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Exploring Industry 4.0 Technologies to Enable Circular Economy Practices in a Manufacturing Context: a Business Model Proposal

Purpose – The purpose of this study was to explore how rising technologies from Industry 4.0 can be integrated with circular economy (CE) practices to establish a business model that reuses and recycles wasted material such as scrap metal or e-waste.

Design/methodology/approach – The qualitative research method was deployed in three stages. Stage one was a literature review of concepts, successful factors, and barriers related to the transition towards a CE along with sustainable supply chain management, smart production systems, and additive manufacturing. Stage two comprised a conceptual framework to integrate and evaluate the synergistic potential among these concepts. Finally, stage three validated the proposed model by collecting rich qualitative data based on semi-structured interviews with managers, researchers, and professors of operations management to gather insightful and relevant information.

Findings – The outcome of the study is the recommendation of a circular model to reuse scrap electronic devices, integrating web technologies, reverse logistics, and additive manufacturing to support CE practices. Results suggest a positive influence from improving business sustainability by reinserting waste into the supply chain to manufacture products on demand.

Research implications/originality – The impact of reusing wasted materials to manufacture new products is relevant to minimizing resource consumption and negative environmental impacts. Furthermore, it avoids hazardous materials ending up in landfills or in the oceans, seriously threatening life in ecosystems. In addition, reuse of wasted material enables the development of local business networks that generate jobs and improve economic performance.

Keywords: Circular economy, additive manufacturing, Industry 4.0, manufacturing sector, sustainable supply chain

1. Introduction

Industry 4.0 is increasingly being explored by academics, researchers, practitioners, and other relevant stakeholders. The idea of Industry 4.0 is underpinned by the advancement of information and communication technologies and data storage. In this sense, it is possible to integrate the workflows of advanced technologies into continuous improvement methodologies, incorporating factors such as the internet of things (IoT), augmented reality, additive manufacturing (AM), big data, cloud computing, simulation, industrial automation, and cybersecurity (Barreto et al., 2017; Li and Yang, 2017; Trompisch, 2017; Wagner et al., 2017). There are great expectations in both, the research and business communities that such technologies will permeate the broadest range of production chains and the service sector (Wood et al., 2014). A considerable number of studies have already been published on the topic, proposing several scenarios and benefits of the implementation of Industry 4.0. For instance, Ivanov et al. (2016), Kang et al. (2016), Lom et al. (2016), Thoben et al. (2017), Wan et al. (2016a), Wollschlaeger et al. (2017), and Zhou et al. (2016) have all suggested that these technologies enable operational efficiency, improved control of data operations, and reduction of energy wastes from machines and processes.

Baccarelli et al. (2017), Liu and Xu (2017), and Schumacher et al. (2016) affirm that these technologies increase productivity because they support greater optimisation and simulation capabilities. This leads to the necessity to use big data and interoperability approaches between applications in order to explore the most of the Industry 4.0 technologies (Foidl and Felderer, 2016; Hortelano et al., 2017; Niesen et al., 2016; Wan et al., 2016b). Another important aspect of Industry 4.0 is the possibility of increasing the customisation of products and delivering a value-add to end users (Li et al., 2017; Wan et al., 2016b; Wang et al., 2017). In addition, the implementation of Industry 4.0 is fostering important social changes in working environments and the possibility of new avenues of communication and entertainment. Hence, also necessary is more research that considers the impacts of such technologies on society and the economy; such aspects tend to be neglected when greater attention is paid to economic and social factors while Industry 4.0 evolves (Einsiedler, 2013; Ivanov, 2018; Prause, 2015; Quezada et al., 2017; Shrouf et al., 2014; Stock and Seliger, 2016).

Several studies have pointed to the need and opportunity for finding a new path of economic development (Parajuly and Wenzel, 2017; Sousa-Zomer et. al., 2018), including dealing with waste generated by society, in a new circular business model that recycles and reuses such waste with the objective of transforming it into higher value-added products to meet the current demands of society (Lieder and Rashid, 2016). However, circular economy (CE) models in sustainable management systems are precarious and do not detail how this approach can be accomplished (Mrugalska and Wyrwicka, 2017), making it difficult to adopt and optimise the CE methods to make them adequate in the particular context for achieving physical-financial goals (Baccarelli et al., 2017; Liu and Xu, 2017). In addition, there is a disconnect between CE and prominent technologies in the sociotechnical context of sustainable manufacturing, such as Industry 4.0, that can significantly increase the productivity of a recycling factory as well as optimise management for workflows in the entire value chain (Baccarelli et al., 2017). Against this backdrop, this study aimed at addressing 3D printing (laser sintering printing) as one of the technologies that can help to achieve the integration of Industry 4.0 with CE practices. However, there were still some technological challenges with consider to the use of AM in CE practices with regards to using various type of waste as inputs to the 3D printers and delivering higher value-added products incorporating digital technologies into current production systems. Thus, the following research questions (RQs) were formulated:

RQ1: How can Industry 4.0 technologies be integrated into CE practices on a theoretical and practical basis?

RQ2: What characteristics should be considered for integrating Industry 4.0 technologies with current CE business models?

RQ3: How can electronic waste and scrap materials be reused with smart production system technologies such as 3D printing?

To answer these questions and bridge the emerging gaps in the literature on this topic, this study aimed to explore sustainable AM as it arises within the context of Industry 4.0, encompassing the technologies involved in proposing a business model that uses web technology, CE practices, and recycling processes through 3D printing. The goal was to reinsert discarded, obsolete or unwanted waste materials into an innovative process chain as feedstock. Aside from proposing the circular smart production system (CSPS) business model, this study used a focus group to discuss model implications for both theoretical and practical matters in the specific context of disposal of junk and scrap from industrial facilities.

2. Literature Review

2.1. Transition towards CE

The Ellen MacArthur Foundation (2013b, p. 14) defined CE as 'an industrial economy that is restorative or regenerative by intention and design'. Some authors (e.g. Despeisse et al., 2017; Geissdoerfer et al., 2017b; Lieder and Rashid, 2016a; los Rios and Charnley, 2017) attribute the introduction of the concept to Turner and Pearce (1990), who used the term to propose an economic model applied to a material balance framework that follows the first and second laws of thermodynamics. However, the term was complemented by Boulding's (1966) work, which describes the planet Earth as a closed and circular system with limited assimilative capacity where, ideally, the economy and the environment should coexist in equilibrium (Geissdoerfer et al., 2017a). In such circumstances, the idea of 'circularity' has emerged to rethink how we use resources not only for production and economic systems but to tackle resource scarcity as human population grows and demands, therefore, grow as well. The CE concepts are now considered to be a potential solution to deal with the challenges of waste generation and resource scarcity and to sustain economic benefits (Genovese et al., 2017b; Lieder and Rashid, 2016b).

According to Geissdoerfer et al. (2017a), CE is 'a regenerative system in which resource input and waste emission and energy leakage are minimised by slowing, closing and narrowing material and energy loops'. However, Nakajima (2000) argues that circularity and service-based systems are not sufficient conditions for sustainable manufacturing. Genovese et al. (2017b) believe that CE is an essential element, and Rashid et al. (2013) even see it as a precondition (if aligned with supply chains) for promoting sustainable development. CE can be achieved through long-lasting processes in design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. It has some similarities to the sustainability concept, such as the use of interdisciplinary approaches to integrate non-economic aspects into development of the sociotechnical context, the need for cooperation between different stakeholders, diversification through taking advantage of distinct opportunities for value creation, and the importance given to system change and innovation. However, CE pushes the frontiers of environmental sustainability and is not just concerned with the delay of cradle-to-grave material flows in the way that sustainable supply chain management (SSCM) is. However, the widespread adoption of CE faces several barriers, among which the following stand out: lack of perception among interested parties about the characteristics of discarded products and the procedural noncompliance of those responsible for an effective product life cycle (Parajuly and Wenzel, 2017); the number of existing industrial plants worldwide for waste treatment and/or recycling is inadequate (Rochetti et al., 2018); the need for changes in the philosophy of design using conventional materials (los Rios and Charnley, 2017); acceptance of recycling and reuse of textile products (Sandin and Peters, 2018); the lack of studies examining the extent to which CE implementation strategies are feasible (Sousa-Zomer et al., 2018); and consideration of the complexity of urban waste (Burlakovs et al., 2018).

CE provides society with a new economic methodology that reintroduces waste as raw material, transforming production systems into circular chains. It generates several benefits, including local waste selection, which supports sustainable logistics (Fleischmann et al., 1997; Islam and Huda, 2018; Savaskan et al., 2004; Shaik and Abdul-Kader, 2018; Srivastava, 2007); reduction of the opportunity cost related to out-of-use electrical hardware recycling in urban environments (Elliott, 2004); adherence to the principles of sustainable development goals (Zamora et al., 2018; Pultrone, 2019); the optimisation and differentiation of products in the market with regards to their supply (Burlakovs et al., 2018); and the rise of new technologies to recover and/or recycle metal materials through AM (Pultrone, 2019). These benefits and barriers should be considered during implementation of CE practices, aiming for business sustainability and a new circular supply chain management that addresses existing challenges through new sustainable management systems that embrace a broad diversity of materials and apply eco-friendly production technologies (Genovese et al., 2017) and that support the creation of new waste management plants in smaller, local environments (Zamora et al., 2018). Thus, we consider that adoption of CE practices, disregarding the socioeconomic context, is necessary to support sustainable supply chains (SSCs) for reducing waste and scrap that would otherwise end up in landfills and aquatic ecosystems. For this reason, SSCM must be combined with CE practices to achieve true circularity.

2.2. *Sustainable supply chain management (SSCM)*

Along with CE, SSCM has been developed in recent decades and has become a strategic approach that allows companies to create a competitive advantage by reducing their energy consumption and use of resources throughout the entire supply chain and operational processes. The influence of sustainability practices on SSCM and operations are expanding due to the major stakeholders holding companies responsible for their environmental and social performance (Genovese et al., 2017). According to Rashid et al. (2013), closed-loop supply chains are considered the most feasible solution for fostering sustainable manufacturing strategies with resource and environmental conservation. These closed-loop production systems usually include recycling, remanufacturing, or reuse chains as end-of-life (EoL) management strategies applied at the end of the useful life of a product in order to improve environmental performance in the context of waste management.

However, the adoption of SSCM faces several regulatory, procedural, technological, and social barriers to achieve the desired maturity levels in SSCM systems (Flygansvær et al., 2018; Geissdoerfer et al., 2018; Gómez-Luciano et al., 2018). A lack of regulations or laws inhibits SSC workflows in achieving continuous and incremental improvements (Silvestre et al., 2018). Further, Hassini et al. (2012) found that market forces, technology, product development, process capabilities, marketing factors, social issues, and sourcing and operations management, transport, and logistics are critical factors in successfully deploying SSCM. However, the implementation of SSCM can generate various social, environmental, and economic benefits for society in the short term through conscious consumption and in the mid-term through the reduction of waste and emissions along the entire sustainable value chain (Hassini et al., 2012; Kong et al., 2018; Taylor and Vachon, 2018). Among other possible benefits are the important technical, social, environmental, governance, and economic factors (Genovese et al., 2017). It is noteworthy that there is a plethora of potential benefits inherent in these dimensions, including customer satisfaction, effective supplier collaboration, positive impacts on and relationships with the local community, rural development, improvement of management skills, continuous improvement of processes, reduction of waste, adoption of environmental practices, and enhancement of technical skills (Gómez-Luciano et al., 2018).

2.3. Smart production systems

From a historical point of view, the first industrial revolution took place in 1750 with the use of water and steam for mechanical production. Later, the early twentieth century saw the second industrial revolution with the advent of assembly lines and mass production using electricity. The third industrial revolution began in the 1970s with the digital automation of production through electronics, information technology (IT), and industrial robotics. The development and integration of these systems led to computer-integrated manufacturing (CIM) systems, currently termed cyber-physical systems (CPS), a milestone marking the beginning of the fourth industrial revolution, also known as Industry 4.0. These CPS enable production systems to be modular and changeable, which is required to mass produce highly customised products (Kagermann et al., 2013). Industry 4.0 is a strategy designed to build a communication system between production equipment and products through a connected smart factory (CSF). CSF is defined as a hyper-connected network-based integrated manufacturing system that promotes the monitoring and autonomous control of all processes, replacing raw materials and preventing waste of supplies and energy and adding value and the coordinating synergy of products and services, all underpinning low-cost, high-variety, and flexible production (Park, 2016).

Manufacturers attempt to enhance the competitiveness of companies by implementing CPS—a framework composed of different types of data acquisition and handling methods, decision-making rules, and other functions—through the convergence of IoT and information and communication technology (ICT) at the manufacturing process level. The goal is to automate decision-making with artificial intelligence (AI) technologies (Lee et al., 2017). However, the way Industry 4.0 technologies can be integrated into existing production environments, and the processes they can support are still under investigation (Kolberg et al., 2016). In addition, despite the fact that smart products can keep up with the necessary resources and orchestrate the production process (Weyer et al., 2015; Ivson et al. 2018), researchers state that automation will not lead to less human interaction and industrial facilities without workers, but competency requirements may change (Dworschak and Zaiser, 2014). In fact, the required individual skills are more likely to increase and become even more specialised. In addition, the capital expenditures underlying the technologies of Industry 4.0 are quite intense, reducing the attractiveness of its implementation (Sanders et al., 2016), especially for manufacturing companies located in the context of emerging economies (Anderl, 2014). Thus, smart production systems still have challenges to overcome, although they can support business sustainability with positive impacts on environmental, societal, and financial performance.

2.4. Additive manufacturing (AM)

AM is the process of producing objects on a three-dimensional (3D) model by joining materials, layer by layer, directly from raw materials in powder, liquid, sheet, or filament form without the need for moulds, tools, or dies (Kellens et al., 2017). 3D printing technologies offer considerable advantages, such as making lateral moves less risky because products can be manufactured on demand with minimal costs; enabling companies to easily move upstream or downstream to rapidly change the degree of vertical integration (depending on the nature of the innovation considered); and enabling business models to become modular and adaptable (Rayna and Striukova, 2016). According to Kellens et al. (2017), there is a growing consensus that 3D printing technologies will be one of the next major technological revolutions. Thus, AM is a revolution for engineering design and manufacturing and has profound economic, environmental, and security implications.

In Rayna and Striukova (2016), AM is also referred to as 3D printing, where a 3D CAD model is created. The utilisation of AM allows manufacturing of a component that is often geometrically complex, composed of a series of layers of material, each of which is 'printed' on top of the former, (i.e. by the deposition of successive layers of the material). In contrast to conventional subtractive processes, such as milling or machining, AM systems are able to print functional components without the need for tools, while producing minimal waste. For instance, hard metal materials that are traditionally difficult to process efficiently using a stripping process can be easily produced by 3D printers (Kellens et al., 2017). The process allows for the rapid construction of parts and models (laser) of the material used in the printer, especially the post-metallic ones used as an example in this study. There are several types of printers, each of which has its own properties and printing processes, such as selective laser sintering, selective laser melting, electronic beam melting, laminated object manufacturing, and binder jetting, among others.

3. Research Method

This study used a qualitative research method that was deployed in three stages (see Figure 1). Stage one was a literature review of the concepts, successful factors, and barriers related to the transition to a CE. It also addressed how SSCM, Industry 4.0, and AM support current CE practices. Stage two provided a conceptual framework for integrating and evaluating the synergistic potential of each of the concepts revealed in stage one. Finally, stage three validated the proposed model by collecting rich qualitative data based on a focus group and semi-structured interviews with managers, researchers, and professors in the field of operations management. The analysis was conducted using category analysis, which emerged from the literature review and from the most relevant issues pointed out by the experts. The approach followed in this work was exploratory in nature because it aimed at collecting the most relevant information available in the literature. It is descriptive because the study sought to reveal how information can be presented to society for CE purposes, and how best to replicate these methodologies and technologies in similar environments. The two approaches used as a research strategy were adapted from Voss et al. (2002): exploration and theory-building.

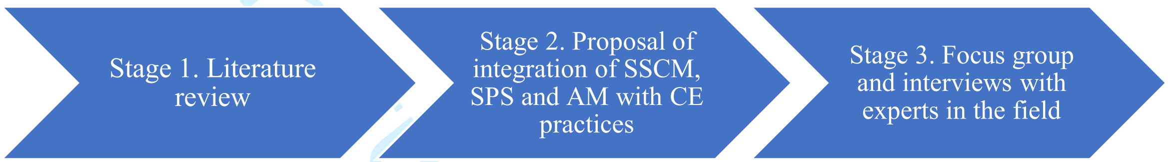

Figure 1: Research Stages

3.1. Data collection

3.1.1. Literature review

A literature review was deployed to locate relevant studies and to evaluate their respective contributions and then formulate RQs. Electronic databases (EDs), including Elsevier (sciencedirect.com), Scopus (scopus.com), and Springer (springerlink.com), were used. The research used classifications for the nature of the objectives, including exploratory and descriptive inductive logic, with data collection from primary and secondary sources using a qualitative approach. In relation to the results, the methodology represented applied research, using the literature to map emerging issues related to Industry 4.0, AM, and CE. For the search of literature, we used *'CE' AND 'SSCM' OR 'Industry 4.0' OR 'AM'* as a keyword string. The review consisted of four stages: (1) formulation of the central RQs; (2) selection and evaluation of studies; (3) content analysis of selected articles; and (4) description of the results. The literature review steps and the selection results are presented in Figure 2. The first step was to determine the barriers, challenges, and obstacles to CE implementation and to examine how it would be possible to monitor or measure their operationalisation through Industry 4.0. In the second step, we conducted the search, considering only scientific papers from journals and reviews related to the environmental and social sciences, engineering, or management that were available in English. In the third step, only titles primarily related to the topics of CE and Industry 4.0 were considered, and the authors reviewed the summaries and read the articles of all relevant texts, adhering to the themes mentioned above.

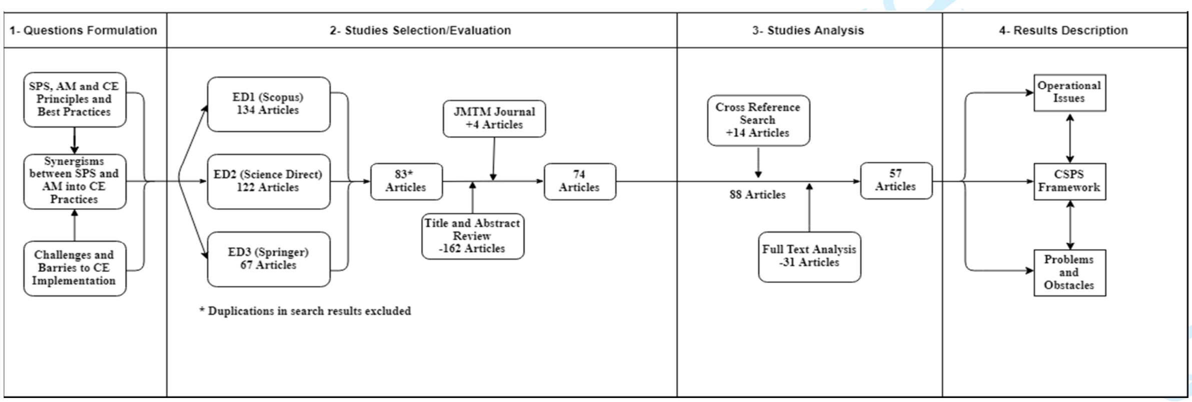

Figure 2: Literature Review Steps

3.1.2. Focus group interviews (FGIs)

For the focus group conducted in the next stage, four discussion rounds were conducted from September 2017 to November 2017 with 19 experts (six mechanical engineers, eight professors of operations management, two automation engineers, and three production engineers) who are specialists in 3D printing and materials engineering. A focus group is a qualitative research method encapsulating principles of stakeholder analysis in a qualitative manner for the accentuation and incorporation of preferences in the decision-making process. The focus group interviews (FGIs) were aimed at discussing potential improvements in scrap metal, polymer, and/or electronic waste management in order to raise the added value of existing wastes for creation of a proposed CE model. At the end, a 'lesson learned' workshop was held with all specialists to propose improvements and to debate the scientific and practical contributions of this process. Initially, a seminar was held for the stakeholders where the presentation opened with an explanation of the study's context and aims, including the stages of the proposed model to achieve triple bottom line results. General information was shared about the respondents and their organisations (e.g. type of institution, name of respondent's department, and his or her position along with their professional experience. Next, the following four sessions were conducted for data collection:

1. An overview of the proposed model, intended to share basic knowledge among participants.

2. Brainstorming with stakeholders about challenges and lessons learned for deployment of the proposed model, discussing facts, data, and mechanisms for implementation.

3. Zoom and filter session presenting the proposed model and evaluating theoretical and practical implications, including outcomes in environmental, social-technical, and economic dimensions.

4. Details on demand session, which was a description of the workflow of CE logistics, AM, and CSPS for replication in future studies.

After the above, an evaluation was completed that consisted of the two stages of interviews focusing on explicit information in the RQs and conducting four FGI sessions to discuss a topic raised by a skilled moderator. As in Mishra et al. (2016), our FGIs were carried out by two researchers, where one researcher facilitated the content and process of the FGI by assisting the participants, and the other recorded the discussion, with prior permission of participants, and subsequently created the transcripts. The duration of each focus group interview was about 60 to 90 minutes. An overview of the moderation guide for focus group discussion is as follows:

1. Introductory questions:
    a. From your perspective, please describe how you define circular manufacturing.
    b. How important is circular manufacturing for your company when compared with other competitive manufacturing capabilities?
2. Main questions:
    a. Based on your experience, what core capabilities are required in manufacturing processes, systems, supply chains, services, managerial practices, and/or technologies to enable a transition from linear to circular manufacturing business models? And how can these be developed?
    b. What are the challenges to implementing circular business models? And what are the key benefits?
    c. How do SSCs provide support for circular manufacturing? What form of advance manufacturing technology does your organisation employ?
    d. How do Industry 4.0 technologies contribute to enabling the circular capability of manufacturing processes and systems?
    e. Please explain the importance of smart production systems and AM in providing a circular economy in your organisation.
3. Closing question:
    a. We want to explore possible lessons learned from circular manufacturing implementation. Is there anything you want to add apart from what we have already talked about?

The opening questions gave participants the chance to become acquainted and feel bonded. For that reason, the questions were constructed so that people could feel confident as the talks progressed, while also identifying common characteristics of the participants. The facilitator functioned as the key person in the four discussion rounds and had the responsibility of coordinating the discussions, while the other researcher was responsible for the recording and taping of the four discussion rounds.

3.2. Data analysis

The abductive data analysis, based on qualitative coding, related to the interpretation and contextualisation of a phenomenon within a conceptual framework (Lewins and Silver, 2007; Nascimento et al. 2017). Finally, the transcripts of the interviews were analysed using open coding to capture any emerging concepts (Strauss and Corbin, 1998; Caiado et al. 2018). In the second phase of the analysis, the data was coded more systematically into theoretical categories which were used to construct the model. In addition, the results of the focus groups and meetings between the authors of this work generated an understanding of the steps and requirements necessary for the proposed model. A critical analysis of the implications of the proposed model for theory and practice was carried out, generating a triangulation between literature, focus groups, and empirical study to create a circular economy model taking into consideration the concepts of Industry 4.0. Therefore, the data analysis was based on the triangulation to generate knowledge through a conceptual framework that detailed the ways to implement CE with the technologies of Industry 4.0 and the challenges to that implementation.

4. CSPS Model

4.1. Overview of the circular model

Numerous initiatives in the manufacturing industry are expected to be reduced due to negative impacts on the environment caused by economic growth. Given this, circular models have been developed for waste reutilisation of solid non-organic materials in urban or industrial environments. The chain is grouped in seven phases with a circular structure, and each phase is associated with the reverse logistics of materials, as described in Figure 3.

Figure 3: Circular model of waste reuse

- Product life cycle: The amount of time the product is supposed to operate under normal conditions. The product may be any manufactured product used in domestic or industrial environments (e.g. a blender, a television, a mobile phone, a microwave oven, a table, backyard chairs, and/or any scrap from industrial processes);
- Selective waste collection: The process of collecting waste after a product's life cycle has ended for any reason (e.g. product is not working, it is obsolete, it is rejected by the user, or the user does not want it anymore, among other causes);
- Waste sorting: This refers to the process of separating waste in authorised recycling centres. Materials can include metal, plastic, wood, glass, or any other recyclable material. The sorting process involves grouping the materials into categories and subcategories in the most chemical processes that transform them into inputs for 3D printers. The transformation of this waste is a critical process for future recycling procedures and will allow fabrication of new and sophisticated products from old materials;
- Waste treatment: This is one of the greatest challenges of the model. In this stage, each type of material must go through specific physical or chemical processes that transform them into input for already developed 3D printers. Transformation is a critical factor for future successful recycling procedures and will allow fabrication of entirely new and sophisticated products from old materials;
- Product printing: This refers to the 3D printing performed with the outcomes of the previous step. By using 3D CAD/CAE tools and the digital twin concept in the designs, it is possible to print products of numerous sizes and forms, from simple decorations to geometrically complex mechanical components used in industrial applications. Products ready to fulfil their purpose immediately after the printing process should go directly to the selling stage. Otherwise, if the item is only one component of a complex product, the item proceeds to the product assembly step;
- Product assembly: This stage refers to the assembly of the final product built from components that have been printed with different materials (e.g. assembling a blender would require 3D printing with metals for the blades and 3D printing with plastic materials for the liquid container and machine base);
- Product selling: Sale of the product is carried out online or in-store. The product made from recycled materials is delivered to the consumer to start a new life cycle, thus completing the cyclical model.

In this section, each phase of the cycle is explained in more detail, as shown in Figure 4 (except for product life cycle and product selling, which are sufficiently explained above and which vary by product and sales techniques). The innovation presented in this study is related to the CSPS model that mixes CE, SSCM, AM, and Industry 4.0 with the stages of selective waste collection, waste sorting, waste treatment, product printing, and product assembly. In this context, an action plan was created to obtain consensus via the FGIs on the implementation of a 'manufacturing model 4.0'. Finally, the stages of the proposed model will be presented according to Figure 4, reporting the guidelines and rules for its application along with potential barriers.

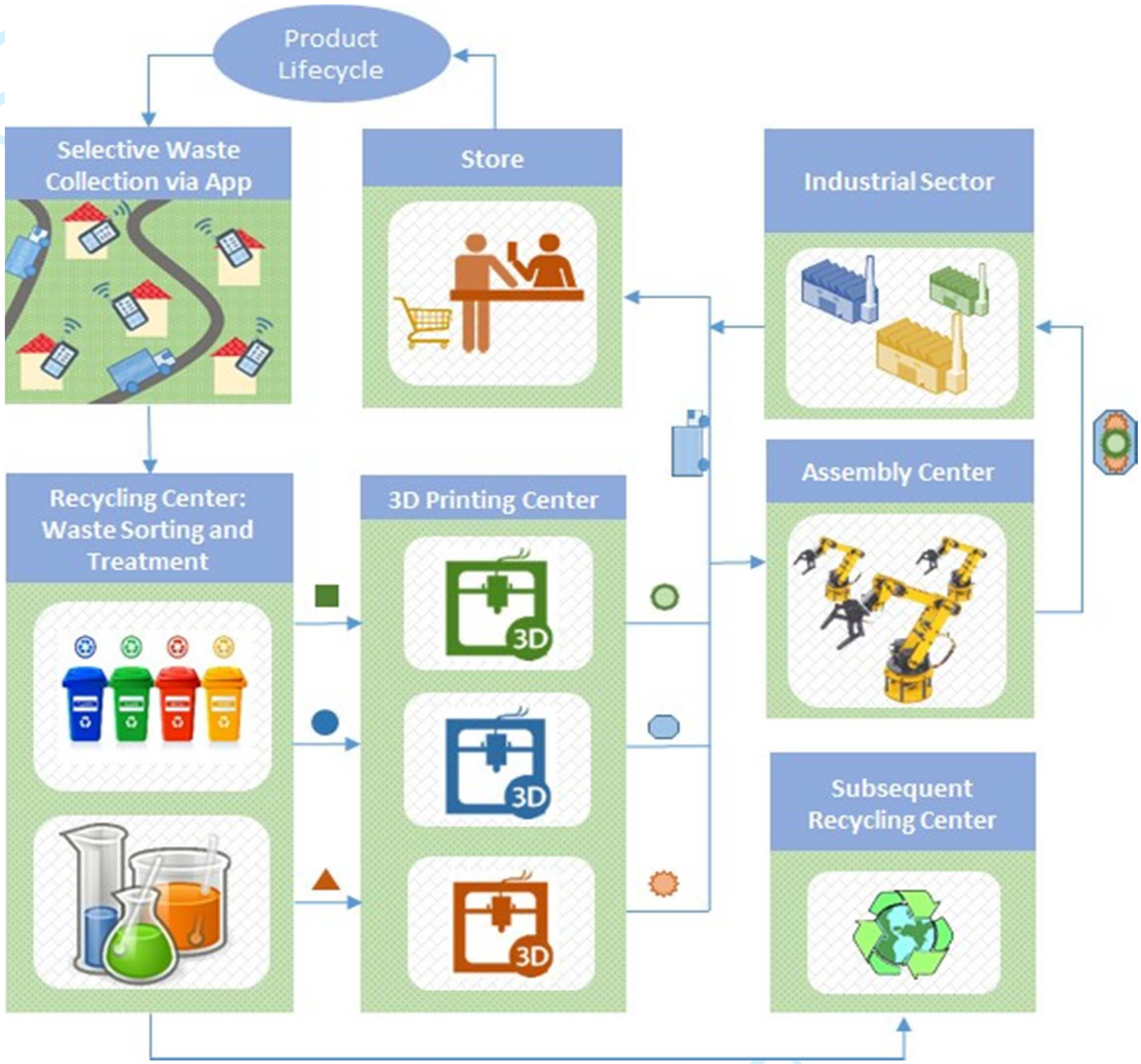

Figure 4: Circular model of waste recycling

4.1.1. <u>Selective waste collection</u>

The selective waste collection phase involves two fundamental elements: cloud computing and the milk run concept (a logistic-transport model that allows decentralisation of waste collection by region and material category). Cloud computing technology facilitates management of all data regarding waste types, amounts of waste, and collection sites in real time. This allows for selective collection of waste based on the collected data. For instance, there could be a large amount of broken household appliances for collection in one neighbourhood, and a large amount of old wooden furniture for collection in another. The waste trucks should be different and have the right capacities to collect appliances or furniture. The traditional collection system of sending a single truck to collect all types of waste at several locations is not ideal.

The collection of waste materials by categories makes the separation stage easier. In order to decide the logistics of collection, it is proposed that a mobile app be used, in which the user registers the waste location with details and chooses the waste categories. Some possible categories of solid non-organic waste would be electrical kitchen appliances, furniture, plastic products, computer hardware, and television sets. With this information provided through the mobile app, it is possible to generate a site map of the waste for disposal throughout the city filtered by category. When combined with the use of specialised software to optimise collection routes based on real-time geographic data and traffic conditions, it is possible to make a smart decision on the type of vehicle needed to collect the waste, customised for each location and using optimised routes.

The concept of the milk run can potentially make the collection process even more efficient. The milk run is a logistics system in which the delivery of one product and the collection of another in a given place are carried out by the same transport (Mei et al., 2017). Figure 4 shows major transport activities that occur in the selective collection and distribution stages to deliver waste to the 3D printing manufacturing sites. In this way, collecting only one type of waste at several sites on a planned route can optimise resources in these stages. It is worth mentioning that it is desirable to have dynamic and fluid processes for collecting waste used in 3D manufacturing in order to minimise inventory. This should be done by producing parts on demand and selectively collecting the raw material according to demand for final products. Once the transportation is restricted to manufactured parts on demand and raw material, it makes sense that, within the same region of the city, transporters deliver the products to customers, and then immediately carry out the collected waste. In this way, the milk run transport system is applied to the cycle, and resource efficiency is enhanced. A final point to consider is that it is desirable to have multiple transport companies involved to reduce the risk of rejected products.

4.1.2. Waste sorting

The separation phase of material leads to the selective collection, taking advantage of the fact that materials arrive at the facility already separated by category. With the help of the mentioned application for mapping the volumes and categories of garbage to be collected, it is possible even before the garbage trucks arrive at the separation centre to obtain an estimate of which sectors of the centre will have to work more or less intensely. For example, if the waste separation centre works with human labour and there are only broken household electronics items coming in, it is not necessary to concentrate employees in the area where they disassemble and separate materials from the category of furniture. In addition, the arrival of products divided by category eases efficient management of the unloading process from collecting vehicles because it allows for obtaining information on the weight, volume, and amount of cargo before its arrival at the separation centre.

If the material separation and unloading activities are automated, which should occur in a true Industry 4.0 context, the data collected via the app would also contribute to the efficiency of the separation centre. Such data can be used by controlling algorithms of conveyor robots that move cargo through the yard or that work with the automatic machinery that actually performs the separation of materials. The collected data can also be used for production simulation and cycle optimisation purposes. Within the separation centre, each category of scrap requires its own separation methods based on its components and materials. The separation procedures for scrap can vary among recycling companies, but essentially, the scraps must be dismantled for the separation of components, and these must be separated by types of material, such as plastic, glass, wood, and metal. These four materials, specifically, can be used as feedstock for 3D printing machine supplies. Glass printing, however, is still a comparatively underdeveloped technology. It is important to note that to date, there are a number of limitations on how such materials should be used as input because 3D printing technology is still taking its first steps. However, it is expected that the obstacles will become fewer over time and the use of this manufacturing knowledge and associated techniques will become ever more widespread.

4.1.3. Waste treatment

The waste treatment phase is the most crucial step for the model. It corresponds to the set of activities associated with the treatment of separated materials in the previous waste sorting phase and is the transformation of these materials into inputs for compatible 3D printers. Importantly, the treatment of the materials is what will, in fact, guarantee or not the operation of this cycle as a whole. Several techniques are currently been used for the production of inputs for 3D printers. For example, the Canadian company Re-DeTec has created a machine called the ProtoCycler for small-scale production or for individual use. It is capable of shredding waste plastic and transforming the material into ABS or PLA filaments—two types of polymers that can be used as inputs for 3D printers already on the market. The Brazilian start-up Print-Green3D is also developing similar techniques for the production of recycled filaments, and it is possible that the level of technical knowledge in this area will increase in the coming years. The same idea could be expanded to the large-scale production associated with a selective collection system that works with large volumes of plastic waste.

3D printing with metallic materials is often done with diversified spray metals or with the inkjet technique. Metals commonly used for these types of printing include stainless steel, titanium, silver, and copper. Other current printing techniques require different input conditions concerning the state of matter and physicochemical properties. It is important to note that for the printing of mechanical components, 3D printing may not provide the surface characteristics specified in the component design or even material properties, such as strength. Therefore, it is possible that other processes must be performed after printing so that the quality of the final product is guaranteed. Some of the ways to manufacture metal powders for 3D printing today are atomisation or chemical treatment. Atomisation, in particular, can be applied to the production of various powders. In this process, molten metal is separated into small droplets that are then quickly cooled before they come into contact with each other or with any other surface. Then, jets of fluid are thrown over the droplets, disintegrating them and turning them into powder. It is possible to produce metallic powders of copper, steel, bronze, aluminium, titanium, and many other metals using this process.

Therefore, in order to create an input for the printers, the treatment of separated waste must include the processing of metals by various chemical procedures to generate ink usable by the printer. For example, stainless steel is used to produce various kitchen items. Therefore, old pots could be a category of garbage acquired through selective collection that would be capable of supplying raw material for the production of inputs and printing of metal parts. This is achieved by proper separation of the steel that is then transformed into a powder.

4.1.4. Product printing

The product printing phase refers to all 3D printing activities that take place within the model cycle. As each printer still currently works with very specific inputs, they should receive these from the previous phase completely ready for the printing process. That is, recycled materials must have all the physicochemical characteristics that are necessary for the printer to operate according to manufacturer specifications. This is the only way to guarantee machine life and print quality. There are already printers capable of working with metallic inputs such as aluminium, steel, and titanium or with various polymers, such as polylactic acid, ethylene glycol, polyethylene terephthalate, or polymethyl methacrylate. Even plastic bottles have already been turned into filaments for 3D printing. In addition, liquid resins and various composites, some of them based on powdered wood, are currently used as input.

In this way, it is possible to say that many materials will soon be compatible inputs for printers, many of which can be found in most urban environments such as the various metals, plastics, and wood currently dumped in landfills or open-pit dumps. Given the diversity of materials and 3D printers for each type, a printing centre with several machines would be able to print a wide variety of parts and products. With 3D printing technology, it is possible to produce architectural model miniatures, toys of all kinds, jewellery, engineering prototypes, medical prostheses and implants, various educational models, bottles with innovative designs, sculptures for decoration, and high-value products in an industrial context, such as mechanical components for machines and robots, among other items. Moreover, within just a few decades, the limitations of this printing technology should shrink significantly. Furthermore, with the aid of other technologies and manufacturing processes, such as micro fusion, it is possible to print models of complex mechanical components using a polymer input that is cheaper than a metallic one. Using micro fusion, the result is often a metal alloy suitable for operation of the component. Due to the array of production possibilities, the presented cycle can produce products for a large variety of customers.

4.1.5. Product assembly

The product assembly phase consists of an automated assembly line that should be as versatile as possible to put together distinct products according to customers' needs. There are many industrial robots with particular workloads, degrees of freedom, and high movement accuracy that can be used in the assembly process. One model commonly used is the selective compliance assembly robot arm (SCARA). In order for the automated assembly phase to be capable of handling a broad range of products, it is necessary to develop a CPS that allows for managing large amounts of data from sensors and that supports optimal decision-making. After all, an optimal automated assembly phase must operate non-stop to achieve production efficiency. Moreover, the data collected through the CPS make it possible to perform computational simulations of real production scenarios as well as hypothetical ones, which permits analysis of the aspects that make the assembly phase profitable. The data also enable quick prevention and correction of operational failures as well as minimisation of unnecessary energy spends. The assembly line sensors controlling the automation of the system should be able to provide positioning signals of a component on a certain assembly stand regardless of the type of material printed. This is important because an assembled final product can be composed of several pieces of distinct materials, thus increasing the range of product possibilities and final customers.

As the whole cycle is based on recycling, an important aspect of the assembly stage is that it is set up in a model that facilitates the final product going through the waste sorting step when its life cycle is over without compromising the efficiency of the new final product. For this to be achieved, it is necessary to design the components and fittings of the final product prior to the printing stage, taking into consideration the process of future recycling and reuse of the component parts. This method of production not only promotes an environmental manufacturing process but also significantly improves the efficiency of the waste sorting step. With this goal, parts can be easily removed from assorted products and reinserted in the assembly step into other printed structures so that not only is a recycling model implemented, but so is a cycle of reuse of components.

5. Analysis and Discussion

To encapsulate Industry 4.0, AM, and the CE concepts, a sequence of steps were presented in the CSPS model: (1) product life cycle; (2) selective waste collection; (3) waste sorting; (4) waste treatment; (5) product printing; (6) if necessary, product assembly; and (7) product selling. These steps were discussed in the FGIs, where the stages most frequently questioned were stages 4 and 5. Stage 5's main challenge is accomplishing the metallurgical engineering to validate the existence of a physicochemical treatment that produces the powder for input into 3D printers. In the validation of stainless steel for this purpose, mechanical tests of fatigue and micrographs should be performed, comparing the performance of the product between traditionally manufactured and recycled with 3D printing. Notably, however, there is a solution for recycling of cast iron, whether grey, white, nodular, malleable, and/or rough (according to the carbon x silicon diagram). After it is sorted and separated by category, a mould is created from a PMMA polymer in the 3D printer. Next, a micro fusion process can be carried out where the scrap cast iron is heated to 1500°C, reaching the liquid state, and is then poured into the PMMA mould. Finally, both materials go through a heating process, and the mould evaporates without leaving any residue.

Step 5 was discussed with regards to its effectiveness and types of printable materials, as well as its printing productivity and reliability as compared to products manufactured using traditional processes. To that end, the FGIs considered that to validate 3D printing, the same tests used in traditional processes must be carried out on 3D printed products, and their performance and quality should be evaluated. It should be noted that this step is strategic for the CSPS model, assuring that the 3D model will provide significant added value and meet market needs. Ultimately, the capability of printing products following the variability of the market reduces the risk of failure and enhances potential sales.

In this way, smart production systems technologies can increase productivity and manufacturing freedom on demand, making it possible to apply just-in-time concepts to sustain continuous production. In this context, the AM is relevant because it makes possible the use of CE by using waste to generate new value-added products. The Industry 4.0 concepts used in the CSPS model are web technologies, designing in CAD/CAE 3D parametric tools, AM, and product assembly using robotic factories with little or no human intervention. Web technologies are used both during the implementation of a collaborative CE in society—aiming to analyse where each category of waste is available by location—and in sales through the internet for companies and/or individuals. Production capacity increases according to product demand since human intervention in manufacturing is minimal and the degree of customisation is high with circular AM being targeted to the needs of each customer. It is interesting to consider the possibilities for designing products in different sectors and tracking in-transit times/locations for effective delivery within deadlines. As a result, there is differentiation in the market and an increase in production capacity, which gives this CE model advantages over traditional business models.

5.1. Research outcomes

5.1.1. Focus group outcomes

The findings of the FGI discussions showed that circular manufacturing is one of the most important factors for achieving higher productivity and reducing waste and pollution. One of the respondents commented, '*Circular manufacturing brings the idea of restoration and circularity to replace the traditional concept of end-of-life*', while another complemented this idea by saying, '*It is the manufacturing that aims to preserve and improve natural capital, optimise resource income, and promote the effectiveness of the system*'. There was a consensus that such a model seeks to increase the use of easier-to-dismantle composting and recycling products so that the materials can circulate in closed loops without generating waste. Thus, it is perceived that this new manufacturing process seeks the use of renewable energy and the elimination of waste through the superior design of materials, products, and supply chains. Regarding the importance of circular manufacturing for the company, it was observed that this is increasingly important as a measure for reducing environmental impact and consumption of resources in manufacturing. The experts stated that this model is aimed at reducing the scarcity of resources and sustaining economic benefits.

Moreover, in relation to the experts' knowledge of what resources would be essential to enable the transition from linear to circular business models, five prominent needs were identified: (1) appropriate product life cycle planning; (2) integrated life cycle options; (3) better alignment between maintenance, reuse, and recycling strategies; (4) the proposal of an integrated management method, considering maintenance plans and operations; and (5) more upgradeability, standardisation, and adaptability of systems. Some of the findings from the FGIs revealed that the challenges to implementing circular business models are that circularly manufactured products are expensive to build due to the high intensity of work. They added that the required reverse logistics and the high costs associated with complexity in planning for remodelling and remanufacturing need to be considered. One participant commented, '*High-speed innovation can make reuse impossible*', which may be an argument for including Industry 4.0 technologies into circular models. In addition, there are no specific guidelines and legal regulations on how to implement CE among sectors, and it seems difficult for managers to estimate the service unit's sales. On the other hand, some key benefits highlighted by the FGIs were the economic savings from reduced use of resources and materials, the resulting loops can enable new models of long-term revenue, and operational and strategic advantages are garnered by reducing resource dependency. In addition, such models have improved resource efficiency, helping to create regional employment, and enabling industries to profit from sharing costs and risks associated with waste.

In regards to the SSC, participants agreed that there are points of convergence with circular manufacturing: including stakeholders' cooperation, integration of socio-environmental aspects, opportunities for co-creation of value, and innovation of business models. One respondent noted, '*Circularity is a prerequisite for supply chains as a prerequisite for sustainable manufacturing, which in turn, is essential for the best eco-environmental performance of developing countries*'. This assertion corroborates the current view that sustainability acts as a driver for redefining the operations function, and SSC has become strategic for companies in creating a competitive advantage. In this sense, this process becomes part of the circular vision that also includes self-sustaining production, viewing the planet as a closed system that balances production with viable relations between technological growth and ecological systems.

With regards to Industry 4.0, participants mentioned that, depending on the level of maturity, digital technologies play an important role in the transition to a more circular economy. If IT is sufficiently mature, it can support the implementation of new business models on a large scale. For example, one of the experts said, '*New technologies can help in data management, and information systems can support material tracking, facilitating collection points for reuse and recycling*'. It is anticipated that technologies such as big data can be used to better calibrate simulations and optimise dynamic models, increasing material recovery rates. The connected fabrication will improve transparency and allow for better control of processes and networks in order to meet multiple demands. In regards to smart production systems and AM, the FGIs generated some patterns across the groups that showed the smart production systems reduce waste, overproduction, and consumption of energy, while AM proposes a new paradigm for the design and manufacture of engineering that has profound economic, environmental, and safety implications. Therefore, it is perceived that Industry 4.0 is a viable path to establishing sustainable manufacturing. Experts also believe that this new digital revolution will bring increased job opportunities, and 3D models will act as enablers of learning and awareness by showing the right ways to do things.

6. Conclusions

The purpose of this study was to explore how Industry 4.0 technologies are integrated with CE practices. This allows for the proposal of a circular business model for recycling waste and delivering new products, significantly reducing resource consumption and optimizing natural resources. In a first stage, the circular business model can be used to recycle electronic scrap, with the proposed integration of web technologies, reverse logistics, and AM as a technological platform to support the model. These have several environmental, sociotechnical, and economic implications for society. First, the impact of reusing materials to manufacture new products minimises resource consumption and negative environmental impacts. The circular model also encourages keeping hazardous materials that seriously threaten life in ecosystems out of landfills and oceans. For this study, it was found that most urban waste is plastic and cast iron, leaving room for improvement in increasing recycling of scrap metal and similar materials. Second, the circular business model promotes a culture of reusing and recycling and motivates the development of collection and processing techniques for urban waste through the use of 3D printing technologies and Industry 4.0. In this way, the involved stakeholders are focused on the technical parts of recycling and can be better dedicated to research, development, and innovation because many of the processes will be automated.

Third, the implementation of circular business models with Industry 4.0 allows for the development of local business networks that contribute to generating local jobs. Many companies could specialise in collecting, processing, manufacturing, and selling products based on the proposed circular business model. There is also opportunity for consulting services that can offer a wide range of assistance with the processes mentioned above, including providing legal and regulatory advice. Finally, it also appears that customers become more aware over time of sustainable products, which increases the possibility of sustainable growth for these business networks. One limitation of the present work is that the perceptions of participants in the focus groups introduces subjectivity. In addition, the sample of experts was small and does not allow generalization of the results. However, the insights provided with this sample provides helpful insights to researchers on the use of Industry 4.0 to support circular business models.

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