the existence of AM barriers for the CE and sustainability (Despeisse et al. 2017; Ford and Despeisse 2016), our research systematises the state of art of this topic, clearly presenting the barriers' definitions, validated by experts with AM and CE experience.

Our study also presents the relationship between these barriers. To the best of our knowledge, no other research has presented the relationships between the AM barriers for the CE. By understanding such relationships, it is possible to develop strategies for a circular AM.

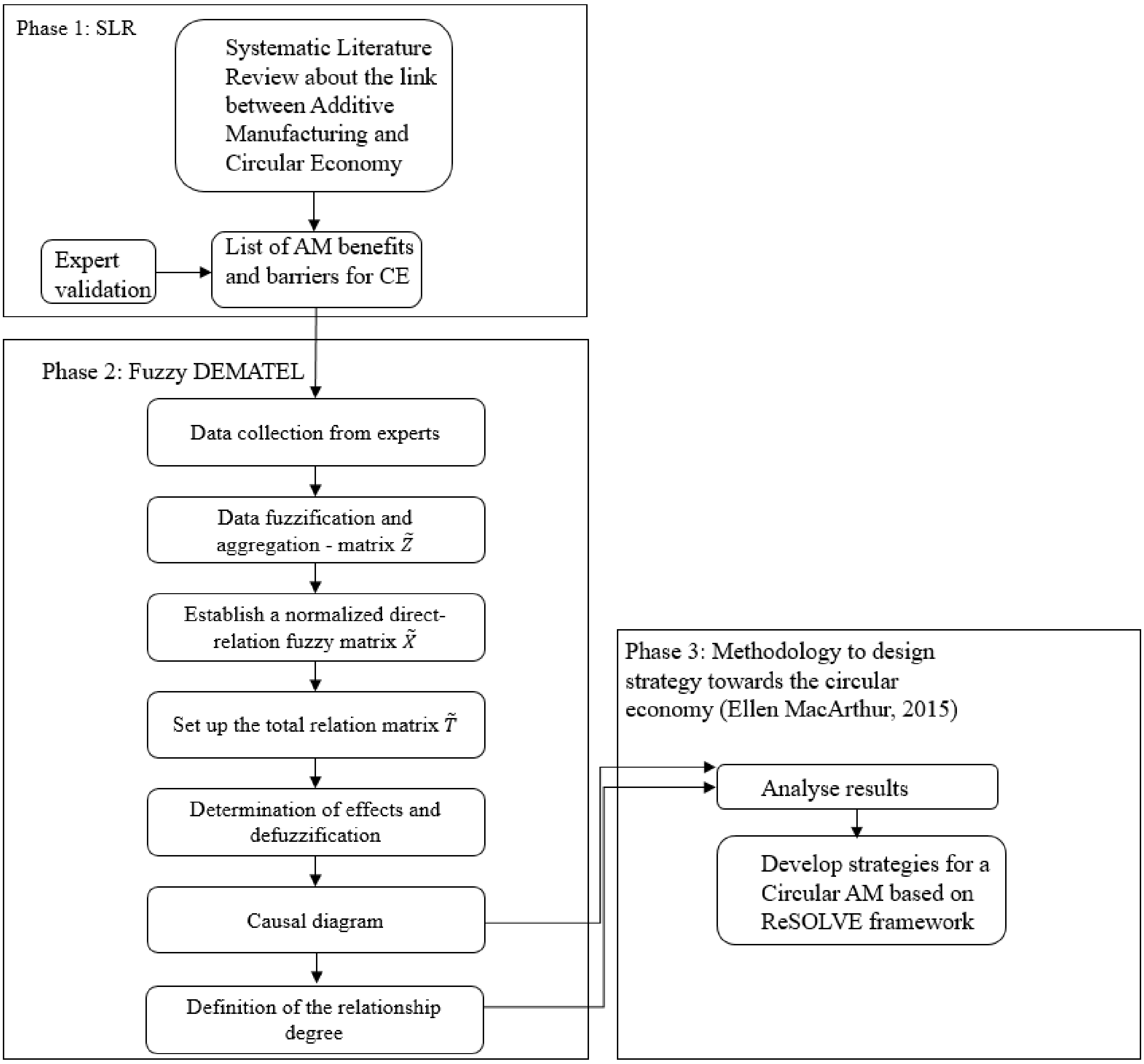
This remainder of this article is organised as follows. Section 2 details the research method. Section 3 provides the results. Section 4 discusses the results and presents the proposed framework. Finally, Section 5 provides conclusions.

## 4.2 RESEARCH METHOD

### 4.2.1 Overview of the Research Method

This study is classified as mixed-method research. This term is used to represent research that integrates quantitative and qualitative techniques in the same research design (Creswell and Plano Clark 2011). Our study followed three phases: first, we conducted a SLR to identify benefits and barriers that AM brings to the CE; second, we used fuzzy DEMATEL to establish the relationship between the barriers, and third we analyse the results to elaborate strategies and action takers. Figure 4.1 illustrates these research phases.

**Figure 4.1** – Research methods



### 4.2.2 Systematic Literature Review

A SLR approach was used to analyse and understand the state of the art on how the phenomenon of AM adoption meets or does not meet the requirements of a CE. We followed the three steps determined by Denyer and Tranfield (2009) to conduct this review. In the first stage, we developed the SLR review plan, the protocol, research questions, and inclusion/exclusion criteria. The literature review was conducted in the second stage with the string definition and article selection from databases. Finally, the articles were classified in the third stage, and a qualitative analysis of the content was performed. NVivo 12 Plus software was used to analyse the content of the articles.

The search was performed using the Scopus, Web of Science, and Engineering Village databases. The search string was a combination of two groups of keywords: those referring to AM (3D printing, additive manufacturing, additive technique, additive process, digital manufacturing, additive fabrication, three dimensional printing, rapid manufacturing, rapid tooling, rapid prototyping, layered manufacturing, digital fabrication); and those referring to CE (circular economy, share, lifespan, regenerate, renewable energy, optimise, loop, recycle, virtualise, virtual product, exchange, reduce, reuse, remanufacture). To choose the CE keywords, we also used words related to the ReSOLVE framework to ensure that even works relating to only one of the actions of CE implementation would be added to our data. After the first filter, which consisted of reading titles and abstracts of the data collected from the databases, 115 articles were selected for a full reading. From these, 69 articles were selected for qualitative analysis (see Appendix A).

Only papers in English were selected to guarantee quality and accessibility. Also, all papers had to be published in a peer-reviewed scientific journal. In addition, the main inclusion criterion for selecting a paper was that it should deal with AM related to the CE or some principle of the ReSOLVE framework in the context of operations management, sustainability, supply chain management, and/or the environment.

### 4.2.3 Fuzzy DEMATEL method

The fuzzy DEMATEL method was used to analyse the relationships among interdependent barriers in this research. The aim of analysing these relationships is to provide some strategies for mitigating them. DEMATEL has been widely used in sustainability-related studies (Bai et al. 2017; Lin 2013; Mavi and Standing 2018; Venkatesh et al. 2017; Zhang et al. 2019). Of course, other multicriteria decision-making methods, such as interpretive structural modelling (ISM) and analytic hierarchy process (AHP) can also be used for this aim, but the decision to use fuzzy DEMATEL was based on the following reasons.

1) DEMATEL is a multi-criteria decision-making method for identifying and prioritising the causal relationships among the components of a system. Unlike other methods, such as ISM and AHP, DEMATEL has the advantage of providing the view of the causal relationships and revealing the overall degree of influence wielded by the factors (Venkatesh et al. 2017).
2) Further, we used fuzzy DEMATEL, the fuzzy set extension to the standard DEMATEL technique. As DEMATEL uses the decision makers' opinions to compare the most relevant criteria for solving a complex problem, we used the fuzzy approach to deal with the uncertainty of their judgments in the decision-making process (Falatoonitoosi et al. 2013). This alternative makes it possible to mathematically express and handle the vagueness and imprecision in human judgments (Lin 2013; Wu and Lee 2007).

Based on these advantages, DEMATEL was applied to determine the effect and cause criteria, with the fuzzy approach handling the uncertainty of human subjectivity. In this way, the model was obtained in terms of linguistics parameterised with fuzzy triangular numbers, with triangular ones being the most used due to their simplicity and computational efficiency proportioned (Siler and Buckley 2005; Wu and Lee 2007).

#### 4.2.3.1 The DEMATEL Method and Fuzzy set theory

DEMATEL is a method that builds and analyses the influence and relationships between variables (Hsu et al. 2013). It is an appropriate tool for helping companies make assertive decisions based on pre-established criteria. DEMATEL was first used by Fontela and Gabus in 1971 in the Science and Human Affairs Program to solve a complex problem. The tool made it possible to extract quantitative interrelationships between multiple factors to solve a problem (Falatoonitoosi et al. 2013; Gharakhani et al. 2014; Panahifar 2015).

Collecting the group's knowledge makes it possible to analyse the interrelationships between the factors and visualise the cause–effect relationship diagram (Gabus and Fontela 1972). According to Shimizu (2010), the method is intended for the elaboration and evaluation of a hierarchical structure based on expert opinion to obtain: (a) the level of relationship that an element *i* exerts on another element *j*; and (b) the level of the relationship that an element *j* receives from another element *i*.

Hsu et al. (2013) highlighted that the influence relationships between all attributes are evaluated equally. The attributes are compared in pairs, and grades are assigned, representing the influence relationship that one attribute exerts on the other. For this, an ordinal categorical qualitative scale with linguistic terms is used. The scale expresses different degrees of influence. Most works using the DEMATEL method have used a numerical scale from 0 to 4 to represent the influences chosen for the research (see Table 4.1 for an example).

**Table 4.1 -** Ordinal qualitative scale.

| Linguistic terms | Abbreviation | Numerical scale |
|---|---|---|
| No influence | N | 4 |
| Very low influence | VL | 3 |
| Low influence | L | 2 |
| High influence | H | 1 |
| Very high influence | VH | 0 |

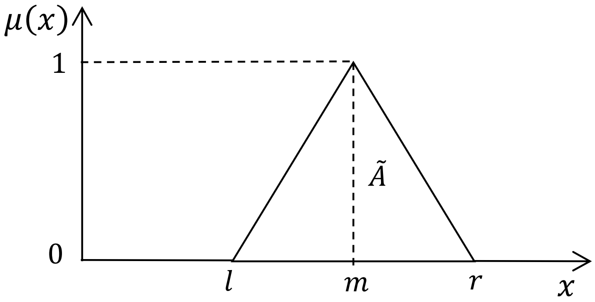
**Source:** Gabus and Fontela, 1972.

DEMATEL identifies the most important criteria for the problem analyzed. Therefore, managers can improve their decisions, restricting the number of variables analyzed and focusing on the most relevant criteria. The causal diagram separates criteria into the cause and effect groups. Thus, it shows the most influential and the most dependent criteria, providing valuable information for decision-making. However, as DEMATEL inputs are based on expert judgments through the paired comparison, there is a level of uncertainty and imprecision. As an alternative, we represent these variables through fuzzy logic (Wu and Lee, 2007).

The fuzzy set theory and fuzzy logic were introduced by Lotfi Zadeh in the 1960s and 1970s, aiming to treat vague or inaccurate information mathematically. Since then, fuzzy logic has been used in various applications, solving real-world problems. According to Zadeh (1973), when the complexity of the system increases, the ability of human beings to describe the system's behaviour decreases. Thus, complex problems cannot be translated into numbers, and the solution would be fuzzy set labels.

Triangular Fuzzy Numbers (TFN) are the most used due to their simplicity and computational efficiency proportioned (Wu and Lee, 2007). A triangular fuzzy number (TFN) is defined by three values (l, m, r) where $l \leq m \leq r$. Fig. 2 shows a TFN given by Eq. (1) and figure 4.2.

**Figure 4.2 -** Triangular fuzzy number



$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x \le l \\ \frac{x-l}{m-l}, & l \le x \le m \\ \frac{x-r}{m-r}, & m \le x \le r \\ 0, & x \ge r \end{cases}$$

**(1)**

Considering two triangular fuzzy numbers $\tilde{A}_1 = (l_1, m_1, r_1)$ and $\tilde{A}_2 = (l_2, m_2, r_2)$, and K any constant, the operations are highlighted in Eq. (2) to Eq. (6) (Chen, 2000; Zadeh, 1965):

$$(l_1, m_1, r_1) \oplus (l_2, m_2, r_2) = (l_1 + l_2, m_1 + m_2, r_1 + r_2) \tag{2}$$

$$(l_1, m_1, r_1) \ominus (l_2, m_2, r_2) = (l_1 - r_2, m_1 - m_2, r_1 - l_2) \tag{3}$$

$$(l_1, m_1, r_1) \otimes (l_2, m_2, r_2) = (l_1 l_2,\ m_1 m_2,\ r_1 r_2) \tag{4}$$

$$k.(l_1, m_1, r_1) = (k.l_1, k.m_1, k.r_1) \tag{5}$$

$$(l_1, m_1, r_1)^{-1} = (1/r_1, 1/m_1, 1/l_1) \tag{6}$$

4.2.3.2 Fuzzy DEMATEL steps

The Fuzzy-DEMATEL method is beneficial in finding out the relationships among factors and ordering the criteria based on the type of relationships and severity of criteria effects on each other. Based on these, DEMATEL is applied to determine the effect and cause criteria, and fuzzy to obtain the model in terms of linguistics parameterized with fuzzy triangular numbers. In the end, the causal diagram provides the degree of importance and influence of each criterion (the barriers in our case). This way, it is possible to develop proper strategies for reducing the barriers of AM to circularity. The main steps of the method are defined as follows (Wu and Lee, 2007; Akiuz and Celik, 2015; Mavi and Standing, 2018).

**Step 1: Definition of expert team**

In this step, the decision-makers of the process must define the goals and the relevant information. The “n” factors or barriers will be selected to solve the problem. The experts are also formed to evaluate the barriers raised on the SRL.

In our research, the data were collected through a questionnaire with four sections that took an average of 40 minutes to answer. It took over a period of four months (June to September 2021) to collect the data. We pre-selected a group of 64 experts and sent them an invitation email. From that group, just Brazilian specialists accepted to participate. So, 24 expert opinions were considered. This group was composed of experts from Academia, with vast academic knowledge (17 specialists) and from industries that apply Additive manufacturing in their daily work, also acting with sustainable issues (7 specialists). The expert's profiles are shown in Table 4.2.

Before sending the questionnaire, meetings were conducted with the experts (through google meet) to explain the research, the questionnaire, and how it should be completed. The first section queried about the expert’s profile. The second section was informative and presented the list of barriers raised by the literature with their respective definitions. The third section contained the necessary structure to fill in the DEMATEL matrix. Furthermore, the fourth section presented questions for research validation. In the validation section, the specialists were asked if they agreed with the barriers presented in the literature and if there were any missing competencies that they could identify. All 24 specialists agreed with the barriers presented and did not identify any missing barriers.

**Table 4.2** – Experts´profiles

| **Expert** | **Position** | **Academic Background** | **Experience with Additive Manufacturing** | **Experience with Circular Economy/Sustainability** |
|---|---|---|---|---|
| 1 | Research | PhD in Mechanical Engineering | 7 years | 9 years |
| 2 | Research | PhD in Industrial Engineering | 3 years | 6 years |

| | | | | |
|---|---|---|---|---|
| 3 | Research | PhD in Industrial Engineering | 9 years | 4 years |
| 4 | Research | PhD in Industrial Engineering | 6 years | 7 years |
| 5 | Research | PhD in Industrial Engineering | 5 years | 1 year |
| 6 | Research | PhD in Industrial Engineering | 3 years | 12 years |
| 7 | Research | PhD in Industrial Engineering | 6 years | 10 years |
| 8 | Research | PhD in architecture | 17 years | 10 years |
| 9 | Research | PhD in Energy and Environmental Planning | 3 years | 4 years |
| 10 | Research | PhD in Mechanical Engineering | 6 years | 10 years |
| 11 | Research | PhD in Industrial Engineering | 9 years | 11 years |
| 12 | Research | PhD in Industrial Engineering | 5 years | 3 years |
| 13 | Research | PhD in Industrial Engineering | 5 years | 9 years |
| 14 | Research | PhD in Industrial Engineering | 5 years | 2 years |
| 15 | Research | PhD in Management Science | 8 years | 10 years |
| 16 | Research | PhD in Chemistry | 3 years | 2 years |
| 17 | Research | PhD in Mechanical Engineering | 5 years | 8 years |
| 18 | CEO | Bachelor´s Degree | 6 years | 4 years |
| 19 | Coordinator at an AM company | Engineer´s Degree | 4 years | 1 year |
| 20 | Founding Partner at an AM company | Master´s Degree | 3 years | 2 years |
| 21 | Manager at an AM company | Master´s Degree | 4 years | 2 years |
| 22 | Research coordinator at an AM company | Master´s Degree | 15 years | 5 years |
| 23 | Founding Partner at an AM company | PhD in aeronautical and mechanical engineering | 4 years | 2 years |

| | | | | |
|---|---|---|---|---|
| 24 | Research coordinator at an AM company | Engineer´s Degree | 6 years | 3 years |

**Step 2: Surveying the respondents.**

In this step it was structured a pair-wise comparison matrix. Each participant was asked to assess the impact barrier i has on barrier j. To assess the influence of one criterion on another, a scale of linguistic terms presented in Table 4.3 was used. The second column shows the corresponding triangular fuzzy number for each of the five linguistic terms. The judgments of each of the $p$ experts will provide the construction of each direct-relation matrixes $E^{k}$, where k = 1,2,…, $p$.

**Table 4.3-** Fuzzy linguistic scale for assessing the influence relationships

| Linguistic Terms | Triangular fuzzy number |
|---|---|
| No influence | (0, 0, 0.25) |
| Very Low Influence | (0, 0.25, 0.5) |
| Low Influence | (0.25, 0.5, 0.75) |
| High Influence | (0.5, 0.75, 1) |
| Very High Inflience | (0.75, 1, 1) |

Source: Wu, 2012

**Step 3: Establish a normalized direct-relation fuzzy matrix.**

At this stage, the average of the $p$ experts' opinions is calculated, as shown in Eq. (7). After this, a normalized direct-relation fuzzy matrix is built up. To obtain the normalized form $\tilde{X}$, the sum of the values of each row or column can not be greater than 1. The normalized matrix $\tilde{X}$ is obtained using Eqs. (8) and (9).

$$\tilde{z}_{ij} = \frac{\tilde{z}_{ij}^{1} \oplus \cdots \oplus \tilde{z}_{ij}^{k} \oplus \cdots \oplus \tilde{z}_{ij}^{p}}{p} \tag{7}$$

$$\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{s} = \left(\frac{l_{ij}}{s}, \frac{m_{ij}}{s}, \frac{r_{ij}}{s}\right) \tag{8}$$

$$s = max_{1 \le i \le n}\left(\sum_{j=1}^{n} r_{ij}\right) \tag{9}$$

**Step 4: Calculate the total-relation fuzzy matrix**.

After having established normalized direct-relation fuzzy matrix $\tilde{X}$, a total relation fuzzy matrix $\tilde{T}$ is calculated. To this, matrix $\tilde{T}$ is calculated using Eqs. (10) to (13), where I represent the identity matrix, of size n.

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \cdots & \tilde{t}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \cdots & \tilde{t}_{nn} \end{bmatrix}, \text{where } \tilde{t}_{ij} = (l_{ij}, m_{ij}, r_{ij}) \quad \textbf{(10)}$$

$$matrix[l_{ij}] = X_l \times (I - X_l)^{-1} \quad \textbf{(11)}$$

$$matrix[m_{ij}] = X_m \times (I - X_m)^{-1} \quad \textbf{(12)}$$

$$matrix[r_{ij}] = X_r \times (I - X_r)^{-1} \quad \textbf{(13)}$$

**Step 5: Calculation of effects**

The effect exerted by the $i$-th barrier $\tilde{d}_i$ can be calculated through the total relation matrix $\tilde{T}$ by Eq. (14). Also, the total effect received by the $j$-th barrier $\tilde{r}_j$ can be determinate by Eq. (15). The degree of importance of the $i$-th Barrier on Circular Economy is represented by $(\tilde{d}_i + \tilde{r}_i)$. Likewise, the vertical axis $(\tilde{d}_i - \tilde{r}_i)$ categorizes the barriers into cause and effect sets, and represents the net effect contributed by the $i$-th barrier on Circular Economy.

$$\tilde{d}_i = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} r_{ij}\right) \quad \textbf{(14)}$$

$$\tilde{r}_j = \left(\sum_{i=1}^{n} l_{ij}, \sum_{i=1}^{n} m_{ij}, \sum_{i=1}^{n} r_{ij}\right) \quad \textbf{(15)}$$

**Step 6: Defuzzification**

However, the final results of $\widetilde{D}_i + \tilde{R}_i$ and $\widetilde{D}_i - \tilde{R}_i$ are still in fuzzy triangular numbers (FTN). To facilitate our analysis, the results must be defuzzified by using CoA (Center of Area). According to Si et al. (2018), CoA of a triangular fuzzy numbers $\tilde{A} = (l, m, r)$ can be given by Eq. (17). The CoA is the most assertive method and the most reliable among the most common procedures (Chu et al., 2004)

$$CoA = \frac{l+m+r}{3} \quad \textbf{(16)}$$

### Step 7: Producing a causal diagram and analyzing results

After the defuzzification, we obtain $(\widetilde{D}_i + \tilde{R}_i)^{def}$ and $(\widetilde{D}_i - \tilde{R}_i)^{def}$. Therefore, it is possible to produce a causal diagram to analyse results. The term $(\widetilde{D}_i + \tilde{R}_i)^{def}$ represents the degree of importance of barrier i on the problem and it is called “Prominence” or “Importance”. On the other hand, the term $(\widetilde{D}_i - \tilde{R}_i)^{def}$represents the influence of barrier i on the others and it is called “Relation”. This then categorizes the barriers into cause and effect sets. When $(\widetilde{D}_i - \tilde{R}_i)^{def}$ is positive, the barrier is a cause one. Likewise, if it is negative, the barrier is the effect factor.

The causal diagram will define the most prominent barriers and classify them into cause (the upper part group on diagram) or effect (the lower part group on diagram) group.

### Step 8: Defining the relationship degree

To add information to our analisys, this paper presents the relationship degree between the barriers. To analyse stronger relationships, we settled a threshold. Setting a reasonable threshold is critical to providing the necessary information for decision-making as it allows us to focus on significant effects (Feng and Ma, 2020).

Thresholds can be determined by a variety of solutions. Usually, it can be determined by decision-makers or through expert discussion. However, different scholars have also proposed other solutions, such as the maximum mean difference entropy method (Li and Tzeng, 2009), the subjective method (Chang et al., 2011), and the calculation of the mean of the comprehensive influence matrix (Shieh et al., 2010).

The present paper sets the threshold around the mean ± standard deviation. Other authors have already set the threshold value by adding the mean with standard deviation (Feng and Ma, 2020; Farooque et al., 2020; Zhang et al. 2019). By analyzing and comparing, our final threshold was set at the mean + 1.5 standard deviations (0.503).

### 4.2.4 Strategies to ensure the data reliability and validity

In this research, we used a qualitative approach for collecting data to ensure the validity and reliability of the work.

First of all, to determine the accuracy of the SLR findings, we took the final list with their descriptions to 3 experts, who could check the accuracy. Then, we send a pilot test to then to obtain feedback. They made minor revisions to the data collections instrument to avoid potential misunderstanding. Additionally, the 24 experts who participated in our study had the opportunity to validate the list. As a minimum point of ambiguity or misunderstanding was pointed out, we incorporated it into the collection instrument to be updated to the next expert. Also, we provide experts with clear and objective descriptions of each barrier. This avoided misinterpretation by the respondents, adding validity to the research.

The meetings between the researcher and experts aimed to clarify the research objective, introduce the questionnaire, and explain the filling of the DEMATEL matrix. The experts filled the questionnaire individually and without the researcher's influence, spending the time they needed to answer. In this way, we ensured that our research was carried out with the least possible bias.

Additionally, the experts invited to participate were carefully chosen. The expert should have experience with additive manufacturing technology and Circular Economy or sustainable issues. Academic and industry experts with different experiences and backgrounds who worked in different companies and held different positions were selected. The only industry experts selected were those working with Additive Manufacturing and engaged in sustainable issues within the company. All this ensured the heterogeneity and experience of the respondents.

Finally, the different sources of information (reports, researchers, experts, and other data sources) were triangulated to develop accuracy and coherent justification for the themes. This process can be claimed to add to the validity of the study.

## 4.3 RESULTS

### 4.3.1 Systematic Literature Review

As the result of the SLR, we obtained the list of barriers that prevent AM from reaching The CE (see table 4.4). It was found 13 barriers that AM brings to circularity. Then, the barriers list and definitions were validated by experts. In addition, we identified some works pointing to benefits that AM brings to circularity. These works were grouped into 15 benefits AM brings to circularity (see Appendix B). However, due to the immaturity of AM technologies, their wider adoption and the realization of these benefits depends on overcoming the significant barriers highlighted.

**Table 4.4** – Main barriers that AM brings to CE.

| **Code** | **Barriers** | **Definition** | **SLR References** |
|---|---|---|---|
| B1 | Lack of eco-friendly AM legislation and public policies. | There are situations in which the use of AM can generate waste and risks. The literature does not mention specific laws or regulations that provide incentives, for example, for the reuse or recycling of this waste. Also, AM technology can generate negative environmental impacts, such as harmful emissions in the form of ultrafine particles and volatile organic compounds in some options of materials used. There are no standards laws and/or public policies that describe the choice of materials to guarantee sustainability and environmental and people health. | 19; 20; 61 |
| B2 | Lack of strategic alignment in the adoption of AM to achieve circular business models. | Because of emerging AM technologies, it is necessary to rethink the business model adopted by companies. There is a lack of empirical evidence on how companies can use AM to meet Circular Economy requirements. Companies that adopt must strategically consider promoting more sustainable actions. | 4; 7; 15; 39 |
| B3 | Lack of skills, experience, and awareness of AM printers. | The use of AM technologies in companies that adopt circular business models implies a redefinition of their organizational culture, aiming at greater awareness and development of workers' skills. The lack of skills, experience and awareness of workers can lead to incorrect use of AM technology, which can result in risks and waste. | 8; 17; 20; 21; 38; 49 |

| | | | |
|---|---|---|---|
| B4 | Possibility (risk) of irresponsible or excessive consumption of 3D printed products. | AM allows customers to co-design products that can best meet their demands and ambitions. This characteristic of freedom makes room for the excessive production of personalized goods; for the design of products that lead to waste, and for the design of products that could pose risks to people's safety and lives, as consumers are free to print with many materials and with printers that have different specifications. | 4; 8; 19; 22; 23; 61 |
| B5 | Toxicological risks associated with the use of AM | Depending on the type of material and technique used in 3D printing, ultrafine particles and volatile organic compounds are released or emitted. This is harmful to both the environment and workers. | 2; 9; 10; 28;30;43 |
| B6 | Low printing/production pace with currently available AM technology. | Circular Economy literature describes the growth of efficiency and performance for its implementation. However, most current used AM machines, such as most of FDM and SLA machines are relatively slow and inefficient, requiring a longer production time. Also, many techniques still need post-processing, which increases the production time. | 19; 24; 51; 55 |
| B7 | Lack of standardization of materials and poor quality of items produced by AM technologies. | The literature highlights that, due to the lack of technical standards, the printing of an item through additive manufacturing can result in lower quality indices. Also, for most used industrial techniques (SLS and FDM), there is frequently a problem of thermal degradation during the process, which affects the material properties and consequently, the product quality. An example is the 3D printing processes of polymers via extrusion, which have relatively low quality. This results in an uncertain performance of products and components manufactured by 3D printing. | 16; 17; 19; 43; 62 |
| B8 | Limitation on the number of Technical cycles of materials used in AM | Materials used in 3D printing suffer degradations at the printing processes that affect their properties, which limits the repeatability of 3D printing. One example is the products extruded with polymers. Also, Recycling cycles are limited because when materials undergo significant thermal degradation during some AM techniques (FDM, for example) their properties are altered, making it difficult to reuse or limiting the number of recycling cycles. | 16; 14;19; 20; 56; 61;62; 68 |
| B9 | Low acceptance of recycled AM raw materials | Most companies and users of 3D printing have a low willingness to consume recycled material as a raw material for AM. As reported in the literature, they prefer to use virgin materials rather than recycled ones. There is a tendency to avoid using recycled material because of concerns regarding the degradation of the quality and the uncertainty regarding the consistency of the diameter and the mechanical properties of the recycled filaments, which directly affect the quality of the final product. | 16; 56; 68; 69 |

| | | | |
|---|---|---|---|
| B10 | Limited availability of recycled materials for AM and limited efficiency of small-scale recycling technologies | Recycling 3D printed products and materials are very challenging since there are some barriers. The general lack of materials that are suitable for recycling in order to be used in 3D printing is seen as a major barrier for AM recycling, second the literature. Also, Recycling processes become more efficient at a larger scale, which favors centralized recycling facilities. Because of that, there is an absence of machines suitable for small-scale recycling. | 19;20; 48; 56 |
| B11 | Lack of sufficient match between novel materials and current 3D printing technologies | Circular Economy implementation literature highlights the production and choice of new products and materials as leverage for its implementation. In AM, novel materials are defined as a group of advanced materials that can be 3D printed for specific new applications. Due to the immaturity of the technology, all the new printers or processes for novel materials have not gone beyond the seven categories of techniques and most still working with a single material with limited industrial applicability. This inhibits sustainable innovative solutions considering a range of different materials and combinations of these. | 19; 34; 35 |
| B12 | High investment in AM raw material | Additive Manufacturing cannot yet be considered a consolidated technology. One of the main barriers is the high prices of raw materials. Although 3D printing of parts is economical compared to conventional manufacturing processes, raw material preparation attributes high cost. In addition, most of the machines are still patented, and this exclusiveness hinders price reduction. Because of this, it can be difficult to adopt the technology in some cases. If circular 3D printing activities are not economically viable, the benefits AM brings to CE will not happen. | 19; 42; 64 |
| B13 | High unit cost of manufacturing AM | The unit cost of Additive Manufacturing is relatively higher when compared to the unit cost of traditional manufacturing. This aspect constitutes one of the main obstacles to the effective use of 3D printing, which, therefore, limits its applicability to promote circular practices. | 19;64 |

### 4.3.2 Fuzzy DEMATEL results

The respondents investigated the interaction among each pair of barriers, provided in Table 3, which was also used to assist them. When we received the answers, the linguistic terms were converted into FTNs.

The calculation of the average of the 24 experts' opinions resulted in matrix $\tilde{Z}$. After that, it was necessary to convert matrix $\tilde{Z}$ into its normalized form, through Eqs. (8) and (9), obtaining matrix $\tilde{X}$. Matriz $\tilde{X}$ is presented in Table 4.5.

After having established normalized direct-relation fuzzy matrix $\tilde{X}$, a total relation fuzzy matrix $\tilde{T}$ was calculated using Eqs. (10) to (13). This was step 4, and the matrix $\tilde{T}$ is presented in Table 4.6.

**Table 4.5 -** Matrix $\tilde{X}$.

| | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | B11 | B12 | B13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **B1** | (0, 0, 0) | (0.04, 0.07, 0.09) | (0.02, 0.03, 0.06) | (0.04, 0.07, 0.1) | (0.06, 0.09, 0.11) | (0, 0.01, 0.04) | (0.01, 0.02, 0.05) | (0.04, 0.06, 0.08) | (0.04, 0.06, 0.09) | (0.04, 0.06, 0.09) | (0.02, 0.03, 0.06) | (0.01, 0.03, 0.06) | (0.01, 0.02, 0.05) |
| **B2** | (0.02, 0.04, 0.07) | (0, 0, 0) | (0.05, 0.08, 0.1) | (0.05, 0.07, 0.1) | (0.04, 0.06, 0.09) | (0.02, 0.04, 0.07) | (0.02, 0.04, 0.07) | (0.03, 0.05, 0.08) | (0.05, 0.08, 0.1) | (0.04, 0.07, 0.09) | (0.03, 0.05, 0.08) | (0.03, 0.05, 0.08) | (0.03, 0.05, 0.08) |
| **B3** | (0.01, 0.03, 0.06) | (0.03, 0.05, 0.08) | (0, 0, 0) | (0.05, 0.08, 0.09) | (0.05, 0.07, 0.09) | (0.04, 0.06, 0.09) | (0.05, 0.08, 0.1) | (0.02, 0.05, 0.07) | (0.03, 0.05, 0.08) | (0.01, 0.03, 0.06) | (0.01, 0.03, 0.06) | (0.02, 0.05, 0.07) | (0.03, 0.06, 0.08) |
| **B4** | (0.03, 0.05, 0.07) | (0.02, 0.04, 0.07) | (0.02, 0.04, 0.07) | (0, 0, 0) | (0.03, 0.05, 0.08) | (0.02, 0.04, 0.07) | (0.02, 0.05, 0.08) | (0.02, 0.04, 0.06) | (0.02, 0.04, 0.06) | (0.02, 0.04, 0.06) | (0.01, 0.03, 0.06) | (0.02, 0.03, 0.06) | (0.02, 0.04, 0.07) |
| **B5** | (0.05, 0.07, 0.09) | (0.04, 0.06, 0.09) | (0.03, 0.06, 0.08) | (0.03, 0.05, 0.08) | (0, 0, 0) | (0.02, 0.03, 0.06) | (0.02, 0.03, 0.06) | (0.03, 0.05, 0.08) | (0.03, 0.06, 0.08) | (0.03, 0.05, 0.07) | (0.03, 0.05, 0.07) | (0.02, 0.03, 0.06) | (0.02, 0.04, 0.06) |
| **B6** | (0.02, 0.04, 0.06) | (0.03, 0.06, 0.08) | (0.03, 0.05, 0.08) | (0.02, 0.05, 0.08) | (0.01, 0.03, 0.06) | (0, 0, 0) | (0.03, 0.06, 0.08) | (0.02, 0.04, 0.07) | (0.02, 0.05, 0.07) | (0.02, 0.05, 0.07) | (0.03, 0.05, 0.08) | (0.04, 0.06, 0.09) | (0.06, 0.09, 0.1) |
| **B7** | (0.01, 0.02, 0.05) | (0.03, 0.05, 0.08) | (0.03, 0.06, 0.08) | (0.04, 0.06, 0.09) | (0.03, 0.04, 0.07) | (0.04, 0.06, 0.08) | (0, 0, 0) | (0.03, 0.05, 0.08) | (0.04, 0.07, 0.09) | (0.04, 0.06, 0.08) | (0.04, 0.06, 0.09) | (0.04, 0.06, 0.09) | (0.05, 0.08, 0.09) |
| **B8** | (0.03, 0.06, 0.08) | (0.03, 0.06, 0.08) | (0.01, 0.03, 0.06) | (0.02, 0.04, 0.07) | (0.04, 0.06, 0.08) | (0.01, 0.03, 0.06) | (0.02, 0.04, 0.07) | (0, 0, 0) | (0.06, 0.09, 0.11) | (0.06, 0.09, 0.11) | (0.04, 0.07, 0.09) | (0.03, 0.05, 0.07) | (0.04, 0.06, 0.09) |
| **B9** | (0.03, 0.05, 0.07) | (0.04, 0.06, 0.09) | (0.02, 0.04, 0.07) | (0.02, 0.04, 0.07) | (0.04, 0.06, 0.09) | (0.02, 0.04, 0.07) | (0.04, 0.07, 0.09) | (0.05, 0.08, 0.1) | (0, 0, 0) | (0.07, 0.09, 0.11) | (0.04, 0.06, 0.09) | (0.03, 0.05, 0.07) | (0.04, 0.06, 0.08) |
| **B10** | (0.03, 0.06, 0.08) | (0.04, 0.06, 0.09) | (0.01, 0.03, 0.06) | (0.02, 0.04, 0.07) | (0.03, 0.05, 0.08) | (0.02, 0.03, 0.06) | (0.03, 0.05, 0.07) | (0.04, 0.06, 0.09) | (0.06, 0.09, 0.1) | (0, 0, 0) | (0.04, 0.06, 0.09) | (0.03, 0.05, 0.08) | (0.03, 0.06, 0.08) |
| **B11** | (0.02, | (0.03, | (0.02, | (0.02, | (0.03, | (0.04, | (0.05, | (0.04, | (0.04, | (0.05, | (0, 0, 0) | (0.03, | (0.04, |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.04, 0.06) | 0.05, 0.08) | 0.03, 0.06) | 0.04, 0.07) | 0.06, 0.08) | 0.06, 0.08) | 0.08, 0.1) | 0.06, 0.09) | 0.06, 0.09) | 0.07, 0.1) | | 0.06, 0.08) | 0.06, 0.08) |
| **B12** | (0.02, 0.04, 0.07) | (0.05, 0.07, 0.1) | (0.04, 0.07, 0.1) | (0.02, 0.04, 0.07) | (0.01, 0.03, 0.06) | (0.03, 0.05, 0.07) | (0.03, 0.05, 0.08) | (0.02, 0.04, 0.07) | (0.03, 0.05, 0.07) | (0.03, 0.05, 0.08) | (0.04, 0.06, 0.08) | (0, 0, 0) | (0.07, 0.09, 0.11) |
| **B13** | (0.02, 0.04, 0.07) | (0.04, 0.07, 0.09) | (0.03, 0.05, 0.08) | (0.02, 0.04, 0.07) | (0.02, 0.04, 0.07) | (0.03, 0.06, 0.08) | (0.03, 0.06, 0.08) | (0.03, 0.05, 0.07) | (0.04, 0.06, 0.09) | (0.04, 0.06, 0.09) | (0.05, 0.07, 0.1) | (0.06, 0.09, 0.1) | (0, 0, 0) |

**Table 4.6 -** Matrix $\tilde{T}$.

| | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** | **B8** | **B9** | **B10** | **B11** | **B12** | **B13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **B1** | (0.01, 0.07, 0.91) | (0.06, 0.15, 1.15) | (0.03, 0.11, 1.01) | (0.06, 0.15, 1.08) | (0.08, 0.17, 1.09) | (0.02, 0.08, 0.94) | (0.02, 0.09, 1.02) | (0.05, 0.14, 1.08) | (0.06, 0.16, 1.16) | (0.06, 0.15, 1.14) | (0.03, 0.11, 1.06) | (0.03, 0.1, 1.02) | (0.02, 0.11, 1.09) |
| **B2** | (0.04, 0.12, 1.09) | (0.02, 0.11, 1.21) | (0.06, 0.16, 1.16) | (0.07, 0.17, 1.21) | (0.06, 0.16, 1.2) | (0.04, 0.12, 1.08) | (0.04, 0.14, 1.17) | (0.05, 0.15, 1.2) | (0.08, 0.19, 1.32) | (0.07, 0.18, 1.29) | (0.05, 0.15, 1.2) | (0.05, 0.14, 1.16) | (0.05, 0.16, 1.25) |
| **B3** | (0.03, 0.1, 1.02) | (0.05, 0.15, 1.21) | (0.02, 0.08, 1.01) | (0.07, 0.16, 1.14) | (0.07, 0.16, 1.14) | (0.05, 0.14, 1.04) | (0.06, 0.16, 1.12) | (0.04, 0.13, 1.13) | (0.05, 0.15, 1.22) | (0.03, 0.13, 1.19) | (0.03, 0.12, 1.12) | (0.04, 0.13, 1.09) | (0.05, 0.15, 1.18) |
| **B4** | (0.04, 0.1, 0.91) | (0.04, 0.12, 1.06) | (0.04, 0.11, 0.95) | (0.01, 0.07, 0.93) | (0.05, 0.12, 1) | (0.03, 0.1, 0.9) | (0.04, 0.11, 0.98) | (0.03, 0.11, 0.99) | (0.03, 0.12, 1.07) | (0.03, 0.12, 1.05) | (0.03, 0.1, 0.99) | (0.03, 0.1, 0.96) | (0.04, 0.12, 1.03) |
| **B5** | (0.06, 0.13, 0.99) | (0.05, 0.14, 1.15) | (0.05, 0.13, 1.03) | (0.04, 0.13, 1.07) | (0.02, 0.08, 1) | (0.03, 0.1, 0.96) | (0.03, 0.11, 1.03) | (0.05, 0.13, 1.07) | (0.05, 0.15, 1.16) | (0.05, 0.14, 1.14) | (0.04, 0.13, 1.07) | (0.03, 0.11, 1.02) | (0.04, 0.12, 1.1) |
| **B6** | (0.03, 0.11, 1.02) | (0.05, 0.15, 1.21) | (0.04, 0.13, 1.08) | (0.04, 0.13, 1.13) | (0.03, 0.12, 1.11) | (0.01, 0.08, 0.96) | (0.05, 0.14, 1.11) | (0.04, 0.13, 1.13) | (0.05, 0.15, 1.22) | (0.04, 0.15, 1.2) | (0.05, 0.14, 1.14) | (0.06, 0.15, 1.1) | (0.08, 0.18, 1.2) |
| **B7** | (0.02, 0.11, 1.04) | (0.05, 0.16, 1.24) | (0.05, 0.14, 1.11) | (0.06, 0.16, 1.17) | (0.05, 0.14, 1.15) | (0.06, 0.14, 1.06) | (0.02, 0.1, 1.07) | (0.05, 0.14, 1.16) | (0.07, 0.18, 1.26) | (0.06, 0.17, 1.24) | (0.06, 0.16, 1.17) | (0.6, 0.15, 1.13) | (0.07, 0.18, 1.22) |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **B8** | (0.05, 0.14, 1.08) | (0.05, 0.16, 1.26) | (0.03, 0.12, 1.1) | (0.04, 0.14, 1.17) | (0.06, 0.15, 1.17) | (0.03, 0.11, 1.05) | (0.04, 0.14, 1.14) | (0.02, 0.1, 1.1) | (0.09, 0.2, 1.3) | (0.09, 0.2, 1.27) | (0.06, 0.16, 1.19) | (0.05, 0.14, 1.13) | (0.06, 0.16, 1,23) |
| **B9** | (0.05, 0.13, 1.1) | (0.06, 0.17, 1.3) | (0.04, 0.13, 1.14) | (0.04, 0.14, 1.2) | (0.06, 0.16, 1.21) | (0.04, 0.13, 1.09) | (0.06, 0.16, 1.19) | (0.07, 0.18, 1.23) | (0.03, 0.12, 1.24) | (0.09, 0.21, 1.32) | (0.06, 0.16, 1.22) | (0.05, 0.14, 1.17) | (0.06, 0.17, 1.26) |
| **B10** | (0.05, 0.13, 1.06) | (0.06, 0.16, 1.23) | (0.03, 0.11, 1.08) | (0.04, 0.13, 1.14) | (0.05, 0.14, 1.14) | (0.03, 0.11, 1.03) | (0.04, 0.13, 1.12) | (0.06, 0.15, 1.16) | (0.08, 0.19, 1.27) | (0.02, 0.11, 1.15) | (0.06, 0.15, 1.16) | (0.05, 0.14, 1.12) | (0.05, 0.15, 1.2) |
| **B11** | (0.03, 0.12, 1.06) | (0.05, 0.15, 1.25) | (0.03, 0.12, 1.1) | (0.04, 0.13, 1.17) | (0.05, 0.15, 1.17) | (0.05, 0.13, 1.07) | (0.07, 0.16, 1.16) | (0.05, 0.15, 1.18) | (0.06, 0.17, 1.28) | (0.07, 0.18, 1.26) | (0.02, 0.1, 1.1) | (0.05, 0.14, 1.14) | (0.06, 0.16, 1.23) |
| **B12** | (0.03, 0.12, 1.05) | (0.07, 0.17, 1.25) | (0.06, 0.15, 1.12) | (0.04, 0.13, 1.15) | (0.03, 0.12, 1.14) | (0.04, 0.13, 1.05) | (0.05, 0.14, 1.13) | (0.04, 0.13, 1.15) | (0.05, 0.16, 1.25) | (0.05, 0.16, 1.23) | (0.05, 0.15, 1.17) | (0.02, 0.09, 1.05) | (0.09, 0.19, 1.23) |
| **B13** | (0.04, 0.12, 1.08) | (0.07, 0.17, 1.29) | (0.05, 0.14, 1.14) | (0.04, 0.14, 1.19) | (0.04, 0.14, 1.18) | (0.05, 0.14, 1.09) | (0.05, 0.15, 1.17) | (0.05, 0.15, 1.19) | (0.07, 0.18, 1.3) | (0.06, 0.18, 1.28) | (0.07, 0.17, 1.21) | (0.08, 0.18, 1.18) | (0.03, 0.11, 1.17) |

The total effect exerted $\tilde{d}_i$ and received $\tilde{r}_j$ are determined by Eqs (14) and (15) respectively. Table 4.7 shows the values $(\tilde{d}_i + \tilde{r}_i)$ of the prominence degree of each barrier and the net effect values $(\tilde{d}_i - \tilde{r}_i)$ of each barrier on Circular Economy.

**Table 4.7 -** Effects.

| | $\boldsymbol{\tilde{d}_i}$ | $\boldsymbol{\tilde{r}_i}$ | $\boldsymbol{\tilde{d}_i - \tilde{r}_i}$ | $\boldsymbol{\tilde{d}_i + \tilde{r}_i}$ |
|---|---|---|---|---|
| **B1** | (0.525, 1.586, 13.74) | (0.471, 1.509, 13.41) | (0.054, 0.076, 0.33) | (0.995, 3.095, 27.15) |
| **B2** | (0.669, 1.944, 15.53) | (0.682, 1.97, 15.79) | (-0.013, -0.026, -0.27) | (1.351, 3.914, 31.32) |
| **B3** | (0.586, 1.77, 14.61) | (0.512, 1.626, 14.02) | (0.074, 0.144, 0.6) | (1.098, 3.395, 28.63) |
| **B4** | (0.42, 1.388, 12.83) | (0.588, 1.783, 14.74) | (-0.168, -0.395, -1.92) | (1.008, 3.17, 27.57) |
| **B5** | (0.534, 1.604, 13.77) | (0.63, 1.821, 14.69) | (-0.096, -0.217, -0.92) | (1.164, 3.425, 28.47) |
| **B6** | (0.587, 1.775, 14.59) | (0.48, 1.498, 13.33) | (0.107, 0.277, 1.26) | (1.067, 3.273, 27.92) |
| **B7** | (0.672, 1.926, 15.03) | (0.578, 1.733, 14.41) | (0.093, 0.193, 0.62) | (1.25, 3.66, 29.43) |
| **B8** | (0.657, 1.91, 15.19) | (0.596, 1.797, 14.78) | (0.061, 0.113, 0.41) | (1.254, 3.707, 29.97) |
| **B9** | (0.712, 2.011, 15.69) | (0.751, 2.115, 16.06) | (-0.039, -0.104, -0.36) | (1.462, 4.126, 31.75) |
| **B10** | (0.616, 1.821, 14,85) | (0.722, 2.061, 15.76) | (-0.106, -0.24, -0.91) | (1.338, 3.882, 30.62) |
| **B11** | (0.636, 1.869, 15.17) | (0.609, 1.814, 14.8) | (0.028, 0.056, 0.37) | (1.245, 3.683, 29.97) |
| **B12** | (0.612, 1.843, 14.98) | (0.597, 1.732, 14.28) | (0.015, 0.111, 0.7) | (1.209, 3.575, 29.27) |
| **B13** | (0.683, 1.975, 15.47) | (0.691, 1.963, 15.39) | (-0.008, 0.012, 0.09) | (1.374, 3.939, 30.86) |

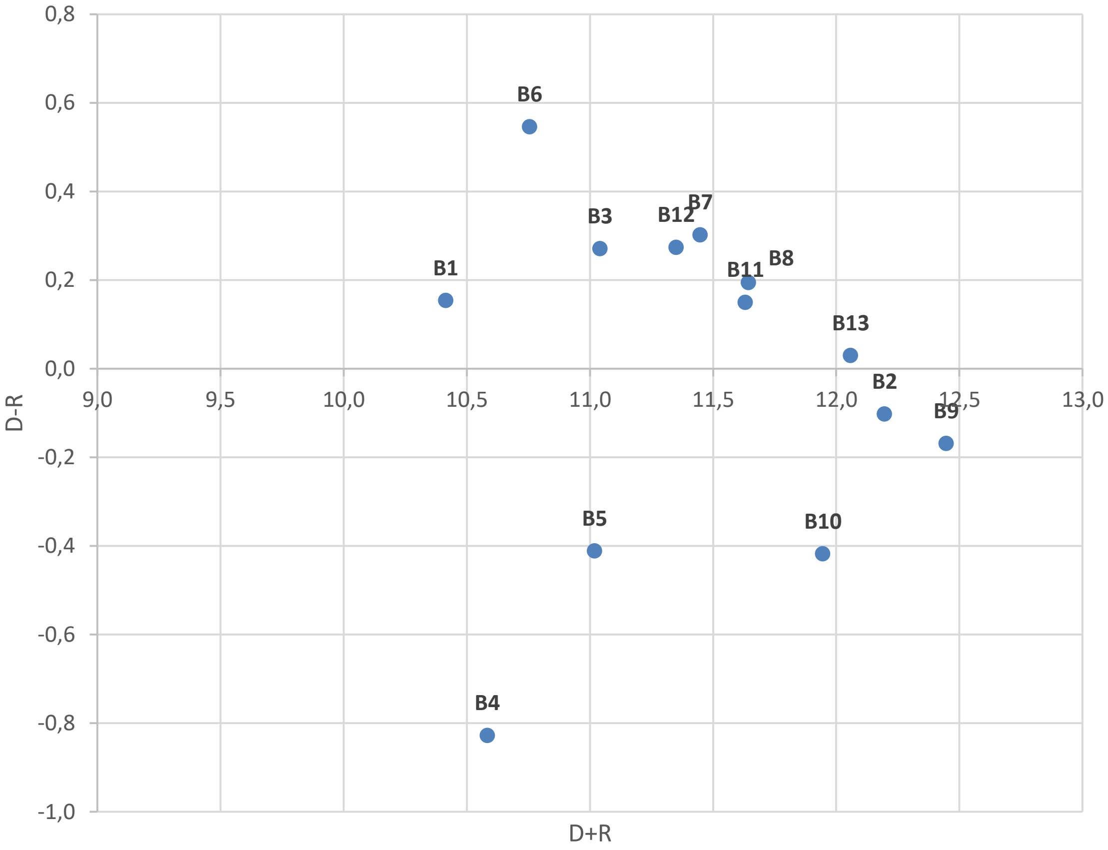
The next step consisted in transform $(\tilde{d}_i + \tilde{r}_i)$ and $(\tilde{d}_i - \tilde{r}_i)$ into crisp values $(\widetilde{D}_i + \tilde{R}_i)^{def}$ and $(\widetilde{D}_i - \tilde{R}_i)^{def}$ respectively, Eq. (16) Table 4.8 shows the defuzzified values.

**Table 4.8 -** Degree of importance and net effect values

| | $\boldsymbol{(\widetilde{D}_i + \widetilde{R}_i)^{def}}$ | $\boldsymbol{(\widetilde{D}_i - \widetilde{R}_i)^{def}}$ |
|---|---|---|
| **B1** | 10,41 | 0,15 |
| **B2** | 12,20 | -0,10 |
| **B3** | 11,04 | 0,27 |
| **B4** | 10,58 | -0,83 |
| **B5** | 11,02 | -0,41 |
| **B6** | 10,75 | 0,55 |
| **B7** | 11,45 | 0,30 |
| **B8** | 11,64 | 0,19 |
| **B9** | 12,45 | -0,17 |
| **B10** | 11,95 | -0,42 |
| **B11** | 11,63 | 0,15 |
| **B12** | 11,35 | 0,27 |
| **B13** | 12,06 | 0,03 |

In the next step, it was built the causal diagram, as presented in Figure 4.3. The prominence degree of each barrier is on the horizontal axis $(\widetilde{D}_i + \tilde{R}_i)^{def}$. Likewise, the influence degree of each barrier is on the vertical axis $(\widetilde{D}_i - \tilde{R}_i)^{def}$.

**Figure 4.3** – Causal Diagram



**B1-** Lack of eco-friendly AM legislation and public policies.
**B2-** Lack of strategic alignment in the adoption of AM to achieve circular business models.
**B3-** Lack of skills, experience, and awareness of 3D printers.
**B4-** Possibility (risk) of irresponsible or excessive consumption of 3D printed products.
**B5-** Toxicological risks associated with the use of AM
**B6-** Low printing/production pace with currently available AM technology.
**B7-** Lack of standardization of materials and poor quality of items produced by AM technologies.
**B8-** Limitation on the number of Technical cycles of materials used in AM
**B9-** Low acceptance of recycled AM raw materials
**B10-** Limited availability of recycled materials for AM and limited efficiency of small-scale recycling technologies
**B11-** Lack of sufficient match between novel materials and current 3D printing technologies
**B12-** High investment in AM raw material
**B13-** High unit cost of manufacturing AM

Our final step consisted in defining a threshold. The significant influencing barriers were captured under the mean + 1.5 standard deviations threshold, with value 0.503. Table 9 presents the overall impact relationships among the barriers. This is important to show the barriers that have more substantial or significant relationships.

**Table 4.9 -** The total influence matrix of each barrier.

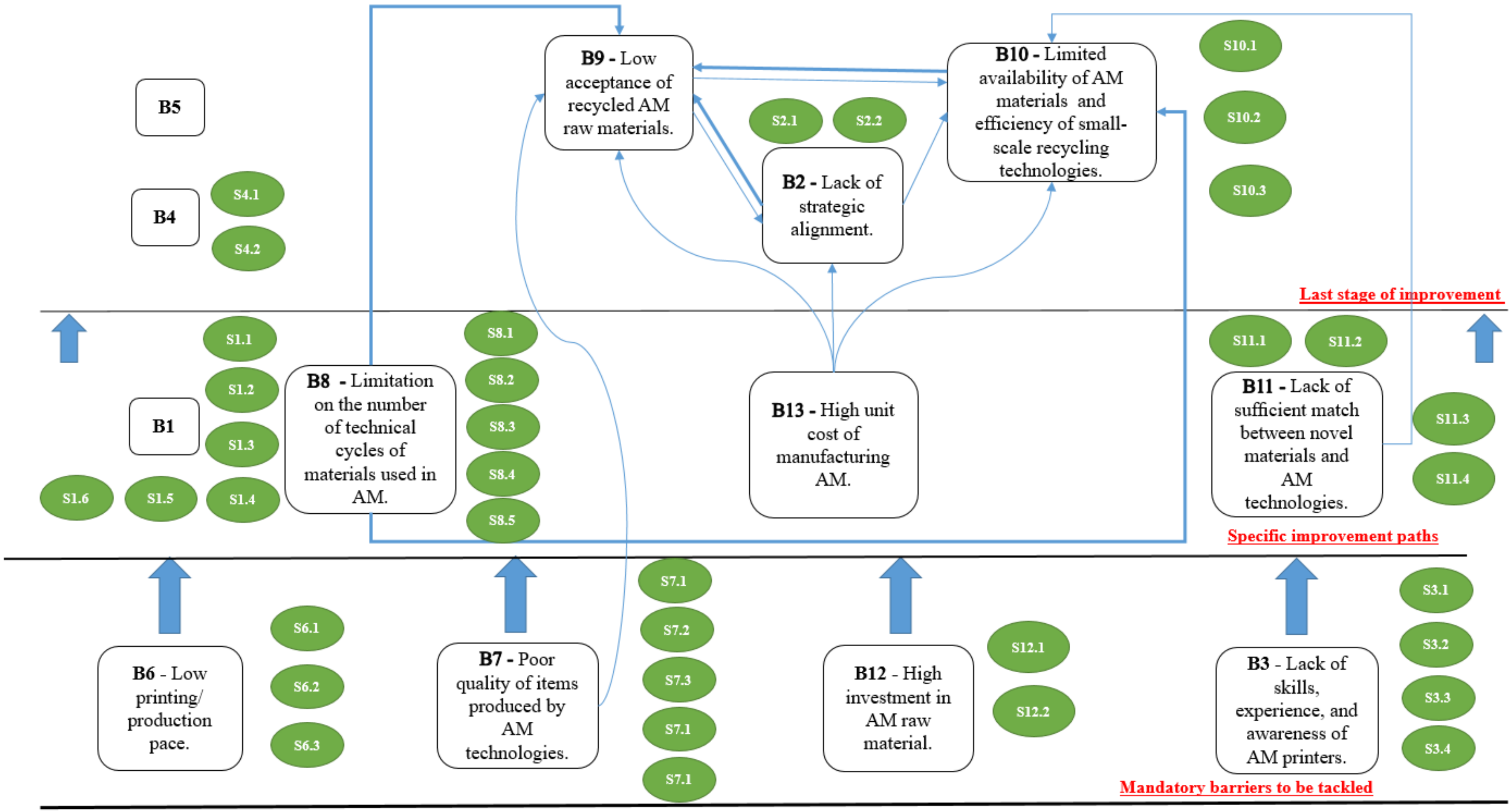
| | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** | **B8** | **B9** | **B10** | **B11** | **B12** | **B13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **B1** | 0,331 | 0,454 | 0,380 | 0,429 | 0,447 | 0,345 | 0,377 | 0,421 | 0,459 | 0,451 | 0,400 | 0,383 | 0,407 |
| **B2** | 0,416 | 0,445 | 0,461 | 0,482 | 0,472 | 0,414 | 0,449 | 0,468 | **0,530** | **0,511** | 0,465 | 0,452 | 0,484 |
| **B3** | 0,381 | 0,467 | 0,369 | 0,457 | 0,455 | 0,411 | 0,448 | 0,435 | 0,476 | 0,452 | 0,424 | 0,422 | 0,461 |
| **B4** | 0,351 | 0,407 | 0,363 | 0,338 | 0,389 | 0,342 | 0,375 | 0,376 | 0,407 | 0,400 | 0,371 | 0,362 | 0,394 |
| **B5** | 0,393 | 0,448 | 0,400 | 0,414 | 0,366 | 0,362 | 0,389 | 0,417 | 0,454 | 0,440 | 0,412 | 0,388 | 0,421 |
| **B6** | 0,388 | 0,471 | 0,417 | 0,434 | 0,418 | 0,350 | 0,435 | 0,433 | 0,472 | 0,463 | 0,443 | 0,438 | 0,488 |
| **B7** | 0,390 | 0,483 | 0,432 | 0,460 | 0,444 | 0,421 | 0,394 | 0,451 | **0,504** | 0,488 | 0,465 | 0,450 | 0,493 |
| **B8** | 0,420 | 0,490 | 0,416 | 0,449 | 0,460 | 0,396 | 0,439 | 0,408 | **0,527** | **0,521** | 0,471 | 0,439 | 0,482 |
| **B9** | 0,428 | **0,511** | 0,436 | 0,464 | 0,478 | 0,421 | 0,472 | 0,494 | 0,463 | **0,537** | 0,483 | 0,455 | 0,497 |
| **B10** | 0,412 | 0,484 | 0,406 | 0,434 | 0,445 | 0,391 | 0,433 | 0,457 | **0,513** | 0,428 | 0,457 | 0,436 | 0,468 |
| **B11** | 0,403 | 0,483 | 0,417 | 0,448 | 0,456 | 0,418 | 0,464 | 0,462 | 0,503 | **0,504** | 0,407 | 0,446 | 0,481 |
| **B12** | 0,403 | 0,496 | 0,443 | 0,440 | 0,432 | 0,406 | 0,440 | 0,440 | 0,486 | 0,480 | 0,457 | 0,388 | 0,502 |
| **B13** | 0,414 | **0,509** | 0,444 | 0,457 | 0,452 | 0,427 | 0,458 | 0,462 | **0,515** | **0,506** | 0,484 | 0,479 | 0,436 |

Note: Text in bold indicates a significant relationship path.

## 4.4 A PATH TO IMPROVEMENT: A FRAMEWORK TO OVERCOME BARRIERS TOWARS CIRCULAR ADDITIVE MANUFACTURING (AM)

In a complex decision problem, several barriers either influence (cause group) or are influenced by other barriers (effect group). So, if we improve one critical barrier, the whole system will improve because of the dependence of barriers on each other. Finding the dependency relationship allows us to identify the barriers in the cause group that can improve the barriers in the effect group and thus improve the whole system. It is also essential to take a careful look into the significant relationships to deliver a path to develop the strategies toward circular AM. Through our analysis both of the casual diagram (Figure 4.3) and the total influence matrix (Table 9), we propose a framework (Figure 4.4) underpinning strategy elaboration. The strategies presented were elaborated following the ReSOLVE methodology to guarantee the strategies for AM would be within the CE context. We organized all strategies into the ReSOLVE, in table 4.10. In addition, we point the action takers for each strategy in the same table.

**Figure 4.4** – A framework of Relationship paths between barriers.



### 4.4.1 Framework first layer: the mandatory barriers to be tackled

Our framework comprises three layers. The first is formed by the group of barriers that most influence other barriers, according to Figure 3. As they form the basis of the framework, they must necessarily be addressed to facilitate and shorten the path to improvement. The coded circles within the framework symbolise the strategies to be taken to overcome barriers. They will be presented in detail as the discussion progresses.

The most critical barriers in the cause group are B6, B7, B12, and B3. Accordingly, they deserve special attention, as their mitigation would also contribute to mitigating other barriers. B6 (low printing/production pace with currently available AM technology) has the highest $(\widetilde{D}_i - \tilde{R}_i)^{def}$ value (0.55) among all factors in the cause group. Although there are constant advances in AM technology, its widespread use in large-scale production is still in its infancy. This is also due to the low printing speed of most current industrially used machines, such as material extrusion. For implementing a CE, it is necessary to optimise waste reduction. As a not yet mature technology, various studies have been carried out to reduce fabrication time and increase efficiency (Jiang et al. 2020; Jin et al. 2019; Volpato et al. 2019). These studies have proposed various strategies, such as increasing layer thickness to reduce total layer numbers, path planning to find the shortest total travel path to save print time, or fabricating in a multilayer-by-multilayer manner. Also, many 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 (Huang 2015; Majeed et al. 2021; Wang et al. 2019).

The technology will likely overcome this barrier over time, as novel strategies and technological developments are studied and implemented. Accordingly, considering the current state of the technology, we propose the following strategies for mitigation:

- **S6.1:** Development of new strategies or higher capacity machines to further increase the efficiency of product development in AM.
- **S6.2:** Improvement in the speed of AM processes with lower energy consumption.
- **S6.3:** Leveraging the use of other technologies associated with AM to promote the efficiency of the process.

The second highest causal barrier evaluated by the experts was B7 (lack of standardisation of materials and poor quality of items produced by AM technologies). Although the cost of printing with some 3D printers, such as fused filament fabrication (FFF), is trivial compared to the other AM techniques, printing errors are substantial enough to impact their economic and environmental merits (Petsiuk and Pearce 2020). This makes circularity more difficult as high material purity and dimensional accuracy are required to reduce rejection rates. Furthermore, poor quality requires subsequent finishing processes, consuming additional energy, resources, and time.

The expert's opinion mirrored what has been claimed in the literature, in that product quality and defects are still one of the key challenges when using 3D printing technologies (Despeisse et al. 2017; Garmulewcz et al. 2018). However, similar to B6, the quality barrier (B7) is not high in terms of its prominence value (11.45) and this barrier is also influenced by the relative immaturity of the technology. To achieve the most efficient standards, technology needs to mature, and further research is required to explore the mechanical and thermal properties of AM technologies and materials. Therefore, several studies and techniques have attempted to reduce the failure rate. AM's association with big data analytics (BDA) promises to enhance the reliability of AM technology, as BDA can determine when imperfections occur (Majeed et al. 2019, 2021). However, one challenge that researchers must overcome is that it is difficult to improve productivity and quality simultaneously (Peng et al. 2018), which means merely improving productivity (B6) is not always feasible because of quality requirements.

With the mitigation of quality problems, other barriers would also be mitigated, as B7 can influence the other barriers. For example, barriers B8 (limitation on the number of technical cycles of materials used in AM) and B9 (low acceptance of recycled AM raw materials) would also be mitigated, as our DEMATEL results and the literature reveal that they are quality-dependent. Therefore, we propose the following strategies:

- **S7.1:** Development of new materials with tuneable properties that enable product reliability and faster speed production.
- **S7.2:** Development of the quality of recycled materials.
- **S7.3:** Development of new quality control methods to minimise failure rates, reducing AM waste.
- **S7.4:** Integration of some AM technologies with new technologies, such as BDA, to enhance AM reliability
- **S7.5:** Implementation of automatic quality tests, through the entire process and not just at the end, to enable easy correction, approval, or disapproval.

The joint third highest $(\widetilde{D}_i - \tilde{R}_i)^{def}$ values (0.27) in causal group are for B12 (high investment in AM raw material) and B3 (lack of skills, experience, and awareness of workers concerning the use of AM). Although they have the same causal value, barrier B12 was considered to be more prominent by the experts, with a $(\widetilde{D}_i + \tilde{R}_i)^{def}$ value of 11.35.

Concerning barrier B12, the high raw material costs currently cause the use of AM in fabricating parts with higher value (Niaki and Nonino 2017). From the raw material supply chain perspective, material cost is significant because the shortage of material suppliers leads to high negotiating power for suppliers. Even though plastic for AM is processed into filament by a range both of small and large companies, the feedstock is supplied by a handful of large polymer producers (Despeisse et al. 2017). Therefore, to overcome B12, a big change is required in the current economic structure within the plastics value chain. Thus, it is necessary to understand how a more distributed model of materials production could emerge. To achieve this, we propose the following strategies:

- **S12.1:** Investigate the possibilities in changing the concentration of the AM raw materials markets to a more distributed model of materials production.
- **S12.2:** Search for low-cost local materials with superior properties.

Concerning barrier B3, the lack of skills and knowledge of 3D printers has been related in the AM literature as a potential risk for the environment, as inexperienced users may utilise more material or use 3D printing incorrectly. This could result in waste and risks to the environment and to people. Therefore, design for AM requires skills and knowledge. However, much of the knowledge related to the technology is owned by the companies that are developing AM (Despeisse et al. 2017). Thus, openly accessible knowledge about these technologies is scarce. To overcome this barrier, actions should be taken to increase learning and knowledge about design for AM.

By driving actions to mitigate barrier B3, barriers B4 (risk of irresponsible or excessive consumption of 3D printed products), B9 (low acceptance of recycled AM raw materials), and B5 (toxicological risks associated with the use of AM) will be diminished as they are also influenced by the lack of knowledge about AM techniques and materials. Some actions to meet new knowledge demands are:

- **S3.1:** Setting up companies offering education and training for operators and designers concerning AM technology use, and providing them with the resources needed for learning and experimentation. This offer should include: material selection; material specification and properties (both virgin and recycled); process selection; application-specific issues; and testing and measurement.

- **S3.2:** National policies need to be implemented to initiate educational programs so that designers and engineers acquire the skills needed in the industry.
- **S3.3:** Offering skills for designers that specifically link MA to the CE to provide opportunities for material reuse, product life extension, and recovery.
- **S3.4:** Educating regarding AM's occupational health and risks and development of safer practices.

### 4.4.2 The second layer: specific improvement paths

The second layer of our framework is formed from barriers that not only exert some influence on other barriers but also hold stronger or significant relationships. The thicker arrows between barriers highlight stronger significant relationships.

According to the experts, barrier B11 (lack of sufficient match between novel materials and current 3D printing technologies) exerts a significant influence on barrier B10 (limited availability of recycled materials for AM), suggesting that the limitation on recycled materials for AM is also due to the limitation on the variety of materials suitable for AM. To mitigate B11, the following strategies are suggested:

- **S11.1:** Development of advanced 3D printing materials with tuneable mechanical, chemical, physical properties.
- **S11.2:** Development of novel 3D printing materials that enable higher dimensional accuracy, faster production, and lower energy consumption in the process.
- **S11.3:** Development in biodegradable and biocompatible materials suitable for AM.
- **S11.4:** Development of new material inputs, using new material inputs from a waste by-products.

One barrier to AM that has been reported is the unit manufacturing cost (B13), which is still significantly higher than the cost of traditional manufacturing. This barrier significantly influences other barriers, such as B2, B9, and B10. AM production remains uncompetitive at medium and large volumes. This means that there is a pressing need to incorporate additional value to the 3D printed parts to compensate for the high cost.

AM is relatively new to the market, and the time, cost, and speed are currently undesirable for high-volume products. However, this is expected to become more cost-effective as larger production volumes become more economically feasible than at present

(Ford and Despeisse 2016).

It is known that polymers (the material most used in AM process) degrade significantly during selective laser sintering (SLS) and fused deposition modelling (FDM) processing. This thermal degradation limits the number of reuse cycles of the process (B8). The significant relationships suggest that this barrier influences companies' acceptance of recycled materials as raw materials in their business (B9), since companies may see the limitation on recycling cycles as a disadvantage. Also, the limited availability of recycled AM materials (B10) is influenced by B8 (as shown in Figure 4) since the material in circulation has a shorter useful life.

To mitigate barrier B8 and barriers under its influence, we suggest the following strategies:

- **S8.1:** Development of AM processes to reduce the time involved in manufacturing the part in order to limit the thermal degradation transmitted to each cycle.
- **S8.2:** The ideal material would also be biodegradable in order to reduce the impact of waste if the material eventually becomes too degraded for satisfactory production.
- **S8.3:** Literature on the degradation of material properties with AM processes is lacking. Therefore, further research is necessary to understand how the number of reuse cycles affects material properties to implement a full CE.
- **S8.4:** Select metals, such as aluminium, for use in AM that can theoretically be infinitely cycled. Furthermore, recycling aluminium uses only 5% of the energy compared with virgin primary production.
- **S8.5:** To ensure that a CE can be sustained indefinitely, materials must both be mechanically and chemically reprocessed. Standards that facilitate this can be promulgated through industry standards-setting bodies such as the International Organization for Standardization (ISO). They can also be supported by government policy.

Barrier B1 (lack of eco-friendly AM legislation and public policies) does not hold any significant relationships, but it does influence other barriers, being part of the causal group. As AM is still early in its adoption curve, there is a current opportunity to consider how policy can influence its development. Some measures can be taken to alleviate other barriers, such as toxicological barriers (B5), recycling barriers (B9 and B10), and barriers related to material selection for AM. To achieve this, we suggest the following strategies:

- **S1.1:** Legislation and regulations regarding the use of materials. Policymakers must consider the toxicology implications of materials choices for AM and regulate this.
- **S1.2:** Standardised methodologies are also urgently required to enable accurate and reliable characterisation of AM emissions.
- **S1.3:** Policymakers should encourage AM material choices that support the CE.
- **S1.4:** The government should develop regulations to further incentivise the use of recycled materials.
- **S1.5:** Policymakers should offer incentives for recycling, reuse, and remanufacturing and develop recycling capabilities on a local scale.
- **S1.6:** Governments should encourage and support the active involvement of all AM supply chain players to participate more in the circular supply chain.

### 4.4.3 The third layer: the last stage of improvement

Barriers in the effect group form the third layer of our framework. As they are in the last layer, they do not have as much potential for improvement as the two first layers. However, interestingly, they hold many significant relationships, so it is essential to examine them carefully.

Despite being an effect barrier, B9 (lack of acceptance of recycled raw materials) is the most highlighted barrier by the experts, with the highest value (12.45) for $(\widetilde{D}_i + \tilde{R}_i)^{def}$. A variety of barriers influence barriers B9. Barriers B2, B7, B8, B10, and B13 exert significant relationships on B9 (Figure 4). The quality issue (B7) has been highlighted in many works as of great relevance to the level of acceptance of recycled materials (Despeisse et al. 2017; Sun et al. 2020). The quality of 3D printing products fabricated with recycled raw material does not match the quality of products printed from commercially available virgin acrylonitrile butadiene styrene terpolymer (ABS). Therefore, increasing the value generated by 3D products made from recycled plastics is one key driver for fostering the adoption of 3D printing in the CE context (Garmulewicz et al. 2016). To do so, two things may be necessary: first, the quality problem of recycled filaments needs to be solved; and second, a change in consumers' perception of recycled products and materials needs to occur. There is a lack of awareness of the value of wasted materials and it is considered to be a wider barrier than the ones posed by AM. To overcome this, investments in education are necessary. It is also necessary to provide incentives for the use of recycled materials, as we propose for B1.

Concerning the quality problems, some adjustments in supply chain players are required. Sun et al. (2020) proved in their study that recycled material suppliers in AM may not voluntarily develop or adopt high-quality recycled materials to produce a higher quality product because it is non-profitable for them. They found that the next actor of the supply chain, the AM organisations that consume the raw materials, should encourage the recycled material suppliers or other developers to improve the quality of the recycled material by providing subsidies, revenue sharing, and other incentives, to suppliers and developers gain more profit. Our DEMATEL results corroborate Sun et al. (2020) analysis since the experts pointed to significant relationships between barriers B9 and B2, meaning the acceptance of recycled materials is linked to the strategic alignment of AM organisations with the CE. In other words, if an organisation that uses AM technology aligns its business models with the CE, there will be more willingness to accept and incentivise recycled materials. Also, the significant relationship shows that the use of recycled materials may stimulate the strategic alignment of AM organisations with the CE. However, little is known about how companies design their business models according to CE principles. Therefore, more investigation and research is necessary. To support organisations that wish to transform their business models into a circular business model, we suggest:

- **S2.1:** Further research at the intersection between the CE and the field of strategic management in AM organisations.
- **S2.2:** Sharing of 3D manufacturing capabilities by a group of companies through the development of technology platforms or manufacturing spaces with the availability of 3D printers, such as 3D Hubs.

Barriers B9 and B10 are also linked with significant relationships. According to the experts, they exert mutual influence on each other, which means the acceptance of recycled materials and the availability of recycled materials are mutually dependent. Barrier B2 also exerts a significant influence on barrier B10, according to the experts. This may suggest that the strategic alignment of AM organisations with the CE holds the power to increase the availability of recycled materials for AM.

Recycling for AM is so challenging because the supply chain structure for recycling is based on large centralised processes, while AM requires small-scale recycling technologies. To improve this, not only must policymakers provide incentives for recycling and develop recycling capabilities at a local scale (as we propose in relation to B1 and B8), the following are also required:

- **S10.1:** Research in AM materials to develop a wider palette of recyclable materials based on renewable sources that meet the needs of their design projects.
- **S10.2:** Choose materials based on abundant and local resources. This would satisfy the need to close the system on a local scale.
- **S10.3:** Enhance and develop new strategies that enable repair, refurbishment, and remanufacturing. In a CE, these strategies are preferred to recycling since they help retain a product's economic and environmental value over time.

Barrier B4 (risk of irresponsible or excessive consumption of 3D printed products) was evaluated as the most influenceable barrier. By mitigating barrier B3, B4 would also be improved. Therefore, the main strategy that should be adopted is raising awareness about the impact of making things, as has already been happening in the maker space movement. The following improvements are also suggested:

- **S4.1:** Share, pool, or rent machines, products, and services for use in 3D printing.
- **S4.2:** Policymakers should provide incentives for the growth of the maker movement, raising people's awareness about waste.

In summary, the above-mentioned strategies for implanting an AM based on a CE were elaborated following the description of the ReSOLVE framework. These strategies are also organised into a framework (Table 4.10).

**Table 4.10** – Strategies for a CE-based AM

| ReSOLVE Action | Strategies for a CE-based AM | Action taker |
|---|---|---|
| Regenerate | Educate regarding the occupational health and risks of AM and development of safer practices | Organizations |
| | Develop more biodegradable and biocompatible materials suitable for AM. | Researchers |
| | consider the toxicology implications of materials choices for AM and regulate this | Policymakers |
| | Develop standardized methodologies to enable accurate and reliable characterization of AM emissions | Industry standards-setting bodies/ Policymakers |
| | Choose materials based on abundant and local resources | Business opportunity/ Organizations |
| | Encourage AM material choices that support Circular Economy, such as biodegradable materials | Policymakers |
| Share | Develop open data for knowledge and skill sharing within and between companies. | Organizations |

| | | |
|---|---|---|
| | Share, pool or renting machines, products and services for the oriented use of 3D printing | Business opportunity/ 3D printing users |
| **Optimise** | Enhance machines' capacity to further increase the efficiency of product development. | Researchers/ organizations |
| | Improve speed of AM processes with lower energy consumption. | Researchers/ organizations |
| | Leverage the use of other technologies associated with AM to promote the efficiency of the process | Researchers/ organizations |
| | Develop new materials with tunable properties that enable product reliability and faster speed production. | Researchers/ organizations |
| | Develop new methods of quality control to minimize failure rates, reducing AM waste. | Researchers/ organizations |
| | Implement automatic quality tests, through the entire process and not just in the end, to enable easy correction, approval, or disapproval. | Organizations |
| | Offer education and training for operators and designers concerning AM technology use to avoid waste | Organizations/ Policymakers |
| | Provide incentives for the growth of the maker movement, raising people's awareness about waste. | Policymakers |
| **Loop** | Develop the quality of recycled materials | Researchers/ organizations |
| | Develop AM process that reduces the time involved in manufacturing the part to reduce the thermal degradation transmitted to each cycle. | Researchers/ organizations |
| | Offer skills issues for designers that specifically link MA to CE to provide opportunities for material reuse, product life extension and recovery. | Organizations |
| | Develop new material inputs, using a new material input from a waste by-product | Researchers/ organizations |
| | Develop AM process that reduces the time involved in manufacturing the part to reduce the thermal degradation transmitted to each cycle. | Researchers/ organizations |
| | Select materials with properties that allow cost-effective cycling. | Organizations |
| | Research into how the number of reuse cycles affects material properties to implement a fully circular economy. | Researchers |
| | Select materials which can have unlimited cycles, like some metals. | Organizations |
| | Develop Standards that facilitate materials to be mechanically and chemically reprocessed. | Industry standards-setting bodies/ Policymakers |
| | Develop regulations to further incentivize the use of recycled materials. | Policymakers |
| | Enhance and develop new strategies that enable repair, refurbishment, and remanufacturing | Organizations |
| | Develop a wider palette of recyclable materials based on renewable sources | researchers |
| | Offer incentives for recycling, reuse and remanufacturing and develop recycling capabilities at a local scale. | Policymakers |
| **Virtualise** | Develop new AM technology platforms with a wider range of designs | Business opportunity |

| | | |
|---|---|---|
| **Exchange** | Integrate some AM technologies with new technologies, such as BDA, to enhance AM reliability | organization |
| | Change the concentration of AM raw materials markets to a more distributed model of materials production | policymakers/ organizations |
| | Search for low-cost materials with superior properties | Researchers |
| | Develop advanced 3D printing materials with tunable mechanical, chemical, physical properties. | Researchers/ Organizations |
| | Develop novel 3D printing materials that enable higher dimensional accuracy, faster speed production and lower energy consumption in the process. | Researchers/ Organizations |
| | Develop research at the intersection between the CE and the field of strategic management in AM organizations | Researchers/ Organizations |

## 4.5 CONCLUSION

Organizations must add value within their business to survive to competitiveness. In other words, they have to be economically sustainable. The Circular Economy is an approach that delivers this sustainability since it tries to promote continued economic development while preserving the resource base that is fuelling this economy (Ellen MacArthur, 2015). Recently, with the advent of Additive Manufacturing technologies, AM adopters are trying to benefit and make profit from the circular advantages of the new technology. However, several barriers prevent them from reaching this goal. This article used an SLR, expert opinions, and Fuzzy DEMATEL analysis to better understand how to overcome these barriers, suggesting strategies to implement a circular AM.

Recent studies have been developed to strengthen the field that addresses the interface between AM and CE. Similar to our findings, several authors have identified the circular potential that AM holds (Despeisse et al., 2017; Garmulewicz et al., 2016). However, significant barriers were also pointed out as limiting a Circular Economy as they prevent some AM circular benefits from being captured. Through a Systematic Review of Literature, we identified these barriers and validate them and their definitions with experts.

We conducted a Fuzzy DEMATEL study to empirically understand the influence relationship between the barriers. The main results of Fuzzy DEMATEL analysis showed that there is a clear dependence relationship between the barriers. Through this understanding, we formulated strategies to increase the circular power of AM technology following a wide accepted methodology for implementing the Circular Economy proposed by Ellen MacArthur Foundation.

### 4.5.1 Theoretical and Practical Contributions

The output of our results was a framework presenting the dependency relationship between the barriers. The layers of the framework depic which barriers would have to be prioritary tackled. Also, we presented significant relationships to focus on critical relationships. Through this analysis, it was possible to set strategies to adapt AM technology to a CE context.

The first layer of our framework showed the most influential barriers of the causal group (B3, B6, B7, B12), may have priority to be tackled. The most influential barriers (B6, B7 and B12) are related to the technology maturity degree. This mean the technology may or not develop towards circularity. This further highlights the need to generate the knowledge to facilitate the cleanest and most sustainable path of a new emerging technology. Our study also showed no change would be successful without also considering the human factor, as discussed at the fourth most influential barrier, B3. The lack of awareness or knowledge regarding AM production and consumption may cause wastes that prevent the technology from achieving its circular potential. So, it is essential that as the technology and the associated industrial activity emerge, printers and consumers understand its impacts, so the technology will not be a source of waste. Therefore, there is urgent need to develop knowledge and sustainable behaviors in society. To develop this, the policymakers and supply chain actors need to corroborate by providing knowledge and financial incentives.

Our study also delivers practical contributions, as AM organizations who wish additional value on their business through a CE will be able to take actions toward a cleaner and sustainable AM. Therefore, our study is the first to show what developments and strategies need to take place in order to facilitate the path for a circular AM. The findings provide opportunities for open collaboration between researchers, potential stakeholders of the supply chain and policymakers to generate innovative and circular solutions for AM.

### 4.5.2 Limitations

Despite the presented contributions, this article also had limitations. Although we intended to be exhaustive on our SLR, some references may be missing. Also, some barriers for circular AM may not yet be reported in the literature, thus, they were not considered in our research. Furthermore, the rapid pace of development of AM technology means that it is highly likely that new applications of AM with further circular and sustainable benefits will soon be created, causing changes in the current barriers.

There are also limitations of the Fuzzy DEMATEL approach. The fact that they were built from experts' opinions (although there was an effort to select adequate experts), could lead to some results based on personal information. So, the conceptual understanding of the authors could cause discrepancies concerning the complex reality of the influences between barriers. For example, the results do not emphasize the importance of regulatory barriers (B1). Despite being a causal barrier, it was neither considered a prominent barrier by the experts nor a high-value causal barrier. Also, no significant relationship was detected in B1. However, as we discuss in the 4.5 section, its mitigation would cause many solutions for other barriers. So, future research should validate the proposed influences in large-scale studies.

Also, the results could change depending on the expert's nationality, since national laws, degree of knowledge and education and, differences in technological advances may vary with the national development. Finally, there was also the issue of the time of experience of the respondents with both approaches: Additive Manufacturing and Circular economy. Experts with many years of experience in AM may not having equivalent familiarity with CE and the opposite is also true. Longitudinal studies in other countries are recommended to understand how these barriers relationships will influence this study's findings

## References

3D HUBS, 2019. 3D Printing Trends Q1/20183D Printing Trends Q1 https://downloads.hubs.com/3D_Printing_Trends_Q1_2019.pdf (accessed 16 October 2021).

Akyuz, Emre, and Erkan Celik, 2015. A fuzzy DEMATEL method to evaluate critical operational hazards during gas freeing process in crude oil tankers. Journal of Loss Prevention in the Process Industries, 38, 243-253. https://doi.org/10.1016/j.jlp.2015.10.006

Amm Nazmul, Ahsan, Habib Md Ahasan, Khoda Bashir, 2015. Resource based process planning for additive manufacturing. Computer-Aided Design 69, 112-125. https://doi.org/10.1016/j.cad.2015.03.006

Arrieta-Escobar, Javier A. Derrien, Delphine, Ouvrard, Stéphanie, Asadollahi-Yazdi, Elnaz, Hassan, Alaa, Boly, Vincent, Tinet, Anne-Julie, Dignac, Marie-France 2020, 3D printing : An emerging opportunity for soil science. Geoderma 378, 114588. https://doi.org/10.1016/j.geoderma.2020.114588

Bai, Chunguang, Joseph Sarkis, and Yijie Dou, 2017. Constructing a process model for low-carbon supply chain cooperation practices based on the DEMATEL and the NK model. Supply Chain Management: An International Journal 22(1), 00-00. https://doi.org/10.1108/SCM-09-2015-0361

Behm, Jocelyn E, Waite, B. R., Hsieh, S. T., & Helmus, M. R., 2018. Benefits and limitations of three-dimensional printing technology for ecological research. BMC Ecology 18(1), 1-13. https://doi.org/10.1186/s12898-018-0190-z

Bloomfield, Mark, and Shaun Borstrock, 2018. Modeclix. The additively manufactured adaptable textile. Materials Today Communications 16, 212–216. http://dx.doi.org/10.1016/j.mtcomm.2018.04.002

Bogers, Marcel, Ronen Hadar, Arne Bilberg, 2016. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. Technological Forecasting and Social Change 102, 225–239. https://doi.org/10.1016/j.techfore.2015.07.024

Candi, Marina, and Ahmad Beltagui, 2019. Effective use of 3D printing in the innovation process. Technovation 80, 63-73. https://doi.org/10.1016/j.technovation.2018.05.002

Cappa, Francesco. Del Sette, F., Hayes, D., & Rosso, F., 2016. How to Deliver Open Sustainable Innovation: An Integrated Approach for a Sustainable Marketable Product. Sustainability 8(12), 1341. https://doi.org/10.3390/su812134

Centobelli, Piera, Cerchione, R., Chiaroni, D., Del Vecchio, P., & Urbinati, A., 2020. Designing business models in circular economy: A systematic literature review and research agenda. Business Strategy and the Environment 29(4), 1734-1749. https://doi.org/10.1002/bse.2466

Cerdas, Felipe, Juraschek, M., Thiede, S., & Herrmann, C., 2017. Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System. Journal of Industrial Ecology 21(1), S80–S93. https://doi.org/10.1111/jiec.1261

Chang, Betty, Chang, Chih-Wei, Wu, Chih-Hung, 2011. Fuzzy DEMATEL method for developing supplier selection criteria. Expert Systems with Applications, 38 (3), 1850-1858. https://doi.org/10.1016/j.eswa.2010.07.114

Chen, Chen-Tung, 2000. Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy sets and systems, 114(1), 1-9. https://doi.org/10.1016/S0165-0114(97)00377-1

Chen, Rui, Yin, H., Cole, I. S., Shen, S., Zhou, X., Wang, Y., & Tang, S., 2020. Exposure, assessment and health hazards of particulate matter in metal additive manufacturing: A review. Chemosphere 259, 127452. https://doi.org/10.1016/j.chemosphere.2020.127452

Chong, Siewhui, Chiub, H. L., Liaob, Y. C., Hungc, S. T., & Pand, G. T., 2015. Cradle to Cradle®design for 3D printing. Chemical Engineering Transactions 45, 1669–1674. https://doi.org/10.3303/CET1545279

Chu, Ta-Chung, Kuo-Shi Huang, and Tzu-Ming Chang, 2004. COA defuzzification method for evaluating Cpkunder fuzzy environments. Journal of Discrete Mathematical Sciences and Cryptography 7(3), 271–280. https://doi.org/10.1080/09720529.2004.10698008

Clemon, L. M., and T. I. Zohdi, 2018. On the tolerable limits of granulated recycled material additives to maintain structural integrity. Construction and Building Materials 167, 846–852. https://doi.org/10.1016/j.conbuildmat.2018.02.099

Colorado, Henry A., Elkin I. Gutiérrez Velásquez, Sergio Neves Monteiro, 2020. Sustainability of additive manufacturing: the circular economy of materials and environmental perspectives. Journal of Materials Research and Technology 9(4), 8221-8234. https://doi.org/10.1016/j.jmrt.2020.04.062

Creswell, J. W., & Plano Clark, V. L. (2011). Choosing a mixed methods design. Designing and conducting mixed methods research, 2, 53-106.

Cunico, Marlon Wesley Machado Cavalheiro, P. M., & de Carvalho, J., 2019. Development and characterization of 3D printing finishing process applying recycled plastic waste. Virtual and Physical Prototyping 14(1), 37-52. https://doi.org/10.1080/17452759.2018.1521248

Dal Fabbro, Pierandrea, La Gala, A., Van De Steene, W., D'hooge, D. R., Lucchetta, G., Cardon, L., & Fiorio, R., 2020. Influence of machine type and consecutive closed-loop recycling on macroscopic properties for fused filament fabrication of acrylonitrile-butadiene-styrene parts. Rapid Prototyping Journal 27(2), 268-277 https://doi.org/10.1108/RPJ-03-2020-0060

Denyer, David, David Tranfield, 2009. Producing a systematic review. The Sage handbook of organizational research methods. Sage Publications Ltd 671–689.

Depalma, K. Walluk, M. R., Murtaugh, A., Hilton, J., McConky, S., & Hilton, B., 2020. Assessment of 3D printing using fused deposition modeling and selective laser sintering for a circular economy. Journal of Cleaner Production 264, 121567. https://doi.org/10.1016/j.jclepro.2020.121567

De Sousa Jabbour, Ana Beatriz Lopes, Jabbour, C. J. C., Godinho Filho, M., & Roubaud, D., 2018. Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. Annals of Operations Research 270(1), 273-286. https://doi.org/10.1007/s10479-018-2772-8

Despeisse, Mélanie, Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S, Minshall, T.H.W., Mortara, L., Reed-Tsochas, F.P. & Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: A research agenda. Technological Forecasting and Social Change 115, 75-84. https://doi.org/10.1016/j.techfore.2016.09.021

Dev, Navin K., Ravi Shankar, and Fahham Hasan Qaiser, 2020. Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. Resources, Conservation and Recycling, 153, 104583. https://doi.org/10.1016/j.resconrec.2019.104583

Ellen Macarthur Foundation, 2015. Delivering the circular economy: A toolkit for policymakers.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition; Seacourt: Oxford, UK.

Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E. A., & Barlow, C. Y., 2017. Business model innovation for sustainability: Towards a unified perspective for creation of sustainable business models. Business Strategy and the Environment, 26(5), 597-608. https://doi.org/10.1002/bse.1939

Falatoonitoosi, E. L. Z. S. S. S. M., Leman, Z., Sorooshian, S., & Salimi, M., 2013. Decision-making trial and evaluation laboratory. Research Journal of Applied Sciences, Engineering and Technology, 5(13), 3476-3480. https://doi.org/10.19026/RJASET.5.4475

Faludi, Jeremy, Bayley, C., Bhogal, S., & Iribarne, M., 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. Rapid Prototyping Journal, 21(1), 14–33. https://doi.org/10.1108/RPJ-07-2013-0067

Farooque, M., Jain, V., Zhang, A., & Li, Z., 2020. Fuzzy DEMATEL analysis of barriers to Blockchain-based life cycle assessment in China. Computers & Industrial Engineering, 147, 106684. https://doi.org/10.1016/j.cie.2020.106684

Feng, Changli, and Ruize Ma, 2020. Identification of the factors that influence service innovation in manufacturing enterprises by using the fuzzy DEMATEL method. Journal of Cleaner Production, 253, 120002. https://doi.org/10.1016/j.jclepro.2020.120002

Ford, Simon, and Mélanie Despeisse, 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. Journal of Cleaner Production 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Franco, D., Ganga, G. M. D., de Santa-Eulalia, L. A., & Godinho Filho, M., 2020. Consolidated and inconclusive effects of additive manufacturing adoption: A systematic literature review. Computers & Industrial Engineering, 148, 106713. https://doi.org/10.1016/j.cie.2020.106713

Gabus, A., & Fontela, E.,1972. World problems, an invitation to further thought within the framework of DEMATEL. Battelle Geneva Research Center, Geneva, Switzerland, 1-8.

Garmulewicz, Alysia., Holweg, M., Veldhuis, H., & Yang, A., 2018. Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold? California Management Review 60(3), 112–132. https://doi.org/10.1177/0008125617752695

Gebler, Malte, Anton J. M. Schoot Uiterkamp, Cindy Visser, 2014. A global sustainability perspective on 3D printing technologies. Energy Policy 74, 158–167. https://doi.org/10.1016/j.enpol.2014.08.033

Gharakhani, D., Taromian, S., Dadras, K., & Fakhar, A., 2014. Fuzzy AHP and fuzzy DEMATEL methods for supplier selection criteria. In International Conference on Computer Science and Information Systems (ICSIS'2014). 17-18. https://doi.org/10.15242/iie.e1014056

Ghaffar, Seyed Hamidreza, Jorge Corker, Mizi Fan, 2018. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. Automation in Construction 93, 1–11. https://doi.org/10.1016/j.autcon.2018.05.005

Ghisellini, Patrizia, Catia Cialani, and Sergio Ulgiati, 2016. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Giurco, Damien., Littleboy, A., Boyle, T., Fyfe, J., & White, S., 2014. Circular Economy: Questions for Responsible Minerals, Additive Manufacturing and Recycling of Metals. Resources 3(2), 432–453. https://doi.org/10.3390/resources3020432

Holmström, Jan, and Timothy Gutowski, 2017. Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? Journal of Industrial Ecology 21, S21–S24. https://doi.org/10.1111/jiec.12580

Hsu, Chia-Wei., Kuo, T. C., Chen, S. H., & Hu, A. H., 2013. Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. Journal of cleaner production, 56, 164-172. https://doi.org/10.1016/j.jclepro.2011.09.012

Huang, Chung-Hung, 2015. Continued evolution of automated manufacturing - Cloud-enabled digital manufacturing. International Journal of Automation and Smart Technology 5(1), 2–5. https://doi.org/10.5875/ausmt.v5i1.861

Jiang, Jingchao, 2020. A novel fabrication strategy for additive manufacturing processes. Journal of Cleaner Production 272, 122916. https://doi.org/10.1016/j.jclepro.2020.122916

Jin, Yuan, He, Y., Fu, G., Zhang, A., & Du, J., 2017. A non-retraction path planning approach for extrusion-based additive manufacturing. Robotics and Computer-Integrated Manufacturing, 48, 132-144. https://doi.org/10.1016/j.rcim.2017.03.008.

Jin, Yuan, Jianke Du, Yong He, 2017. Optimization of process planning for reducing material consumption in additive manufacturing. Journal of Manufacturing Systems 44(1), 65–78. https://doi.org/10.1016/j.jmsy.2017.05.003

Kellens, Karel, Baumers, M., Gutowski, T. G., Flanagan, W., Lifset, R., & Duflou, J. R., 2017. Environmental Dimensions of Additive Manufacturing Mapping Application Domains and Their Environmental Implications. Journal of Industrial Ecology 21(1), S49–S68. https://doi.org/10.1111/jiec.12629

Khorram Niaki, M. and Nonino, F., 2017b. Impact of additive manufacturing on business competitiveness: a multiple case study. Journal of Manufacturing Technology Management, (28)1, 56-74. https://doi-org.ez31.periodicos.capes.gov.br/10.1108/JMTM-01-2016-0001

Kim, Yuna, Yoon, C., Ham, S., Park, J., Kim, S., Kwon, O., & Tsai, P. J. (2015b). Emissions of nanoparticles and gaseous material from 3D printer operation. Environmental Science & Technology 49(20). 12044-12053. https://doi.org/10.1021/acs.est.5b02805

Kim, Duck Bong, Witherell, P., Lipman, R., & Feng, S. C., (2015a). Streamlining the additive manufacturing digital spectrum : A systems approach. Additive Manufacturing 5, 20–30. https://doi.org/10.1016/j.addma.2014.10.004

Kunovjanek, Maximilian, and Gerald Reiner, 2019. How will the diffusion of additive manufacturing impact the raw material supply chain process ? International Journal of Production Research 58(5), 1540–1554. https://doi.org/10.1080/00207543.2019.1661537

Laverne, Floriane, Marquardt, R., Segonds, F., Koutiri, I., & Perry, N., 2019. Improving resources consumption of additive manufacturing use during early design stages: a case study. International Journal of Sustainable Engineering. 12(6), 365-375. https://doi.org/10.1080/19397038.2019.1620897

Le, Van Thao, Henri Paris, Guillaume Mandil, 2018. Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies. International Journal on Interactive Design and Manufacturing 12(2), 525–536. https://doi.org/10.1007/s12008-017-0395-y

Lee, Jian-Yuan, Jia An, and Chee Kai Chua, 2017. Fundamentals and applications of 3D printing for novel materials.Applied materials today 7, 120-133. https://doi.org/10.1016/j.apmt.2017.02.004

Li, Chung-Wei, and Gwo-Hshiung Tzeng, 2009. Identification of a threshold value for the DEMATEL method using the maximum mean de-entropy algorithm to find critical services provided by a semiconductor intellectual property mall. Expert Systems with Applications, 36(6), 9891-9898. https://doi.org/10.1016/j.eswa.2009.01.073

Lin, Ru-Jen, 2013. Using fuzzy DEMATEL to evaluate the green supply chain management practices. Journal of Cleaner Production 40, 32-39. https://doi.org/10.1016/j.jclepro.2011.06.010

Ma, Junfeng. Harstvedt, J. D., Dunaway, D., Bian, L., & Jaradat, R., 2018. An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment. Journal of Cleaner Production 192, 55–70. https://doi.org/10.1016/j.jclepro.2018.04.249

Majeed, Arfan, Zhang, Y., Ren, S., Lv, J., Peng, T., Waqar, S., & Yin, E., 2021. A big data-driven framework for sustainable and smart additive manufacturing. Robotics and Computer-Integrated Manufacturing 67, 102026. https://doi.org/10.1016/j.rcim.2020.102026

Majeed, Arfan, Jingxinang Lv, Tao Peng, 2019. A framework for big data driven process analysis and optimization for additive manufacturing. Rapid Prototyping Journal 25(2), 308–321. https://doi.org/10.1108/RPJ-04-2017-0075

Martinsuo, Miia, and Toni Luomaranta, 2018. Adopting additive manufacturing in SMEs: exploring the challenges and solutions. Journal of Manufacturing Technology Management 29(6), 937–957. https://doi.org/10.1108/JMTM-02-2018-0030

Matsumoto, Mitsutaka, Yang, S., Martinsen, K., & Kainuma, Y., 2016. Trends and research challenges in remanufacturing. International Journal of Precision Engineering and Manufacturing - Green Technology 3(1), 129–142. https://doi.org/10.1007/s40684-016-0016-4

Mavi, Reza Kiani., & Craig Standing, 2018. Critical success factors of sustainable project management in construction: A fuzzy DEMATEL-ANP approach. Journal of cleaner production, 194, 751-765. https://doi.org/10.1016/j.jclepro.2018.05.120

Millard, Jeremy. Sorivelle, M. N., Deljanin, S., Unterfrauner, E., & Voigt, C., 2018. Is the maker movement contributing to sustainability? Sustainability (Switzerland) 10(7). 1-29. https://doi.org/10.3390/su10072212

Nascimento, Daniel Luiz Mattos, Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., & Tortorella, G., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. Journal of Manufacturing Technology Management 30(3), 607–627. https://doi.org/10.1108/JMTM-03-2018-0071

Panahifar, Farhad, Heavey, C., Byrne, P. J., & Asif Salam, M., 2015. Partner selection factors for successful CPFR implementation using fuzzy DEMATEL. Journal of Economics, Business and Management, 3(12), 1138-1145. https://doi.org/10.7763/JOEBM.2015.V3.348

Peng, Tao, Kellens, K., Tang, R., Chen, C., & Chen, G., 2018. Sustainability of additive manufacturing : An overview on its energy demand and environmental impact. Additive Manufacturing 21, 694–704. https://doi.org/10.1016/j.addma.2018.04.022

Peeters, Bob, Nadine Kiratli, and Janjaap Semeijn. "A barrier analysis for distributed recycling of 3D printing waste: Taking the maker movement perspective." Journal of Cleaner Production 241 (2019): 118313.

Peeters, Bob, Nadine Kiratli, Janjaap Semeijn, 2019. A barrier analysis for distributed recycling of 3D printing waste: Taking the maker movement perspective. Journal of Cleaner Production 241, 118313. https://doi.org/10.1016/j.jclepro.2019.118313

Petsiuk, Aliaksei L., and Joshua M. Pearce, 2020 Open source computer vision-based layer-wise 3D printing analysis. Additive Manufacturing 36, 101473. https://doi.org/10.1016/j.addma.2020.101473

Ponis, Stravos, Aretoulaki, E., Maroutas, T. N., Plakas, G., & Dimogiorgi, K., 2021). A Systematic Literature Review on Additive Manufacturing in the Context of Circular Economy. Sustainability, 13(11), 6007. https://doi.org/10.3390/su13116007

Rejeski, David, Fu Zhao, Yong Huang, 2018. Research needs and recommendations on environmental implications of additive manufacturing. Additive Manufacturing 19, 21–28. https://doi.org/10.1016/j.addma.2017.10.019

Ren, Shan, Zhang, Y., Liu, Y., Sakao, T., Huisingh, D., & Almeida, C. M., 2019. A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions. Journal of cleaner production, 210, 1343-1365. https://doi.org/10.1016/j.jclepro.2018.11.025

Saboori, Abdollah, Aversa, A., Marchese, G., Biamino, S., Lombardi, M., & Fino, P., 2019. Application of directed energy deposition-based additive manufacturing in repair. Applied Sciences 9(16), 3316. https://doi.org/10.3390/app9163316

Sanchez, Fabio A. Cruz, Boudaoud, H., Camargo, M., & Pearce, J. M., 2020. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. Journal of Cleaner Production, 264, 121602. https://doi.org/10.1016/j.jclepro.2020.121602

Santander, Pavlo Sanchez, F. A. C., Boudaoud, H., & Camargo, M., 2020. Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. Resources, Conservation and Recycling 154, 104531. https://doi.org/10.1016/j.resconrec.2019.104531

Sauerwein, Mariet, and E. L. Doubrovski, 2018. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications 15, 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028

Sauerwein, Mariet, Doubrovski, E., Balkenende, R., & Bakker, C., 2019. Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production 226, 1138-1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Shieh, Jiunn-I., Wu, Hsin-Hung, Huang, Kuan-Kai, 2010. A DEMATEL method in identifying key success factors of hospital service quality. Knowl. Based Syst. 23 (3), 277-282. https://doi.org/10.1016/j.knosys.2010.01.013

Shimizu, T., 2010. Decisão nas organizações. 3 ed. São Paulo, Atlas.

Shukla, Manish, Ivan Todorov, and Dharm Kapletia, 2018. Application of additive manufacturing for mass customisation: understanding the interaction of critical barriers. Production Planning and Control 29(10), 814–825. https://doi.org/10.1080/09537287.2018.1474395

Si, S. L., You, X. Y., Liu, H. C., & Zhang, P., 2018. DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. Mathematical Problems in Engineering, 2018(1). https://doi.org/10.1155/2018/3696457

Siler, William, and James J. Buckley, 2005. Fuzzy expert systems and fuzzy reasoning. John Wiley & Sons.

Sitotaw, Dereje, Berihun Ahrendt, D., Kyosev, Y., & Kabish, A. K., 2020. Additive Manufacturing and Textiles—State-of-the-Art. Applied Sciences 10(15), 5033. https://doi.org/10.3390/app10155033

Stentoft, Jan Philipsen, K., Haug, A., & Wickstrøm, K. A., 2020. Motivations and challenges with the diffusion of additive manufacturing through a non-profit association. Journal of Manufacturing Technology Management. 32(4), 841-861. https://doi.org/10.1108/JMTM-04-2020-0125

Strack, Guinevere, 2019. Additive manufacturing approaches for biological power generation. Current Opinion in Electrochemistry 17, 167–173. https://doi.org/10.1016/j.coelec.2019.06.002

Strange, Roger, and Antonella Zucchella, 2017. value chains and international business. Multinational Business Review 25(3), 174–184. https://doi.org/10.1108/MBR-05-2017-0028

Sun, Luoyi Wang, Y., Hua, G., Cheng, T. C. E., & Dong, J., 2020. Virgin or recycled ? Optimal pricing of 3D printing platform and material suppliers in a closed-loop competitive circular supply chain. Resources, Conservation & Recycling 162, 105035. https://doi.org/10.1016/j.resconrec.2020.105035

Tang, Yunlong, Kieran Mak, and Yaoyao Fiona Zhao, 2016. A framework to reduce product environmental impact through design optimization for additive manufacturing. Journal of Cleaner Production 137, 1560–1572. https://doi.org/10.1016/j.jclepro.2016.06.037

Tian, Xiaoyong, Liu, T., Wang, Q., Dilmurat, A., Li, D., & Ziegmann, G., 2017. Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. Journal of Cleaner Production 142, 1609–1618. https://doi.org/10.1016/j.jclepro.2016.11.139

Turner, Chris Moreno, M., Mondini, L., Salonitis, K., Charnley, F., Tiwari, A., & Hutabarat, W, 2019. Sustainable production in a circular economy: A business model for re-distributed manufacturing. Sustainability 11(16), 4291. https://doi.org/10.3390/su11164291

Tziantopoulos, Konstantinos Tsolakis, N., Vlachos, D., & Tsironis, L., 2019. Supply chain reconfiguration opportunities arising from additive manufacturing technologies in the digital era. Production Planning and Control 30(7), 510–521. https://doi.org/10.1080/09537287.2018.1540052

Unruh, Gregory, 2018. Circular Economy, 3D Printing, and the Biosphere Rules. California Management Review 60(3), 95–111. https://doi.org/10.1177/0008125618759684

Venkatesh, V. G., Zhang, A., Luthra, S., Dubey, R., Subramanian, N., & Mangla, S., 2017. Barriers to coastal shipping development: An Indian perspective. Transportation Research Part D: Transport and Environment, 52, 362-378. https://doi.org/10.1016/j.trd.2017.03.016

Vidakis, Nectarios Petousis M, Tzounis L, Maniadi A, Velidakis E, Mountakis N, Papageorgiou D, Liebscher M, Mechtcherine V., 2020. Sustainable Additive Manufacturing: Mechanical Response of Polypropylene over Multiple Recycling Processes. Sustainability 13(1), 159. https://doi.org/10.3390/su13010159

Volpato, Neri, Galvão, L. C., Nunes, L. F., Souza, R. I., & Oguido, K., 2020. Combining heuristics for tool-path optimisation in material extrusion additive manufacturing. Journal of the Operational Research Society, 71(6), 867-877. https://doi.org/10.1080/01605682.2019.1590135

Wang, Yuanbin Lin, Y., Zhong, R. Y., & Xu, X., 2019. IoT-enabled cloud-based additive manufacturing platform to support rapid product development. International Journal of Production Research 57(12), 3975–3991. https://doi.org/10.1080/00207543.2018.1516905

Weller, Christian, Robin Kleer, Frank T Piller, 2015. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. International Journal of Production Economics 164, 43-56. https://doi.org/10.1016/j.ijpe.2015.02.020

Woern, Aubrey L., & Joshua M. Pearce, 2017. Distributed manufacturing of flexible products: Technical feasibility and economic viability. Technologies, 5(4), 71. https://doi.org/10.3390/technologies5040071

Wu, Wei-Wen, 2012. Segmenting critical factors for successful knowledge management implementation using the fuzzy DEMATEL method. Applied Soft Computing, 12(1), 527-535. https://doi.org/10.1016/j.asoc.2011.08.008

Wu, Wei-Wen., & Lee, Y. T., 2007 Developing global managers' competencies using the fuzzy DEMATEL method. Expert Systems with Applications, 32(2), 499–507. https://doi.org/10.1016/j.eswa.2005.12.005.

Yadav, Dinesh Garg, R. K., Ahlawat, A., & Chhabra, D., 2020. 3D printable biomaterials for orthopedic implants: Solution for sustainable and circular economy. Resources Policy 68, 101767. https://doi.org/10.1016/j.resourpol.2020.101767

Yang, Sheng, Min, W., Ghibaudo, J., & Zhao, Y. F., 2019. Understanding the sustainability potential of part consolidation design supported by additive manufacturing. Journal of Cleaner Production 232, 722–738. https://doi.org/10.1016/j.jclepro.2019.05.380

Zadeh, L. A., 2001. Fuzzy sets: information and control, 1965. ROLIN, FA Teoria Fuzzy e sua aplicação em sensoriamento remoto. UFPR. Curitiba

Zadeh, Lotfi. A., 1973. Outline of a new approach to the analysis of complex systems and decision processes. IEEE Transactions on systems, Man, and Cybernetics, (1), 28-44. https://doi.org/10.1109/TSMC.1973.5408575

Zhang, Abraham, Venkatesh, V. G., Liu, Y., Wan, M., Qu, T., & Huisingh, D., 2019. Barriers to smart waste management for a circular economy in China. Journal of Cleaner Production, 240, 118198. https://doi.org/10.1016/j.jclepro.2019.118198

Zhao, Peng, Rao, C., Gu, F., Sharmin, N., & Fu, J., 2018. Close-looped recycling of polylactic acid used in 3D printing: An experimental investigation and life cycle assessment. Journal of Cleaner Production 197, 1046-1055. https://doi.org/10.1016/j.jclepro.2018.06.275

Zhong, Shan, and Joshua M. Pearce, 2018. Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. Resources, Conservation and Recycling 128, 48–58. https://doi.org/10.1016/j.resconrec.2017.09.023

APPENDIX A – Selected articles from SLR

| n° | Authors | Methodology | Contributions to our study | |
|---|---|---|---|---|
| 1 | AHSAN; HABIB; KHODA, 2015 | Case Study | Proposes an optimization of the process plan for the minimum resource need in the AM manufacture parts. | Refers to 1 barrier |
| 2 | BEHM et al., 2018 | Literature Review | Provides an overview of ecological research using 3D printing. | Refers to 4 benefits and 1 barrier |
| 3 | BLOOMFIELD; BORSTROCK, 2018 | Experiment | Studies a flexible material for 3D printing that is infinitely configurable. | Refers to 5 benefits |
| 4 | BOGERS; HADAR; BILBERG, 2016 | Literature Review | Studies changes in the supply chain as they are transformed from centralized to decentralized. | Refers to 3 benefits and 2 barriers |
| 5 | CANDI; BELTAGUI, 2019 | Survey | Analyzes the adoption of AM for innovation. | Refers to 1 benefit |
| 6 | CAPPA et al., 2016 | Case Study | Provides evidenceS based on collaborative development of more sustainable, competitive, and marketable AM products. | Refers to 2 benefits |
| 7 | CENTOBELLI, 2020 | Literature Review | Links circular economy to digital innovations (including AM). | Refers to 1 barrier |
| 8 | CERDAS et al., 2017 | Case Study/ Life cycle Assessment | Compares the environmental impact between a 3D printed product and an equivalent conventionally manufactured product. | Refers to 1 benefit and 1 barrier |
| 9 | CHEN et al., 2020 | Literature Review | Studies the dangers of particulate metal material in additive manufacturing. | Refers to 1 barrier |
| 10 | CHONG et al., 2015 | Literature Review | recommends a distributed recycling platform for 3D printed products to aid in the recirculation of regenerated materials. | Refers to 2 benefits and 1 barrier |
| 11 | CLEMON; ZOHDI, 2018 | Experiment | Proposes a framework and an easy-to-use tool that identifies variational trends of composites improved with recycled material | Refers to 1 benefit |
| 12 | COLORADO; VESLÁSQUEZ; MONTEIRO, 2020 | Literature Review | Studies the circularity of recycled materials for AM. | Refers to 1 benefit |
| 13 | CUNICO et al., 2018 | Experiment | Introduces 3D printing surface finish post-processing using recycled plastic waste. | Refers to 1 benefit |
| 14 | DAL FABBRO et al., 2020 | Experiment | Evaluate multiple closed-loop recycling processes of a material using AM machines. | Refers to 1 barrier |

| | | | | |
|---|---|---|---|---|
| 15 | DE SOUSA JABBOUR et al., 2018 | Literature Review | Studies the connection between 4.0 technologies and the CE. | Refers to 1 barrier |
| 16 | DEPALMA et al., 2020 | Literature Review/Experiement | Assesses the circularity potential for end-of-life plastic material using 3D printing techniques. | Refers to 1 benefit and 3 barriers |
| 17 | DESPEISSE et al., 2017 | Literature Review/ Case Study | Assesses the circularity potential for end-of-life plastic material using 3D printing techniques. | Refers to 2 barriers and 2 benefits |
| 18 | FALUDI et al., 2015 | Life Cycle Assessment | Compares the environmental impacts of two AM machines with a traditional computer numerical control milling machine | Refers to 1 benefit |
| 19 | FORD; DESPEISSE, 2016 | Literature Review/ Case Studies | Studies the advantages and challenges of AM for sustainability. | Refers to 3 benefits and 8 barriers |
| 20 | GARMULEWICZ et al., 2018 | Literature Review/ Case Study | Studies local distributed production of new products from recycled materials. | Refers to 5 benefits and 4 barriers |
| 21 | GEBLER; UITERKAMP; VISSER, 2014 | Literature Review/Quantitative Assessment | Studies AM's global sustainability perspective. | Refers to 3 benefits and 1 barrier |
| 22 | GHAFFAR; CORKER; FAN, 2018 | Literature Review | Studies AM technology in the construction sector as an innovative eco solution. | Refers to 3 benefits and 1 barrier |
| 23 | GIURCO et al., 2014 | Literature Review | Studies the movement towards CE and the evolution of future manufacturing trends. | Refers to 1 benefit and 1 barrier |
| 24 | HOLMSTRÖM; GUTOWSKI, 2017 | Literature Review | Opines on AM's relationship with sustainability | Refers to 1 barrier |
| 25 | HUANG, 2015 | Conceptual theory | Shows how supply chains will be optimized or even replaced with AM prevalence | Refers to 2 benefits |
| 26 | JIANG, 2020 | Case Study | Examines a new AM manufacturing process strategy to reduce total manufacturing time. | Refers to 1 benefit |
| 27 | JIN; DU; HE, 2017 | Case Studies | Proposes a process planning strategy with a focus on material consumption in AM. | Refers to 2 benefits |
| 28 | KELLENS et al., 2017 | Literature Review | Provides an overview of currently available studies that analyze the environmental dimensions of AM | Refers to 2 benefits and 1 barrier |
| 29 | KIM et al., 2015a | Literature Review/ Simulation and modeling | Proposes an information systems architecture for AM. | Refers to 2 benefits |
| 30 | KIM et al., 2015b | Experiment | Evaluates the emission characteristics of toxic material during 3D print-type fused deposition modeling. | Refers to 1 barrier |
| 31 | KUNOVJANEK; REINER, 2019 | Literature Review/ Simulation | Integrates the potential for reducing material inventories through the adoption of AM in manufacturing | Refers to 1 benefit |

| | | | | |
|---|---|---|---|---|
| 32 | LAVERNE et al., 2019 | Case Study | Proposes strategies to reduce material and electrical energy consumption in four AM machines. | Refers to 2 benefits |
| 33 | LE; PARIS; MANDIL, 2018 | Literature Review/ Case Study | Proposes an alternative strategy for Remanufacturing using AM. | Refers to 1 benefit |
| 34 | Lee et al., 2017 | Literature Review | Provides an understanding of the fundamentals of 3D printing processes and the recent development of novel 3D printing materials, as biomaterials and others. | Refers to 2 barriers |
| 35 | MA et al., 2018 | Case Study/Life cycle Assessment | Develops a lifecycle assessment framework to understand the sustainability performance of the 3D printed product's lifecycle. | Refers to 2 benefits and 1 barrier |
| 36 | MAJEED et al., 2021; | Literature Review/ Case Study | Studies the integration of AM with other 4.0 technologies, such as Big Data and Sustainable Smart Manufacturing, at the beginning of the product's life cycle. | Refers to 3 benefits |
| 37 | MAJEED; LV; PENG, 2019 | Literature Review/ Case Study | Presents a framework based on big data analytics to optimize the AM production performance process. | Refers to 4 benefits |
| 38 | MARTINSUO; LUOMARANTA, 2018 | Interviews | Explores the barriers companies face in their supply chains when adopting AM. | Refers to 2 barriers |
| 39 | MATSUMOTO et al., 2016 | Literature Review | Studies remanufacturing for AM. | Refers to 1 benefit |
| 40 | MILLARD et al., 2018 | Case Study/Survey | Examines the sustainability of digital content production, including AM, by anyone. | Refers to 3 benefits |
| 41 | NASCIMENTO et al., 2019 | Literature Review/ Semi-structured Interviews | Explores how industry 4.0 technologies, including AM, can be integrated with CE. | Refers to 3 benefits |
| 42 | NIAKI; NONINO, 2017 | Case Studies | Identifies AM impacts on manufacturing, business strategies and business performance | Refers to 2 barriers |
| 43 | PENG et al., 2018 | Literature Review | Provides an overview of AM sustainability. | Refers to 2 barriers |
| 44 | REJESKI; ZHAO; HUANG, 2018 | Literature Review | Describes the potential environmental implications of AM related to key issues. | Refers to 1 barrier |
| 45 | SABOORI et al, 2019 | Literature Review | Studies the capability of an AM process technique (Directed Energy Deposition) for remanufacturing. | Refers to 1 benefit |
| 46 | SANCHEZ et al., 2020 | Literature Review | Studies the opportunities that recycled plastic used in AM brings to CE | Refers to 1 benefit |
| 47 | SANTANDER et al., 2020 | Case Study | Study a method of recycling plastics using 3D printing | Refers to 1 benefit |
| 48 | SAUERWEIN et al., 2019 | Literature Review/Semi-structured Interviews | Studies opportunities that AM offers to design projects that are useful for a CE. | Refers to 1 benefit and 1 barrier |

| | | | | |
|---|---|---|---|---|
| 49 | SAUERWEIN; DOUBROVSKI, 2018 | Experiment | Demonstrates the potential of using local waste streams for AM processes to achieve CE. | Refers to 3 benefits |
| 50 | SHUKLA; TODOROV; KAPLETIA, 2018 | Literature Review/ Interpretative Structural Modelling (ISM) | Studies the relationships between AM barriers to mass customization. | Refers to 1 barrier |
| 51 | SINGH; RAMAKRISHNA; GUPTA, 2017 | Literature Review | Relates zero waste to AM. | Refers to 1 barrier |
| 52 | SITOTAW et al., 2020 | Liretarure Review | Describes the state-of-the-art of AM application in the Textile industry. | Refers to 2 benefits |
| 53 | STENTOFT et al., 2020 | Case Study | Identifies some AM barriers and shows how they can be reduced. | Refers to 3 barriers |
| 54 | STRACK, 2019 | Literature Review | Covers recent AM approaches to biological power generation. | Refers to 1 benefit |
| 55 | STRANGE; ZUCCHELLA, 2017 | Literature Review | Studies how the widespread adoption of new digital technologies, including AM, can affect the organization of activities in the value chain. | Refers to 1 barrier |
| 56 | SUN et al., 2020 | Case Study | examines the prices of the 3DP platform and material suppliers in the context of a closed-loop circular supply chain. | Refers to 3 barriers |
| 57 | TANG; MAK; ZHAO, 2016 | Case Study | Proposes a framework that minimizes the environmental impact in the AM process. | Refers to 3 benefits |
| 58 | TIAN et al., 2017 | Experiement | Proposes cleaner production for thermoplastic composites based on recycling and remanufacturing of 3D printed composites. | Refers to 2 benefits |
| 59 | TURNER et al., 2019 | Case Study | Explores the feasibility of a redistributed business model for manufacturers employing AM as part of a circular production and consumption system | Refers to 1 benefit |
| 60 | TZIANTOPOULOS et al., 2019 | Literature Review | Explores the impact of AM on the supply chain. | Refers to 2 benefits |
| 61 | UNRUH, 2018 | Literature Review | Presents a strategy to guide managers and policymakers in a relationship between EC, MA and the rules of the biosphere. | Refers to 4 benefits and 3 barriers |
| 62 | VIDAKIS et al., 2020 | Experiment | Studies the mechanical response of a material in multiple 3D printing processes. | Refers to 2 barriers |
| 63 | WANG et al., 2019 | Simulation | Proposes a cloud platform for 3D printing services to integrate physical and soft resources, printing support, and design and process planning. | Refers to 4 benefits |
| 64 | WELLER et al., 2015 | Literature Review | Analyzes AM technology from an economic perspective. | Refers to 1 barrier |
| 65 | WOERN; PEARCE, 2017 | Experiment | Demonstrates the use of recycled plastic instead of virgin plastic for AM, saving 98% of material cost. | Refers to 1 benefits |

| | | | | |
|---|---|---|---|---|
| 66 | YADAV et al., 2020 | Literature Review | Studies the use of biomaterials for the 3D fabrication of medical implants. | Refers to 1 benefit |
| 67 | YANG et al., 2019 | Life Cycle Assessment/ Case Study | Provides a new perspective for a selection of a more sustainable 3D assembly design. | Refers to 1 benefits |
| 68 | ZHAO et al., 2018 | Experiment | Studies recycling in 3D printing | Refers to 1 benefit and 2 barriers |
| 69 | ZHONG; PEARCE, 2018 | Case Studies | Studies recycled plastic waste in 3D printing filaments | Refers to 1 benefit and 1 barrier |

APPENDIX B – AM benefits for implanting a CE.

| Action | Benefit | References |
|---|---|---|
| **Regenerate** | AM promotes the use of biodegradable materials and the use of energy from renewable sources | 2; 20; 22; 49; 54; 57; 61; 66. |
| | AM promotes the recovery, retention, and restoration of ecosystem health | 6; 18; 19; 20; 21; 43; 57. |
| **Share** | AM promotes asset sharing | 4; 40. |
| | AM promotes reuse and second-hand use | 3; 52. |
| | AM allows life extension through design for durability and upgradeability | 13; 40;52. |
| **Optimize** | AM allows growth in product performance/efficiency | 27; 32; 35; 37; 63; 67. |
| | AM promotes the removal of waste in production and supply chain | 1; 4; 8; 19; 22; 26; 27; 28; 31; 32; 43;57; 59; 60; 61. |
| | AM leverages the use of big data and automation | 25; 29; 36; 37; 41; 63. |
| **Loop** | AM encourages the remanufacturing of products or components | 28; 33; 39; 45; 58. |
| | AM encourages the recycling of materials | 2; 10; 11; 12; 13; 20; 23; 41; 46; 47; 49. |
| | AM expands the scale of waste recovery and resource reuse | 2; 4; 10; 16; 17; 19; 20; 21; 41; 48; 49; 61. |
| **Virtualize** | AM encourages indirect dematerialization | 4; 6; 19; 20; 21; 25; 37; 40; 60; 61; 63. |

| | | |
|---|---|---|
| **Exchange** | AM promotes the replacement of old materials with advanced materials | 3; 22. |
| | AM promotes the application of new technologies | 29; 36; 37; 63. |
| | AM promotes the choice of new products and services (capacity for innovation) | 2; 3; 5. |

# 5 RESEARCH CONCLUSION

To achieve the study objectives, the research was developed in two stages, represented here by two articles. This chapter presents the main contributions of these studies, the limitations, and new directions suggestions for future research on the subject.

## 5.1 RESEARCH CONTRIBUTIONS

Some initial studies suggest that AM (Additive Manufacturing) is a promising technology to achieve sustainability and develop more circular material flows. However, there is still uncertainty regarding the impacts and benefits of AM on CE (Circular Economy). To fill this gap, a multi-method study was carried out to identify existing research on the relationship of Additive Manufacturing technologies and the Circular Economy. As a result, we proposed a framework that presents the benefits and barriers of AM for CE. To do so, we used a multi-method research approach: (i) the consultation of secondary qualitative data to find the best way to categorize our results through the CE literature; (ii) a systematic literature review (SLR), to understand how the phenomenon of AM adoption meets or does not meet the requirements of a CE; and (iii) interviews with experts to validate our framework.

This first study contribute to systematically highlighting the benefits and barriers of AM for CE and also contribute to reveal specific actions that companies that use AM should perform to be aligned with the ReSOLVE framework. Also, the results indicate that the broader potential of AM as a beneficial technology for CE depends on overcoming critical barriers. These findings could be of great relevance for companies and society since the study examines how AM technology brings companies and society closer to or farther from the CE. The AM technologies tend to contribute to the deployment of CE, generating a new path of production and restructuring the supply chain.

In the second article, we showed how organizations using AM technology can add value to their business through a Circular Economy (CE) business model. So, the main goal of this research was to propose strategies for implementing AM in a CE context. To purpose these strategies, we used a multi-method research approach: (i) A Systematic Literature Review (SLR) to identify the barriers that prevent AM for reach the CE requirements; (ii) A Fuzzy DEMATEL analysis to understand the interdependence relationships between the barriers raised in the first study. The main results of Fuzzy DEMATEL analysis showed that there is a clear dependence relationship between the barriers, which was used to guide improvement actions. Through the Fuzzy DEEMATEL results, we elaborate a framework depicting what barriers would have to be priority tackled. Also, we presented significant relationships on the framework to focus on critical relationships. Therefore, knowing this facilitated the process of presenting the strategies to facilitate the path for a circular AM.

AM organizations who wish additional value on their business through a CE will be able to take actions toward a cleaner and sustainable AM. Therefore, this study was of great relevance since it was the first to show what developments and strategies need to take place in order to facilitate the path for a circular AM. This could be of great benefit for society, the environment and organizations.

## 5.2 LIMITATIONS AND FUTURE DIRECTIONS

Some of the limitations of this research were highlighted during the development of the study. First, there is a limitation on the SLR, where some important articles might have been excluded from our final sample in the SLR due to our choice of keywords Also, some barriers for circular AM may not yet be reported in the literature, thus, they were not considered in our research. There are also limitations of the Fuzzy DEMATEL approach. The fact that they were built from experts' opinions (although there was an effort to select adequate experts), could lead to some results based on personal information. So, the conceptual understanding of the authors could cause discrepancies concerning the complex reality of the influences between barriers. Also, the results could change depending on the expert's nationality, since national laws, degree of knowledge and education and, differences in technological advances may vary with the national development. Finally, there was also the issue of the time of experience of the respondents with both approaches: Additive Manufacturing and Circular economy. Experts with many years of experience in AM do not have equivalent familiarity with CE and the opposite is also true.

For future reaearch, we suggest: (i) Conducting complementary reviews and continuously update the framework as a “live” body of knowledge; (ii) future research to validate the proposed influences in large-scale studies and; (iii) Conducting longitudinal studies in other countries are recommended to understand how these barriers relationships will influence this study’s findings.

This work was carried out with the support of the Coordination for the Improvement of HigherEducation Personnel - Brazil (CAPES) - Financing Code 001.