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A Sustainable Circular 3D Printing Model for Recycling Metal Scrap in the Automotive Industry

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Abstract

Purpose - Industries and businesses are pursuing Industry 4.0 (I4.0) technologies and adopting a circular approach focused on improving manufacturing processes through the reduction of wastes, CO2 emissions, and mineral exploration to mitigate the impact of climate change. In this sense, Additive Manufacturing (AM), often referred to as 3D printing, can play a vital role in the closed-loop of operations. However, academics and practitioners have scarcely discussed the feasibility of AM implementation alongside Circular Economy (CE) practices, the techniques and methods required, or how AM could benefit sustainability and circularity. This paper proposes a novel circular sustainable 3D printing model for scrap recycling in the automotive industry to address these gaps.

Design/methodology/approach – The methodology uses a literature review-based approach followed by empirical research using metal scraps as the raw material for fabricating a powder to input a metal 3D printer for generating sustainable automotive components. A conceptual sustainable circular model for the automotive industry is proposed. Next, is conducted a focus group comprised of AM and automotive industry experts for evaluations.

Findings - The results indicate that the proposed model can reintroduce waste back into the manufacturing chain as raw material for the on-demand manufacture and supply of automotive components and that it may also have social and environmental implications.

Originality - This paper's contributions are threefold: it explores the combined use of I4.0, CE, and Sustainability in the automotive industry, develops a new model to support the circularity and sustainability of the scrap chains, and proposes the use of AM as a catalyst of CE practices by reproducing recycled components with a 3D printer for fully functioning components.

Keywords: Industry 4.0; Automotive Industry; 3D Printer; Circular Economy; Climate Change; Recycled Material; Scrap Metal.

1. Introduction

The effects of climate change are perceived by society as increasingly severe and intense and causing frequent catastrophes and expectations of a threatening future. According to the United States Environmental Protection Agency report, the industry comprises 22.9% of the total emissions, with iron and steel and metallurgical coke production the main factor with 41.3% of the total emissions in the industry in 2019 (EPA, 2021). Considering these facts, the main opportunities for reducing emissions in the industry are Energy Efficiency, Fuel Switching, Recycling, Training, and Awareness (EPA, 2021). One of these opportunities is the recycling of iron and steel to manufacture new raw materials from scrap, generating new products, and reducing waste, CO2 emissions, and mineral exploration (De Souza and Pacca, 2021).

Known as the "4th Industrial Revolution", Industry 4.0 (I4.0) marks the transition from embedded systems to cyber-physical systems in technological evolution. One crucial aspect of I4.0 is to enable technologies to create objects or equipment that link the virtual and physical worlds through intelligent networks and independent management processes. The fundamental concepts associated with the virtual environment encompass the Internet of Things (IoT), Big Data, Cyber Security, Cloud Computing, Cyber-Physical Systems, Advanced Robotics, Virtual Reality, Augmented Reality, Artificial Intelligence, Autonomous Vehicles, Additive Manufacturing, and Blockchain (Núñez-Merino et al., 2020). Meanwhile, I4.0's physical domain includes Autonomous Robots and Additive Manufacturing (AM) (Nascimento et al., 2019; Bousdekis et al., 2021). In this context, AM technology has enabled three-dimensional parts to be created directly from CAD models by adding materials layer by layer. However, this study addresses an innovative method, as it focuses on the use of recycled materials. Some of the required methodologies were found in some works that proposed a variety of implementations.

For example, Sauerwein et al. (2019) and Sun et al. (2020) compared the use of recycled powders in as-built sample components with those manufactured from virgin powder made from various materials. Based on the experimental results obtained with the different techniques used in their research, they state that the average particle size, microstructure, mechanical tests to gauge horizontal and vertical elasticity and mechanical properties are similar to the original materials, with some divergences due to previously analyzed and corrected experimental methods. In conjunction with this study, their research introduces the main idea of the Circular Economy (CE) practices that can be applied to I4.0 and consequently, allow new ways to be found for waste generated by society to be turned into the optimized products that society demands.

All these processes may already form part of a smart production system. Zawadzki and Żywicki, (2016) suggest that production control should be analyzed for rational decisions to be made about the material flow to comply with the rudimentary idea of the automotive manufacturing control concept, which supports individualized products and the application of automated and knowledge-based design systems. So, this study builds on the 3D printing process and technologies with the use of recycled scrap metal and new approaches to material property treatment to achieve integration with CE practices and I4.0. There are some precepts of CE principles that can be practically applied to the automotive industry to deliver highly sustainable value-added products. The following research questions (RQ) can be formulated:

RQ1: Is it possible to implement AM in the automotive industry through CE practices?

RQ2: What are the techniques and methods that enable AM and CE implementation in the automotive industry?

RQ3: How can AM benefit the sustainability of the automotive industry with a circular 3D printing model?

To address these questions, this study aims to propose a novel sustainable circular 3D printing model for recycling metal scraps in the automotive industry. This study intends to answer these questions by exploring the possibility of implementing sustainable AM in the automotive industry, which broadens the context of AM implementation, with a proposal for a model that uses step-by-step processes and recycled materials in 3D printing and CE practices. This study will present a sustainable and practical methodology to enable the consolidation of a design framework. Thus, theory underlies the integration of AM and CE practices with the processes needed in the production stage of a real-world industry to generate a new approach to smart production.

2. Methodology

2.1. Research Design

This study seeks to propose a novel sustainable circular 3D printing model for scrap recycling in the automotive industry by providing an innovative methodology for producing metal powder for use in AM processes with CE practices. The results can be applied to characterize the properties of metal powders used in AM processes and their inclusion in the automotive industry's Sustainable Supply Chains (SSCs). Figure 1 presents the steps followed in this research.

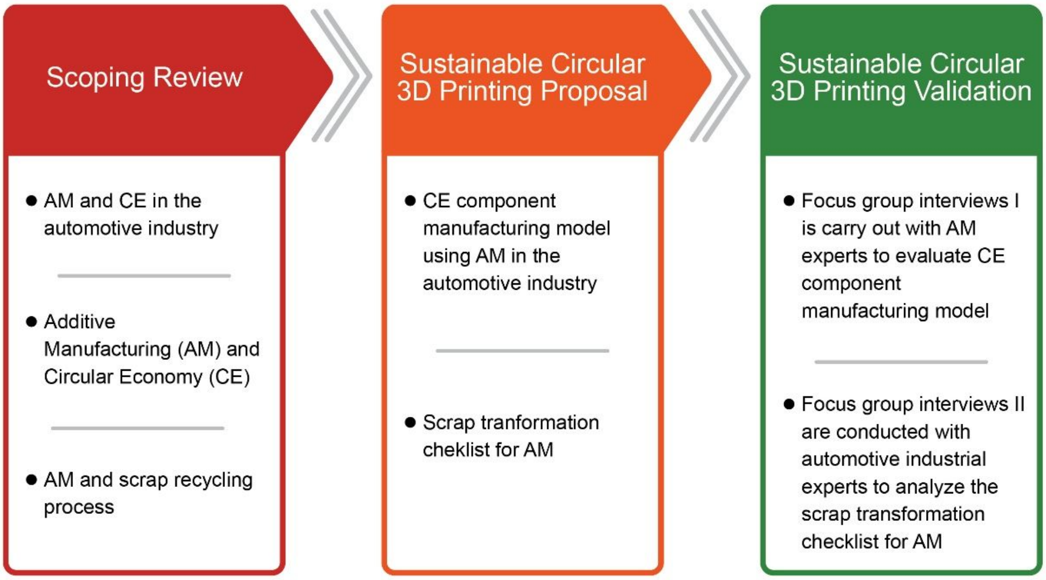

Figure 1. Research Steps

2.2. Data Collection

The literature and documents reviewed were carried out to find relevant research studies and evaluate their respective contributions to guide the proposal of the model and focus groups (Voss, 2002). The selected databases were Web of Science (WoS) and Scopus (Julianelli et al., 2020). A systematic approach was conducted with an exploratory data collection and selection from a scoping review procedure (Di Pasquale et al., 2020). The first search logic included ("Additive Manufactur*" and "Circular Economy" and Automotive) in Scopus, generating only four results. The same search was performed in WoS, also generating four results. Thus, the following search ("Additive Manufactur*" and "Circular Economy") in Scopus resulted in 90 results, and the same search in WoS generated 94 results. The literature search to support the scrap recycling processes ("Powder Metallurgy" and "Additive Manufactur*" and Recyc*) generated 26 results in Scopus and 13 results in WoS. All searches were limited to publications in these databases until 02/11/2022 and were published in the English language. The Focus Group Interviews (FGI's) were conducted with AM and automotive industry experts to validate and generalize the use of AM as a CE catalyst in the automotive industry. The profiles of the 12 FGI's are displayed in Table 1.

Table 1 - Profiles of the FGI's Experts

Code	Experience	Specialities	Role
A1	12 years	Industrial Assembly	Mechanical Engineering in Automotive Industry
A2	17 years	Planning and Control	Industrial Engineering in Automotive Industry
A3	11 years	Instrumentation	Electrical Engineering in Automotive Industry
A4	20 years	Project Management	Management Engineering in Automotive Industry
A5	22 years	Project Management	Engineering Coordinator in Automotive Industry
A6	15 years	Software Engineering	Systems Engineering in Automotive Industry
A7	16 years	Software Engineering	Systems Management in Automotive Industry
A8	14 years	Product Design	Mechanical Engineering in Automotive Industry
A9	21 years	AM Specialist	AM coordinator in R&D Center
A10	06 years	AM Specialist	Mechanical Engineering in Manufacturing Company
A11	12 years	AM Specialist	AM engineering in R&D Center
A12	18 years	AM Specialist	Mechanical Engineering in AM Machine Supplier

The interviewees were selected considering the processes and best practices that guided this research. Based on this, academics who had investigated AM for at least five years and experienced automotive industry practitioners with at least ten years in this sector were invited to participate in the study (Vasileiou et al., 2018). The FGI's were held with eight expert engineers from a leading international commercial vehicle manufacturer between June 2018 and May 2019 for the authors to familiarize themselves with vehicles of interest to the current automotive industry, map the vehicle's components and obtain technical information and sufficient additional knowledge to implement the designed model. Besides, the authors carried out another FGI's between January 2022 and February 2022 with four AM experts. As a starting point, it was necessary to authorize the registration of search information such as data, photos, and videos. Focusing on the study RQs, the following is an overview of the question guide for the FGIs.

Automotive industry experts main questions:

a. Are there any sustainable components in any of the vehicles produced by the company?
b. Have any components used in the vehicles already been produced by 3D printing? If so, which?
c. What components can be recycled in the automotive industry?
d. What are the main alloys used in automotive industry components?
e. How are the choices made for the materials for each component?
f. How are defective components (or those that have reached the end of their service life) disposed of?
g. Are there any losses during assembly or other operations?
h. Is it possible to obtain any discarded automotive parts from the industry itself for use in the research?

i. How are component failures detected? In general, are these failures due to project choice?

j. What mechanical tests should be done to validate the reproduced components?

Automotive industry experts Closing questions:

k. What are the prospects for sustainable vehicles (mainly new electric vehicles)?

l. How can AM technologies benefit sustainability for the factory?

AM experts questions:

a. What about the scalability of the AM method?

b. Can it produce enough parts to sustain all of the automotive industry?

2.3. Data Analysis

The analysis of the data collected in the previous section began by selecting studies that were carried out in three stages of the scoping review, namely: (i) title and abstract reading; (ii) results and conclusion reading; and (iii) complete articles reading. The inclusion criteria included research works related to (AM and CE) or (AM and CE and automotive industry) or (AM and scrap recycling process). The scoping review is a practical and increasingly popular way to collect, organize and analyze useful information and develop a big picture of existing scientific evidence (Armstrong et al., 2011). Therefore, collating and summarizing the results and findings on AM and CE to achieve sustainable practices in the automotive industry is reported in the literature review (Section 3) and scrap transformation checklist (Section 4.2.2), guiding the creation of the model and FGI's.

In the FGI's, a seminar for workers was held at the meetings, explaining the study's context and aims, including the stages of the proposed model to achieve the results. The questions were shared with the AM and automotive industry experts to discuss and validate the sustainable circular 3D printing model, also AM scalability and economic aspects in general for the automotive industry.

The FGI's were focused on several socio-technical discussions (Nascimento et al., 2019).

3. Literature Review

3.1. *Additive manufacturing (AM) and circular economy (CE)*

Yadav et al., 2020 pointed to I4.0 and CE as the future for organizations to achieve global sustainability. A crucial aspect of the I4.0 scenario is to allow technologies to create objects or equipment that work with the virtual and physical worlds coupled with intelligent networks and independent management processes (Bousdekis et al., 2021). AM often referred to as 3D printing, eminently represents the I4.0 concept and unlike conventional subtractive manufacturing processes, it encompasses additive means of production, in which three-dimensional physical objects are produced (Gebler et al., 2014). Amid this growing awareness of aspects such as sustainability and energy efficiency, it is also considered one of the most effective technologies, with the potential to provide adequate responses to markets, in a long-term sustainable perspective. AM offers the possibility of forming parts exactly with the required shape and material, without waste (Faludi et al., 2017) and is associated with potentially strong stimuli for sustainable development (Gebler et al., 2014).

On the other hand, according to Slotwinski and Garboczi (2015), some of the barriers to the use of AM materials include: the relationship between material properties and powder properties is limited; a characterization of AM materials is required, including input material characteristics such as powder size, shape, and chemistry; there are no standardized AM-specific methods for conducting interlaboratory studies of AM materials; the underlying factors responsible for machine-to-machine variability; and the qualification of raw materials, including metal powders, is limited. Although AM represents a relatively new technology with some manufacturing challenges, AM's mid-term global market potential through 2025 is estimated at US$230–550 billion (McKinsey Global Institute, 2013). This technology is becoming increasingly relevant as research activities on new metallic materials, printing processes, simulation and optimization techniques and algorithms are growing (Isasi-Sanchez et al., 2020). Recently, AM has gained a lot of attention as the process has proven to be compatible with industrial manufacturing beyond prototyping (Gershenfeld, 2012). Therefore, AM is likely to be fully incorporated into industrial processes in the near future (Isasi-Sanchez et al., 2020).

Furthermore, CE has been heralded as a new entrepreneurial mindset that can help organizations and society progress towards sustainable development (Ibn-Mohammed et al., 2021). According to Despeisse et al., (2016), CE allows processes to be considered in terms of sustainability, as the end of a process is the beginning of another, which greatly minimizes waste in processes that are normally discarded to the environment. MacArthur et al. (2015) suggest that CE is based on two key cycles, the technical cycle which focuses on extending the shelf life of a product through circularity strategies that include reuse, recycling, repair, refurbishment and remanufacturing (Zhao et al., 2015), and the biological cycle that uses renewable materials, reuse energy and can regenerate ecosystems. However, very little attention has been paid to operationalizing CE principles and practices at the level of manufacturing systems (Kumar et al., 2019). CE adoption can encompass a range of sustainability practices (Ghisellini et al., 2016), such as remanufacturing and "cradle-to-cradle" practices (Ünal and Shao, 2019) and offers opportunities for new business models; nevertheless, they can provide new perspectives to ensure sustainability (Durán-Romero et al., 2020).

Given this, layered manufacturing of AM can lead to structural changes in the economy and society and can fill the missing link to promote the spread of circular systems to realize effective circular economies (Angioletti et al., 2018). AM is described by Gershenfeld (2012) as part of a social transition, which "turns data into things and things into data" and therefore contributes to a knowledge-based economy (Gebler et al., 2014). There is widespread interest in manufacturing that awaits a shift from linear to circular systems, where biological and technical safeguards are possible (Unruh, 2018). Therefore, it is possible to identify a convergence of AM in the CE context, as AM practices provide greater flexibility, customization and agility in the delivery of new products or spare parts to the market (Gunasegaram et al., 2021) and can be widely explored and adapted to processes, projects and products to benefit CE, with their benefits extending to sustainable SCs (Sun et al., 2020).

3.2. AM and CE in the Automotive Industry

By 2025 the top five markets for AM are, according to McKinsey Global Institute (2013), consumer products, aerospace manufacturing, automotive manufacturing, medical components and tools, with consumer products and automotive manufacturing representing the largest potentially applicable markets for AM, as they are expected to have a combined share of 86% of the total manufacturing market (Gebler et al., 2014). In this context, AM presents an opportunity for the automotive sector to better manage the life cycle of its products and utilize recycled materials in new projects or spare parts (Sauerwein et al., 2019; Sun et al., 2020). Therefore, aiming at the continuous and incremental improvement of manufacturing processes in the automotive industry, operational excellence and CE practices are viable means to achieve greater sustainability and profitability of product designs (Dev et al., 2020; DePalma et al., 2020).

Corporations, including car manufacturers, are increasingly exploring extended CE strategies to increase the sustainability of their products (Julianelli et al., 2020). The CE paradigm focuses on reducing non-renewable materials and energy, promoting renewable raw materials and energy, and maintaining products/materials in use throughout the life cycle of a system (Gebler et al., 2014). In addition to these processes, the remanufacturing of recycled waste is a critical factor and necessary practice to enable the implementation of CE using AM technologies (Colorado et al., 2020). Remanufacturing is a practice that uses recycled materials to create new products that are printed in AM and validated through mechanical tests, i.e. they are mainly needed in the context of the automotive industry (Hernandez Korner et al., 2020). This process is necessary as many AM printed parts can be assembled in a more complex industrial assembly process and/or require some mechanical treatment to validate the remanufactured process versus the traditional process (Yadav et al., 2020; Ferreira et al., 2021; Ponis et al., 2021). Therefore, AM and CE can be widely used in sustainable projects, processes, products and businesses in the automotive industry. This integrated practise can be used both in new projects and in the maintenance of existing products to drive sustainable practices (Dev et al., 2020; Son et al., 2021).

4. Sustainable Circular 3D Printing Model

4.1. CE Component Manufacturing Model using AM in the Automotive Sector

Based on the information obtained from the scoping review and FGI´s, the researchers developed a CE model for metal automotive parts. The model aims to take advantage of the metal parts of automobiles that reach the end of their useful life to manufacture new parts with the same characteristics as the old parts. For this, a car is disassembled, and the metal parts are classified according to their metallic properties. They are then be subjected to a novel mechanical treatment that transforms them into a metal powder that can be used in the heads of metal 3D printers to produce the metal components that can be fitted in a new sustainable vehicle. The proposed model is illustrated in Figure 2.

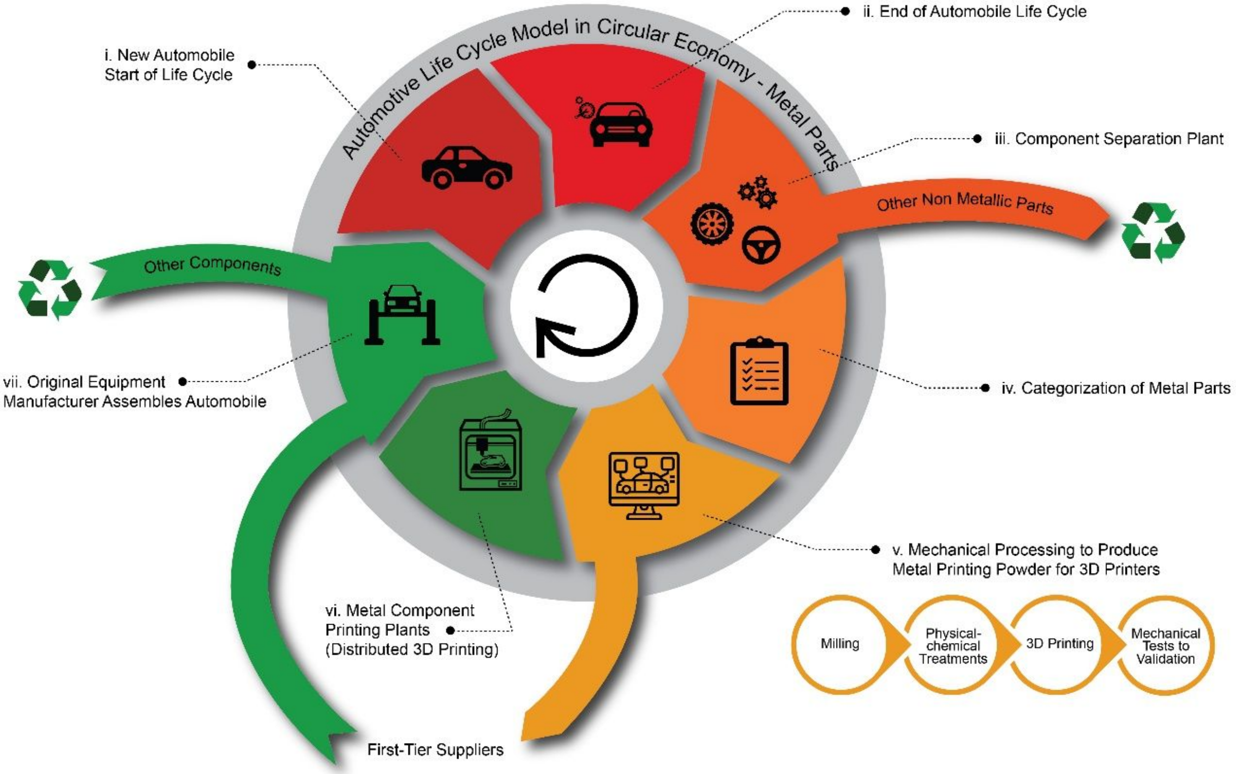

Figure 2. Automotive life cycle model in a Circular Economy Metal parts

i) The automobile reaches the end of its life cycle: When an automobile is no longer in use, generally due to ageing, it is not time to discard it completely, but to take advantage of its components.

ii) Component separation plant: In specialized plants, the automobile is disassembled and its components are sorted by material. There will be metallic components and non-metallic components. The non-metallic components are sent to specialized recycling suppliers. The metallic components proceed to the next phase.

iii) Categorization of metallic parts: Not all a vehicle's metallic parts have the same mechanical characteristics (hardness, tensile strength, compressive strength, torsional strength, etc.). So, the metallic components are classified according to their characteristics. It is important to note that the aim is to manufacture new metal parts from the input of each category so that the newly manufactured parts have the same properties as the inputs.

iv) Mechanical process to obtain metal powder for 3D printers: This is a novel process that allows a metal powder to be obtained from each metal category defined in the previous phase. This powder can then be used in 3D printers to build new metal parts with the same characteristics as the inputs. So, categories of metal powder are obtained that will be used to print the new metal parts. For example, the metal powder for manufacturing metal body parts will differ (a different category) from the metal powder used to print vehicle chassis components. This novel process is described in greater depth in the following section.

v) Metal component 3D printing plants: The metal powder is distributed to plants with 3D printers for the production of new vehicle parts. Depending on the component to be manufactured, the corresponding metal powder category will be used so that the metallic properties of the new component are identical to those of the category used as an input. The plants will be located in geographic areas close to the Original Equipment Manufacturer (OEM). Certain components will be supplied directly from these 3D printing plants to the OEM, while others will be supplied to Tier 1 suppliers who will perform operations on them (e.g., constructing a new component by welding different parts together).

vi) Automotive assembly: The OEM receives the metal components, from either the 3D printing plant or Tier 1 suppliers. They also receive recycled non-metallic components from other suppliers. The OEM factory produces a new car with all the components.

vii) Beginning of the automotive life cycle: the new vehicle is put on the market and its use begins.

The following section focuses on the novel mechanical process to obtain the metal powder for the 3D printers.

4.2. Scrap Transformation Checklist for AM

4.2.1. Overview of the Transformation Checklist

Scrap transformation is a vital process for future recycling procedures as it enables the fabrication of new and sophisticated products or prototypes from old materials. There is a wide range of projects in a number of different industries that are required to be sustainable due to their current negative impacts on the environment. In light of this, the collected data have been used to develop a scrap transformation model for reutilizing solid metal scrap materials in the automotive industry. As shown in Figure 3, the scrap transformation chain is formed of a sequence of four main stages with each stage associated with a process applied to the input material. The concept of the model was constructed as a step-by-step procedure based on mechanical and chemical processes found in the literature, the need to overcome the barriers and obstacles faced by real-world industries, and in terms of the sustainability of a process that conceptualizes I4.0 and CE.

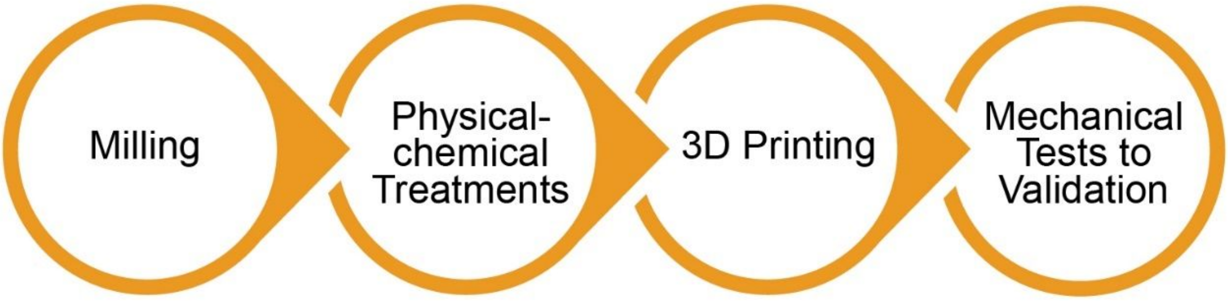

Figure 3. Focus of the four main stages of the transformation of scrap into new components

In the first step, “Milling”, the materials are ground to produce inputs with the desired properties for 3D printers. However, when solid materials are transformed into particles, breaking them causes fractures in their structure and, consequently, the loss of their mechanical properties, which are indispensable for the desired quality of the final product. So, the second stage comprises physical-chemical treatments that are applied to recover their mechanical properties and also to improve other properties such as their morphology, microstructure, and intrinsic properties.

The third stage considers component printing using 3D CAD/CAE tools and the designed digital concepts. Products with different shapes and sizes can be printed, mainly for geometrically complex mechanical components used in industrial applications. Here, parameters are considered such as the 3D printer type (SLS, SLM, LOM, BJ, EBM, among others), the laser power input (if applied), scan speed, hatch distance, the temperature, whether it is necessary to have an inert gas content to protect the print chamber from combustion and other parameters that are dependent on the material type. Finally, the last step consists of running various mechanical tests to check the characterization of the material as well as the performance of the sustainable component produced in the 3D printer. In other words, this phase deals with the assembly of the end product built from components that have been printed using the treated materials. The first use of the component will probably be orientated toward prototypes, mainly in the automotive and aerospace industries, and involve in-depth testing. However, the recycled end product can be sold directly to customers to start a new life cycle.

4.2.2. Focusing on the Scrap Transformation Checklist

This section explains each stage of the process in greater detail and is divided into substages directly related to the literature, as shown in Figure 4. The innovation presented in this study is a scrap transformation checklist that combines CE practices and AM for automotive industry.

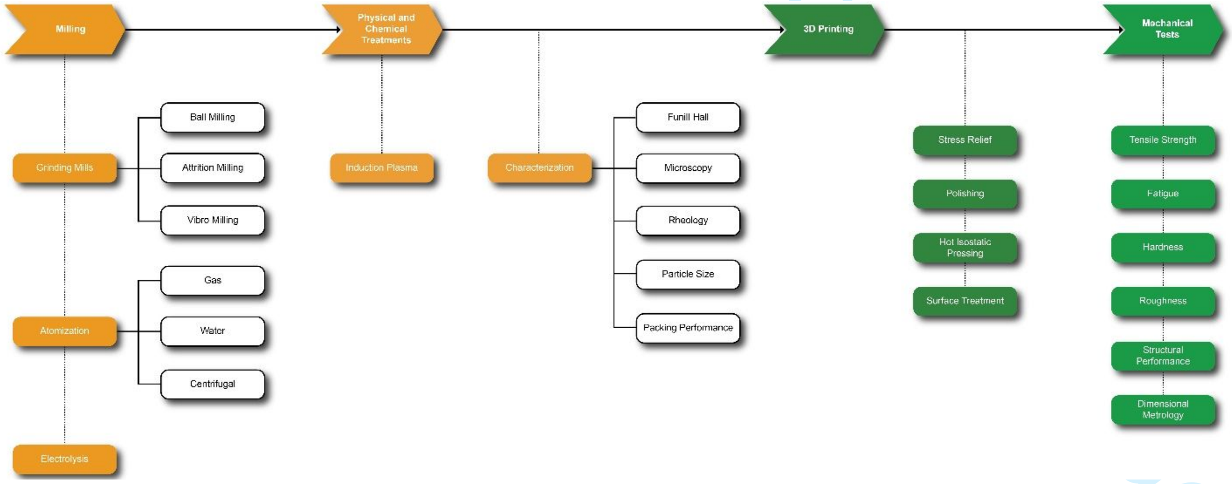

Figure 4. Extensions of the four main stages in the transformation of scrap into new components

To facilitate the scrap transformation process, a table is provided that indicates what the industry needs to adopt during the milling phase with respect to particle size, morphology, and time and cost criteria (see Table 2).

Table 2. Comparative table of different powder production processes

Technique	Estimated Particle Size (µm)	Morphology	Time (hrs.)	Cost
Grinding Mills	1.5 - 100	Irregular	10 – 25	Moderate
Gas Atomization	10 – 40	Spherical	< 1	High
Water Atomization	20-2000	Rounded	< 1	Moderate
Electrolysis	0.1 – 30	Dendritic	2 – 10	Moderate
Oxide Reduction	1 – 10	Porous	1 – 7	Moderate
Carbonyl	1 - 10	Spherical	Not specified	Low
Hydride–Dehydride (HDH)	< 150	Porous	1 – 4	Moderate

The waste treatment phase is the most crucial step in the model as this is where the scrap materials are turned into inputs for compatible 3D printers. These inputs require good metrology control with an analysis of the particle characteristics, as mentioned in the literature. The 3D printing stage is the construction process and begins with a one-piece graphic design in 3D CAD systems (i.e., Building Information Modelling) that enables any design defects to be detected before starting tooling production. The last part of this phase consists of applying post-treatment processes to 3D components that guarantee any new characteristics that are required. The last of these processes contemplate a series of mechanical tests to be performed on the sustainable printed component.

4.2.2.1. Milling Processes

Milling is the first step in the scrap transformation process. It consists of breaking down, separating, sizing, or classifying aggregate material to fabricate powder (Kim et al., 2020). There are several processes for obtaining metal powder and their choice depends on the material's property set and the powder's desired characteristics (Dire et al., 2021). The most used processes are Grinder Mills; Atomization; Electrolysis; Oxide Reduction; Production from Carbonyl Derivatives, and Hydride–Dehydride (HDH). Each technology needs to operate under certain operating conditions and deliver different characteristics of the powder produced (Dawes et al., 2015).

4.2.2.2. Induction Plasma

After the milling process, the particles lose their mechanical properties, which need to be recovered by applying a physical-chemical process. According to Boulos (2011), Plasma Induction is a property recovery and particle spheroidization process through the application of a plasma induction heating and melting process. An improvement in the density and packaging is expected, along with the removal of unwanted particles, a reduction in the oxygen that can accumulate in reused materials (as in this work), the elimination of internal cavities and fractures in the powder, and a change in the morphology of the particle, which is preferably left with a spherical surface. Plasma Induction can effectively process powders with high purity, good sphericity, small particle size, and no internal pores (Yu et al., 2017). Plasma spheroidization can provide consistent results in manufacturing or recycling powders. In the plasma process, the powder particle size, morphology, and yield are influenced by some key factors, including the power of the plasma generator, gas composition, and pressure (Dire et al., 2021).

4.2.2.3. Powder Metallurgy

The powder's post-treatment (Induction Plasma) characteristics need to be examined to determine the properties achieved in the process and whether they conform to what was expected or whether the process needs to be repeated (Kim et al., 2020). So-called Powder Metallurgy (PM) has a huge influence on the manufacture of products in the AM industry. According to Dawes et al., (2015), the SSCs for metal powders used in AM is currently growing exponentially, and with this growth come new powder suppliers, new powder manufacturing methods, and increased competition. The high number of potential SSCs options provides AM service providers with a significant challenge when making decisions on powder procurement. Powder behavior is dependent on the main properties: flowability; density; size distribution; compressibility (or packing); cohesive strength, and morphology (including particle sphericity). By understanding and controlling these, the material's final properties can be improved for different applications and become more reliable in AM production, thus creating a desire for I4.0 scenarios.

4.2.2.4. 3D Printing

This stage refers to the 3D printing process carried out with the outcomes of the previous stage. The process allows the rapid construction of parts and models through the sintering (using a laser) of the material used in the printer, mainly the metal powders that are addressed in this study. In engineering, 3D printing allows to try out new prototypes, even those with complex internal structures and geometries, and to address problems and find solutions to them, which is something that traditional methods just cannot offer (Biedermann et al., 2021). Products ready for use immediately after the printing process are expected to go directly to the testing stage, but these can be applied if they require any unique mechanical or thermal treatments for the use they are to be put to destination (Riquelme et al., 2022). Thanks to the diversity of materials, 3D printing technology can produce high-value products in an industrial context using the scrap treated at the beginning of the new model design process (Xie and Dittmeyer, 2021).

4.2.2.5. Mechanical Tests for Validation

According to Meggiolaro and Castro (2009), a material's properties quantify the different responses of the material to the loads imposed on it. The main properties that need to be tested are hardness, ductility, elasticity, yield stress, and rupture strength. When discussing AM issues, some authors had already established applications and results in AM-produced specimens. Le et al., (2016), Beretta et al., (2017), and Asgari et al., (2018) investigated the fatigue and tensile strength performance of several materials (e.g., Ti6Al4V, Inconel 718, and AlSi10Mg) produced by 3D printers. In the tests, regions of porosity were responsible for early crack initiation, which limited the parts' fatigue life.

Applications are the most important step in producing a component (e.g., automotive, aerospace, nuclear, and biomedical industries). These industries provide the next major opportunity for AM with structural performance as one of the key challenges that they have to address. Walker et al., (2017) studied and tested a range of components produced with the AM implementation in the above-mentioned industries. These tests demonstrated that the 3D printed components achieved maximum structural performance such as strength, stiffness, vibration performance, failure detection, and weight reduction; mainly from automotive and aerospace is the light-weight materials to enable structural elements to deliver the same, or enhanced, technical performance while using less material. Precision metrology is another key factor for inspecting the dimensional tolerances and surface quality of AM manufactured parts (Xin et al., 2021).

5. Discussion

Considering the results obtained, a summary of the primary key findings of this work is presented through a mind map (see Figure 5), and a subsequent broad discussion between scoping review, the sustainable circular 3D printing model and FGI's is conducted in favour of generating knowledge.

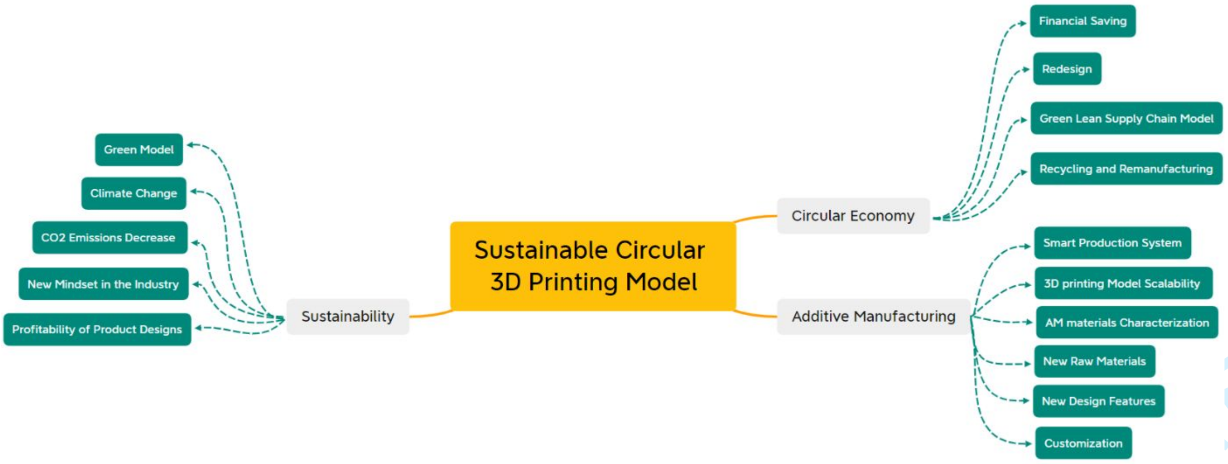

Figure 5. Key Findings Summary Mind Map

As shown in Figure 5, it is possible to identify the implications and relationships derived from the sustainable 3D printing model for recycling scrap metal in the automotive industry context. The data extracted from the automotive industry experts' interviews were analyzed along with the literature review, answers relevant to the search were obtained, regarding sustainable components in the industry the contemporary specialists stated that: "*there are simple sustainable components in the automotive industry like tires and fabrics with natural fibers", which shows that actions to improve sustainability are possible.* Specialists affirmed that components manufactured with 3D printers are already in use *"[made] not with metal materials but only polymer and resin: door handles, some pipes, support assemblies, and design aids*". The components that can be recycled are all parts that can fulfill their role in the project after the process to reintroduce them via the 3D printer (Nascimento et al., 2019). All the metal alloys are used in the automotive industry, with aluminum alloys and stainless-steel components the main materials chosen for scrap sorting in the literature (Kim et al., 2020; Xin et al., 2021).

Specialists from the automotive industry assure that "*the criterion for choosing material for component production is desirable structural performance*", which illustrates the importance of the validation tests mentioned in this work (Asgari et al., 2018). In terms of the discard process, they state that "*currently in the automotive industry there are no processes to dispose of components with an expired service life or the scrap from the production stage. On the contrary, we need to outsource the work and pay for their disposal*". This may increase internal costs, which could be avoided if the CE model were adopted to reintroduce discarded materials into the SCs (Colorado et al., 2020; Hernandez Korner et al., 2020).

There were stated to be losses during the manufacturing operations that could be avoided with an effective sustainable circular 3D printing model intervention. Aiming at a scope that included not only production but the use of third-party products, for example in the detection of failures of mechanical components, the engineering experts stated that "*we normally use VP30, a liquid penetrant that makes cracks visible in components. It would be good if we had our own discard process for these products*". This shows that other types of processes may exist for recycling that can be addressed in future research, for example. Regarding tests to validate the components, "*they will depend on their function. If the component undergoes vibration, traction, compression, or fatigue, mechanical properties such as the hardness and tensile strength will need to be evaluated*". This confirms the importance of including a test stage as the model's fourth stage.

The final issues are directly linked to the study RQs; the FGIs experts have full expectations and anticipate the adoption of sustainable components that could be beneficial to both industry and the environment. Concerning the benefits that come from implementing the model: "*The benefits are overcoming multiple financial and environmental challenges*". A critical analysis of the implications of the proposed model for theory and practice pinpointed the changing power of choice in a real engineering project, which shows that the AM and CE concepts can be integrated and implemented. The FGIs generated an understanding that the steps in the model can be applied in a real-world industry.

Although the objective of this work is not to study the financial implications of the contributed components recycling model, from the scoping review, it could be deduced that this model would have important financial repercussions in the automobile industry. Then, AM in the automotive manufacturing process is increasing due to the significant need for flexible and agile SCs with economic benefits (Gunasegaram et al., 2021). Vasco (2021) affirms that achieving a high level of customization is one of the significant advantages of this technology, and accordingly the manufacturing cost is not increased. Besides, AM technology allows having a "digital warehouse" instead of a stock of physical parts, where all the 3D model files can be stored to be used when required, which already means a positive economic impact (Vasco, 2021). The feasibility of AM on industrial use will be increased with the entry of recycled raw material supply (Sauerwein et al., 2019; Colorado et al., 2020).

The cost of raw materials for parts production is potentially reduced, fostering competition on the market (Sun et al., 2020). Other authors (Giffi, Gangula and Illinda, 2014; Thiesse et al., 2015) affirm that another AM positive economic impact related to manufacturers and a significant environmental benefit is provided with decentralized manufacturing. The logistics can be simplified through digitalization (Vasco, 2021). In this way, the physical flow of products can be reduced significantly and leads to a substantial reduction of emissions and the gain in logistics lead time for transporting imported parts (Betim et al., 2018; Julianelli et al., 2020).

FGI's AM experts discussed the relationship of AM scalability in the automotive industry. According to them "*with the technology currently available, AM would be able to sustain the spare parts area for end-of-life cars due to the low volume. They claim that to feed the automotive industry's demand today, AM needs to have mass production of spare parts.*" Moreover, "*the solution that AM makes available for metal parts is the direct way of production using binder jetting, for example, that is, machines that manage to give us this productivity*." However, the number of machines needed for this nowadays still do not serve the market as a whole, but that does not impede that with the evolution of production we can reach that point (Xie and Dittmeyer, 2021; Riquelme et al., 2022). Also, FGI's AM experts affirm that "*Depending on the size of the printer and if it is not a very large part to be printed, it is possible to reach a range in the thousands in one month for a single machine*". Therefore, FGI's AM experts conclude that we would have two ways to use AM in the automotive industry.

The first way is the "*already mentioned spare parts, as the number of parts needed is small. It also enters into a minimum batch regime that makes AM competitive without significant design* *changes, and it can be considered to replace a part made a traditional process by AM and be economically sustainable.*" The second path would be "*the aggregation of function, a piece that we can produce only using AM process. Materials with complex geometry can be made more accessible than traditional processes, which can be very expensive, and this part can bring performance gains to your final product*". According to AM experts "*today we do not have the scalability to serve the entire automotive sector, but with the growth and advancement of demand, we have the scalability to grow to that point*".

6.Conclusions

The purpose of this study was to propose a novel circular model and a new sustainable 3D printing process for recycling scrap metal in the automotive industry. For this, we have explored the integration of I4.0 and CE to answered the three study RQs. Considering the model presented in Section 4, it can be seen that an applied research proposal is evaluated in a large automotive company and AM experts ranging from the broader concept of the proposed CE model to the specific automotive sector metal scrap recycling checklist. The application of the CE model and detailed checklist was evaluated by experts from the automotive industry, which reinforces the consistency of model replication in industries of a similar type.

From a theoretical point of view, our investigation indicated that the literature review revealed that using a 3D printer to fabricate components is a promising line of development, even when dealing with powders directly manufactured from specialized industries or reused powders (Sauerwein et al., 2019; Sun et al., 2020). It is worth emphasizing a point of attention for mechanical tests to compare the performance of the traditionally manufactured product and the recycled 3D printed product (Le et al., 2016; Beretta et al., 2017; Asgari et al., 2018). All the above-discussed issues reveal that these processes can increase productivity and on-demand manufacturing in industries while generating an aggregation of qualitative value and benefits at no extra cost (Vasco, 2021).

In terms of practical implications, a sequence of metallurgical operations was presented to carry out step five of the CE component manufacturing model using AM in the automotive industry (Section 4.1) that uses a scrap transformation checklist for AM (section 4.2), proposing a new process of a physical-chemical treatment that transforms the scrap into powder for 3D printer inputs in conjunction with the I4.0, AM, and CE concepts. The main practical steps are (1) Milling; (2) Physical-Chemical Treatment; (3) 3D Printing, and (4) Mechanical Tests for Validation. These steps had previously been discussed and a more detailed explanation was given of each possible substage. The main challenge is to achieve metallurgical engineering and physical-chemical treatments at production factory-level size, speed, and complexity.

The main limitation of the present work was the lack of milling and plasma induction (the two main processes to manufacture powder from the scrap) equipment at the site where the research was carried out. A lack of investment and subsidies to carry out the processes also hampered the progress of this work. However, the research provided helpful insight into I4.0 use supporting CE practices. The financial aspects of the design, supply, construction, assembly, operation and maintenance of a waste recycling plant were not evaluated in the proposed model, which focused on aspects of technical feasibility and thus, the work could be extended or deepened in the future by analyzing the financial implications of the model provided for the CE implementation in the automotive industry.

Concerning future research, we hope that the proposed model will be applied in practical case studies to support the results of this study. All the processes in the model designed in this study can be carried out, from the separation of the scrap to its milling and the application of the treatments required to recover its mechanical properties, to all the characterization tests of the powder's chemical, morphological, microstructure, rheology properties and the 3D printing of the component using the input produced along with the 3D printing post-treatments. Lastly, the final tests can be carried out on the recycled printed component following all the norms required for validation and the results reproduced in a new scientific article. The idea is to reduce costs while maintaining the product's benefits.

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