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The circular economy and Industry 4.0: synergies and challenges

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Abstract

Purpose – The proposal is to answer the following question: based on previous studies, which are the new paths and challenges related to the circular economy (CE) and Industry 4.0 (I4.0)? To answer this question, the research objective is to analyze studies approaching the interface between CE and I4.0.

Design/methodology/approach – A systematic literature review (SLR) was conducted on previously published studies pertaining to Scopus and Web of Science bases, and 63 articles were found.

Findings – The authors present five new paths and challenges amid the relationship between CE and I4.0: applying those technologies to clean production, using blockchain and big data in the circular supply chain, raising additive manufacturing impact on the CE, seek for a better understanding on how I4.0 technologies can properly support the CE in the stakeholders' view and discerning the factors for implementing those theoretical fields onto supply chains.

Research limitations/implications – Previous studies' sample basis is still recent, lacking research depth. Search strings might have minimized the number of selected studies: there could be a bigger sample.

Practical implications – Practical contributions of this study lay on the applicability of the raised propositions into several sectors' industries.

Social implications – The authors suggest a transition agenda towards CE, using I4.0 technologies for operational, tactical and strategic personnel within organizations, as well as potential utilization strategies in specific study fields, like supply chain management and product manufacturing per se.

Originality/value – The study presents new paths and challenges amid technologies pertaining to I4.0 and its interfaces with the CE. In the result presentation and analysis, the existing interfaces are described.

Keywords Circular Economy, Industry 4.0, Systematic literature review

Paper type Research paper

1. Introduction

The circular economy (CE) is an economic system that aims at reducing resource consumption and eliminating waste, while promising economic development continuity (Kouhizadeh, Zhu, & Sarkis, 2019). The CE is still an emerging concept, and as such, it still lacks implementation tools, and its possible connection to digital technologies is still not widespread. In most instances, transition towards CE requires rethinking and redesigning business models and current routines (Kristoffersen, Blomsma, Mikalef, & Li, 2020).

Within those new business models, new digital technologies may bolster said transition through collecting, analyzing and integrating data. Earlier studies on the themes have shown

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CE and Industry 4.0 (I4.0) advancements as a potential future for organizations, with those concepts being quickly adopted by several organizations to reach global sustainability. I4.0 and CE facilitating factors have broad influence on supply chain-related activities, with suppliers being considered an essential component in that process and, thus, activities connected to them having direct effects on the supply chain sustainable performance (Yadav, Luthra, Jakhar, Mangla, & Rai, 2020). Moreover, we cannot ignore the COVID-19 pandemic influence; it has affected the processes of all those productive chains virtually, causing organizations blocking, social isolation, people distancing and labor migration. This scenario leads companies to question their location and investment strategies (Kumar, Singh, & Dwivedi, 2020).

Therefore, this study presents new paths and challenges amid the technologies related to I4.0 and their interfaces with the CE. It brings the research proposal of answering the following question: based on previous studies, which are the new paths and challenges in the relationship between CE and I4.0? To answer this question, this research objective is to analyze studies approaching the existing interface between CE and I4.0. To this end, a systematic literature review (SLR) of 63 articles has been conducted. To hold up the proposal, this paper is structured – after this section – as follows: a theoretical background, covering CE and I4.0; a section on methodological procedures, describing the SLR protocol; the result presentation and analysis and finally, the conclusions.

2. Circular Economy and Industry 4.0

This section discusses the foundational concepts of the study. We start by the key CE definitions and then discuss I4.0. Both sub-sections prioritize concepts raised by the authors covered by the SLR.

2.1 Circular economy

The CE proposes reducing structures, waste and demand for limited virgin material, as well as promotes eliminating the idea of environment as a "sinkhole" to dump used materials; moreover, resource loss and destruction shall be reduced or eliminated through lower pollution and lower biodiversity loss in habitats associated with resources extraction (Kristoffersen *et al.*, 2020). This model offers a sustainable solution for the disposal issue and minimizes the need for virgin material for manufacturing purposes. This concept has been widely appreciated throughout the world to accommodate the challenge of implementing a greener economy and more effective environmental resources usage (Chauhan, Jakhar, & Chauhan, 2021).

CE requires engaging in several sustainable practices, as global agendas highlight that economic development must also consider social and environmental aspects (Sehnem, Provensi, Silva, & Pereira, 2021). With that, CE might encompass all three major sustainability dimensions: economic prosperity, social justice and environmental quality (Elkington, 1994). Therefore, fundamental changes are necessary in social, industrial and consumption spheres for CE implementation. The CE is a promising approach to reach sustainable development, as manufacturing companies perform a vital role on its implementation at the industrial level, based on their influence on product life cycle definition (Pieroni, McAloone, & Pigosso, 2021). In this context, the CE performs an important duty in industrial production, promoting traits like resource recycling and materials – and also energy – use minimizing. It aims to benefit the economy, the environment and society and to reach great balance and harmony among the three. The CE is perceived as a new business model in which balance and harmony between economy and society is expected to be reached (Ma, Zhang, Yang, Ren, & Liu, 2020). In summary, it is the system that proposes replacing open linear inefficient production cycles' waste by close cycles, in which waste is minimized or converted into value entries, contributing to productivity increase, optimizing natural and human resources use. The CE is by definition restorative and regenerative and aims at keeping products – classified in technical and biological –, components and materials at prominent level of utility and value (Sehnem, Vazquez-Brust, Pereira, & Campos, 2019).

The CE lays on many pillars. In this study, some of them are highlighted: (1) 10 R's (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover) may help companies to get competitive advantage (Bag, Gupta, & Kumar, 2021); (2) cleaner production, which aims at being sustainable through energy conservation, emission reduction and higher production efficiency, is a basic approach that seeks to optimize process environmental management (Ma *et al.*, 2020; Lu *et al.*, 2020); (3) product-service system, which encompasses products, services, agent networks and support infrastructure, working with a continuous flow with the objective of becoming competitive, meeting customer needs and minimizing environmental impact in comparison to traditional business models (Wang *et al.*, 2020); (4) ReSOLVE model, a CE system that uses processes that apply recycling, reusing and remanufacturing within a closed system, which incorporates six guiding principles to this transition: regenerate, share, optimize, loop, virtualize and exchange (Kouhizadeh *et al.*, 2019); and (5) industrial symbiosis, a structure that is based on industrial ecology to perform mutually beneficial cooperation among organizations, sharing water, resources, energy, by-products and residual material, so all agents profit from it; the industrial symbiosis projects material flows in which materials and energy consumption are optimized, residue generation is minimized and one process's effluents serve as input for other processes (Sehnem *et al.*, 2019).

2.2 Industry 4.0

The I4.0 concept was first announced during Hannover Fair, in Germany, in 2011. The fair repost describes that I4.0 would create new values, build new business models and represent the solution for several social problems through communication networks based on emerging technologies (Chauhan & Singh, 2019). In recent years, this transformation has raised interest worldwide (Rejikumar, Raja, Arunprasad, & Sreeraj, 2019). I4.0 is guided by real-time data and offers alternative approaches to reach sustainable production and consumption, minimizing waste, energy consumption and environmental deterioration (Yadav *et al.*, 2020).

I4.0 comprises different technologies, like Internet of Things (IoT), cloud-computing, additive manufacturing, cyber security, cyber-physical systems (CPSs), blockchain, augmented reality, artificial intelligence (AI), big data, simulation system integration and autonomous robots. I4.0 techniques carry capabilities of reducing energy, equipment and also minimizing human resource employment. It is a futuristic construction, which fosters the evolution and solution of autonomous production systems (Kumar *et al.*, 2020). Nowadays, studies on I4.0 have become more popular, tracing to these technologies' recent advancements (Wang *et al.*, 2020).

I4.0 tools may be used to integrate all productive processes' key functions and to share common data, information and knowledge throughout the supply chain. These tools can also be applied to automatize critical operational activities. Nonetheless, I4.0's major impact is its ability to produce and access information in real time, allowing better visibility and the risk mitigation in the supply chain network (Bag *et al.*, 2021). Therefore, I4.0 has enabled companies to independently exchange information and perform activities and controls (Chauhan *et al.*, 2021).

I4.0 is transforming operations management in areas such as industrial automation and manufacturing, supply chain management, lean production and total quality management (Kristoffersen *et al.*, 2020). It bears the ability of using historical data to improve product quality by identifying abnormal behaviors and adjusting performance limits in productive systems. Additionally, better information sharing throughout the value chain helps operations real-time controlling and adjusting, according to variable demand, thus increasing operational efficiency and providing information on new products, services and business models' potential (Kristoffersen *et al.*, 2020). With that, this approach builds on the integration of business and manufacturing processes, and all value chain agents are intricately connected to production and sustainability issues. Cleaner production and corporate social responsibility bring important implications to I4.0 advancements around the world (Lu *et al.*, 2020).

3. Methodological procedures

For the theoretical basis setting, an SLR was conducted. It included the search items of previously published studies in Scopus and Web of Science databases. A total of 63 articles were found, all available in their complete form and published in high-impact journals. The search was done on October 17, 2020, in the following languages: English, Spanish and Portuguese. Each article was thoroughly read. To analyze the articles, the Tranfield, Denyer and Smart (2003) research protocol was adopted. Therefore, stages, phases, steps and details are described in Table 1.

Stages	Phase	Steps	Details
Stage I: Review planning	1	Review proposal	Meta-analysis of previous studies that discuss CE and I4.0
	2	Review protocol development	The applied protocol has followed the parameters below (1) Search Strings: "circular economy" OR "circular economy*" AND "Artificial intelligence" OR "Industry 4.0" OR "digital Technologies" OR "smart factory" OR "Deep learning" OR "Machine learning" OR "Artificial Neural Networks" OR "Natural Language Processing" OR "Expert systems" OR "Fuzzy" OR "convolutional neural network" OR "advanced manufacturing". Search strings that sought to include the studied themes (2) Consulted databases: Scopus and Web of Science (3) Criterion for including studies: business, management and accounting-related publications (4) Studies should be available in complete form
Stage II: Review conduction	3	Studies selection	Data plotting into as Excel spreadsheet, with specific columns to arrange data of interest for this study, like title, author, year, journal, general objective of the study, study type, research limitations and recommendations to future studies
	4	Data synthesis	Information was synthetized in graphics, tables, and charts, to enable answering the research question
Stage III: Results presentation	5	Data analysis	Mapping of current status of previous studies on CE and I4.0, looking for new research paths based on research objectives, limitations as well as recommendations for future studies
	6	Discussion and conclusions	Reflection on key findings. Based on the evidence, we have built propositions for new studies, unprecedented and original. Conclusions were laid out aiming at highlighting practical and theoretical contributions of this study

Table 1. Study methodological path

4. Results presentation and analysis

In this section, we bring a brief description of the analyzed articles' profile, the main researched journals, their publication year and the study classification. Thereon we present the possible interfaces between CE and I4.0. The third sub-section describes CE field advancements supported by I4.0, and finally, the possible new avenues for studies, based on key objectives, gaps and future studies' suggestions, are discussed.

4.1 Profile of the analyzed articles

All 63 analyzed articles were extracted from high impact journals of international bases. As shown in Table 2, most of the studies were published in *Journal of Cleaner Production*, and the second most frequent source was *Benchmarking: An International Journal*. However, there was a spread of sources for information collection, with seven journals bringing two articles each, and 18 journals bringing only one article, hereby grouped under "Others" label.

The majority of the studies focus on theoretical reviews on the themes at issue, but experiments and case studies form a considerable number of papers. Finally, surveys (quantitative research) appear at lower number, although still relevant in the sample. The years 2019 and 2020 were the ones with the vast majority of published studies: of note, 2021 already counted two studies, despite the research being conducted in 2020. Nonetheless, 2017 and 2018 also make part of the sample. These numbers emphasize that the researched studies have been recently published in the researched journals.

4.2 Existing interfaces between circular economy and Industry 4.0

In this sub-section, existing interfaces between CE and I4.0 are described.

Companies with lower adoption of I4.0 techniques have more difficulty in implementing 10R, they have smaller number of employees and lower investment power. Conversely, manufacturing companies with high degree of I4.0 techniques adoption show a higher level of advanced manufacturing resources and, consequently, bigger ability to adopt 10R. Advanced manufacturing capabilities have a positive influence in sustainable development results. I4.0 application has moderating effects on 10R utilization in manufacturing systems. I4.0 utilization may enhance operational performance in advanced manufacturing through 10R adoption and increase CE performance, thus supporting the achievement of sustainable development goals (Bag *et al.*, 2021).

The usage of I4.0 technologies may convey positive results towards social, corporate and sustainable responsibility of operations. Highly advanced technology utilization on sustainable practices might provide competitive advantage to manufacturing organizations in developed economies, considering that I4.0 technologies help transitioning

Journal	Total	%
Journal of Cleaner Production	27	42.86
Benchmarking: An International Journal	4	6.35
Business Strategy and the Environment	2	3.17
Global Business Review	2	3.17
International Journal of Production Research	2	3.17
Journal of Industrial Integration and Management	2	3.17
Management Decision	2	3.17
Journal of Manufacturing Technology Management	2	3.17
Supply Chain Management: An International Journal	2	3.17
Others	18	28.57

Table 2.
Profile of analyzed journals

from linear economy to CE. Advanced I4.0 practices may reduce costs, improve sustainability and supply clients with customizable products. In the cyber-physical environment, machines carry the ability to communicate, collect information and reveal decisions through data collection in real-time through tools, like IoT, AI, big data, cloud information, etc. (Kumar *et al.*, 2020).

Cleaner production methods are paramount to achieve success in CE approaches. I4.0 supports those methods, focusing on their smart technologies, increasing the interconnection capabilities of people and information resources, on top of the value chain, tending to potentialize innovation, well-being and employment. Therefore, by adopting I4.0, the CE can sufficiently distribute, create and collect value through business strategies and also generate competitive advantage gains with that (Lu *et al.*, 2020). Based on IoT technology, real-time energy data can be collected and analyzed to reach better performance, which needs to be under control throughout the whole manufacturing process. Big Data offers new opportunities for implementing clean production strategies, due to the increase in generated data on intensive energy use by manufacturing industries (Ma *et al.*, 2020; Wang *et al.*, 2020).

4.3 Advancements for the circular economy field supported by Industry 4.0

In this sub-section, we list the contributions that I4.0 can bring to the CE. The following possible advancements are evident:

Artificial neural networks: Networks that recognize useful patterns for traceability of products that are offered to market. Those networks seek materials circularity at project and execution, thus contributing to CE. Artificial neural networks have also brought attention to the utilization of machine learning algorithms to estimate the amount of recyclable, reusable and residual material in productive processes. They also help material's end-of-life (EoL) traceability and predictability, supporting predictability of new product purchase (Akanbi, Oyedele, Oyedele, & Salami, 2020).

Automation: A set of technologies that use sensors, IoT, Radio-frequency identification (RFID) among others. It is an alternative to the development of ethical commercial practices and can be used for predictive purposes or even for cognitive analyses. It aims at minimizing the total cost and electric energy consumption by production equipment (Rajput & Singh, 2020).

Big data: The system that generates large volumes of data and formats and reduces them, thus generating a hidden information pattern. It allows data virtualization, so they can be stored in the most efficient and economic way, which happens with the cloud storage option. This technology supports a cleaner production, reducing carbon emissions and lead times (manufacturing time) in production cycles (Rajput & Singh, 2020; Bag & Pretorius, 2020).

Blockchain: Distributed digital books that keep encrypted records and transactions and having the ability to independently operate, with no need of communicating with other agents to check transactions credibility. Blockchain involves some dimensions that can transform and benefit current business processes. These resources support information transparency, which makes this technology trustworthy. It aims at boosting circularity practices. A few examples of information that might be offered by this technology are material and product source, involved agents, processes, energy consumption and EOL. The utilization of these technologies can maximize recycling and circularity programs results (Kouhizadeh *et al.*, 2019; Ma *et al.*, 2020).

Convolutional neural networks: A class of artificial neural network that is employed with digital images processing and analysis. These networks can be used in the CE to capture an entry image, assign relevance (weigh and biases can be learned) and object traits, thus being able to define the differentiation among objects. For instance, they can identify if an object was manufactured with reused material from a virgin material object (Akanbi *et al.*, 2020).

Deep learning (DL): Computational technique that uses multiple hidden processing layers to learn data representation and relationship with several abstraction levels. DL models are neural networks made out of three main layers: input, hidden and output. Generated data are used for site optimization, making the navigation experience more interesting to the client. The use of a set of algorithms for modeling attractions is an innovative perspective for applicability in the CE (Lieder, Asif, & Rashid, 2020; Akanbi *et al.*, 2020).

Digitalization: This technology has added new possibilities to data management, AI and resilience networks and systems in industrial manufacturing processes. It contributes to the CE through data generation, process cost reduction, accurate and real-time information providing for decision-making (Rajput & Singh, 2020).

Internet of Things (IoT): This technology uses device combinations to produce data, send them to other devices and, thereafter, send them to the cloud. Those codes are useful when business analysts deal with data management and mining, extracting valuable information. These data are generally collected by smart sensors that increase credibility in decision-making and eliminate inconsistencies. An opportunity to exploit IoT is digitalizing CE practices, implementing smart industrial environments (Rosa, Sassanelli, Urbinati, Chiaroni, & Terzi, 2019; Bag *et al.*, 2021; Rajput & Singh, 2020).

Machine learning: Technology in which computers have the ability to learn, according to the expected response, through association of different data. These data can be images, numbers, maps, pictures, etc. Machine learning algorithms are data-based simulations, and the simulation models can be used to generate large volumes of data. Simulation programs can create large random data flows over time. Available studies have shown that the combination of environmental impact factors to service elements and price changes has significant effect on client preference, particularly regarding carbon emission reduction (Lieder *et al.*, 2020).

Additive manufacturing: This technology, also described as 3D-printing, is a set of techniques that enable the production of a growing array of goods through the arrangement of material layers, one on the other, in a continuous or incremental manner, as opposed to subtraction and formal manufacturing methodologies. It can support product and process life cycle management, being able to update current recycling systems through new sustainable practices, like, for instance, digitalizing manufacturing process or aiding component or product remanufacturing (Rosa *et al.*, 2019; Tavares, Godinho Filho, Ganga, & Callefi, 2020).

Fuzzy DEMATEL systems: Theses systems allow translating imprecise information – expressed by a set of linguistic rules – into mathematical terms. The method is broadly used and is able to show the causal relation among a complex system's elements. This mathematical method can be applied to the CE to support decision-making for adopting strategies on controls, classification, series predicting, planning and optimization, through cause–effect relations (Khan & Haleem, 2020; Kumar *et al.*, 2020; Khandelwal & Barua, 2020).

Smart factory: It is the concept that describes production in the I4.0 focus. It consists of structures that contribute to waste reduction and support operational and processing systems efficiency. This technology aims at product quality, safety and sustainability enhancement. All these factors contribute to CE development (Sharma, Jabbour, & Jabbour, 2020).

Based on what is presented on the researched studies, it is possible to verify that I4.0 technologies contribute to CE application through several aspects. Those technologies' utilization, combined with manufacturing, supply chain and product development – among others – practices, enable maximizing those two theoretical fields utilization.

4.4 Content analysis based on objectives, research limitations and recommendations for future studies

There are many findings and theoretical assumptions raised by previous studies. According to data analysis and categorization, we present those assumptions within a classification, then generate propositions for further research and answer this research's question. We describe these findings divided in theoretical reviews, case studies, experiments and surveys.

Theoretical reviews: Several articles have described their objectives as developing a research structure showing key paths around I4.0 and CE constructs and trying to understand this new connection paradigm to solve problems related to sustainable manufacturing principles. Such articles suggest both theoretical and managerial agendas, aiming at promoting sustainable production and consumption through technological advancements' analysis, as well as the potential barriers to implementation, as mentioned by Bag and Pretorius (2020), Chauhan and Singh (2019), Rajput and Singh (2019), Erro-Garcés (2019), D'Amato *et al.* (2017) and Engeland, Beliën, Boeck and Jaeger (2018). Van Fan, Chin, Klemeš, Varbanov and Liu (2019) have presented an overview of clean production achievements and a selection of recent relevant works on optimization tools and process design. Some of those reviews have focused on establishing theoretical frameworks for I4.0 (Rejikumar *et al.*, 2019). On their turn, Sehnem *et al.* (2019) investigate overlaps, complementarities and differences amid CE models literature, like reverse logistics, close circuit, industrial symbiosis and industrial ecology.

Experiments: Other papers presented conceptually practical findings, among which it is possible highlight (1) analysis of the intensity of lean manufacturing key drivers that foster the technique adoption in developing economies manufacturing companies (Yadav *et al.*, 2019); (2) project and implementation of a web based decision-making supporting tool for supply chain strategies (Paul & Bussemaker, 2020); (3) integration of both fields (I4.0 and CE) and the attempt to understand the new paradigm to tackle problems related to CE principles (Chauhan, Sharma, & Singh, 2019) and (4) proposal to manage supply management using a machine learning model for energy control in multiple costing structure sustainability (Wang & Zhang, 2020).

Case studies: key objectives in this category deal with the search for identifying the major challenges hindering I4.0 and CE features adoption in an India automobile industry sustainable supply chain in the study by Yadav *et al.* (2020). In a similar way, one study sought to explore the connection between those concepts in Brazil, as well as presented strategic paths to overcome limitations for circumventing challenges in emerging economies (Cezarino, Liboni, Oliveira, Oliveira, & Stocco, 2019). The study by Gue, Promentilla, Tan, and Ubando (2020) had an objective to supply a systematic analysis of the interrelations among the drivers for the transition to CE. The investigation on issues and opportunities for developing a smart management system for sustainable waste was the highlight of the study by Fatimah, Govindan, Murniningsih, and Setiawan (2020). Another focal point was the identification of barriers that influence CSCM (circular supply chain management) adoption by India plastic industry (Khandelwal & Barua, 2020). The exploration of capacity providers' potential contribution to a sustainable I4.0 environment as an added perspective on a smart and sustainable business model management decision, aiming at major corporations transformation, was the objective described in the study by Lardo, Mancini, Paoloni and Russo (2020).

Surveys: It was possible to identify and analyze the cause–effect relations amid the implementation barriers for food circular supply chains in China (Farooque, Zhang, & Liu, 2019). Another study has analyzed CE practices' effect on company performance within a circular supply chain and explored the moderating role big data plays in these relations (Del Giudice, Chierici, Mazzucchelli, & Fiano, 2020). Finally, identifying the most relevant performance indicating factors under different perspectives, with a focus on operational excellence towards sustainability in leather industry, was the core of the study by Moktadir *et al.* (2020).

Performing the analysis of verified studies' limitations has enabled us to group the following findings: sample size is modest, or the study was conducted in only one market sector, as in the studies by Lu *et al.* (2020), Akinade and Oyedele (2019), Bag *et al.* (2021), Del Giudice *et al.* (2020), Engeland *et al.* (2018), Sandvik and Stubbs (2019) and Wang *et al.* (2020) ; the theoretical review being conducted in two languages at the most (English or Spanish) (Chauhan & Singh, 2019; Erro-Garcés, 2019) or in only one database, Scopus (Sehnem *et al.*, 2019); studies with interviewees' subjective answers were highlighted by Del Giudice *et al.* (2020), Kumar *et al.* (2020), Rajput and Singh (2019) and Yadav *et al.* (2019); empirically validating the proposed theoretical model was suggested by Chauhan *et al.* (2019) and Chidepatil *et al.* (2020); study being conducted in only one country was the limitation described in the studies by Khandelwal and Barua (2020), Bag *et al.* (2021), Akinade and Oyedele (2019), Akanbi *et al.* (2020), Yadav *et al.* (2020) and Zhang *et al.* (2019) and finally, the fact that the research constructs (CE and I4.0) still are relatively new, demanding further investigation was considered an limitation, as described by Del Giudice *et al.* (2020) and Rejikumaret *et al.* (2019). Therefore, this complete analysis gives a broad view to raise theoretical assumptions for future studies. They are presented in the next sub-section.

4.5 Theoretical propositions for future studies

Based on the identification of potential existing interfaces between CE and I4.0, the advancements in the CE field supported by I4.0 and the content analysis based on objectives, research limitations and recommendations for future studies, we present five theoretical assumptions for future research works.

Proposition 1. Verify the applicability of I4.0 technologies to foster clean production in manufacturing industry.

Aiming at making manufacturing more efficient, much research effort is dedicated to reach cleaner production and mitigate environment damage, while industry is constantly facing problems to adopt cleaner production. Previous studies have shown results evidencing that I4.0 technology usage – like IoT, big data and digitalization – constitutes a CE advancement, enabling environment-damaging gas emission reduction, lower electric energy utilization and mitigating materials waste. Those techniques may also support smart remanufacturing systems. This proposition is based on the studies by Ma *et al.* (2020), Yadav *et al.* (2020), Rajput and Singh (2019, 2020), Rosa *et al.* (2019), Kerin and Pham (2019, 2020), Farooque *et al.* (2019), Erro-Garcés (2019), Moktadir *et al.* (2020), Lu *et al.* (2020) and Yadav *et al.* (2019).

Proposition 2. Analyze blockchain and big data utilization as support in circular supply chain optimization.

Blockchain and big data technologies, combined with the CE, can transform organizational activities through innovation. These technologies' features include transparency–traceability, reliability–safety and operational activity smart execution. Those potential features may boost material reuse, upcycling, circularity and recycling programs, as well as circular supply chain performance management. This is based on Kouhizadeh *et al.* (2019) and Del Giudice *et al.* (2020).

Proposition 3. Assess the additive manufacturing adoption impact on CE activities' increase.

Verifying the relationship between CE objectives and cost reduction by using 3D-printing as a production system is necessary, as it is still the object of academic debate. To form this proposition, we are based on the articles by Rosa *et al.* (2019) and Tavares *et al.* (2020).

Proposition 4. Seek for a better understanding on how I4.0 technologies can properly support CE in the stakeholders' view.

Understanding the interaction among of the Stakeholder pressures (focused on customers, suppliers, employees, public sphere, partners and community), tangible resources and human capabilities to enable I4.0 and CE technologies adoption, considering Brazil is lagging among developed economies in the quest for CE capacity through industrial technology changes. The key hurdles lay on the lack of articulation of public and private spheres for fostering new circular business models. The foundational studies for this proposition were the ones by Cezarino *et al.* (2019), Engeland *et al.* (2018), Sehnem *et al.* (2019), Zhou, Song, and Cui (2020) and Bag and Pretorius (2020).

Proposition 5. Understand the driving and hindering factors for I4.0 and CE adoption in small and medium organization supply chain.

Future studies can investigate barriers or enablers for the implementation of recent technologies in various sectors. Many areas, like health sector supply chain, started to explore I4.0. Nonetheless, few specific studies report such exploration. For a future perspective, a detailed study of the barriers and the understanding of underlying technologies ease I4.0 effective implementation. Studies that support future investigations avenue were those by Rajput and Singh (2019), Engeland *et al.* (2018), Chauhan *et al.* (2019), Wang and Zhang (2020), Khandelwal and Barua (2020), Rejikumar *et al.* (2019) and Farooque *et al.* (2019).

5. Final considerations

This study analyzes papers that had approached the existing interface between CE and I4.0. Digital revolution has brought many challenges and opportunities for organizations' manufacturing. However, the impact of the adoption of I4.0 technologies in CE still lacks research and applications in the organizations, particularly in the Brazilian market (Cezarino *et al.*, 2019). These technologies can positively influence sustainable production and CE capabilities, as I4.0 and sustainability integration is still at its initial stages. Managers in the organizations, particularly the manufacturing ones, need to consider I4.0 technology adoption to enhance company sustainability performance (Zhang *et al.*, 2019).

The proposed objective for this study is reached as we present new paths and challenges pertaining to both approached theoretical fields. To get to this answer, we have performed an analysis on the potential existing interfaces between CE and I4.0 and the major CE advancements that are supported by I4.0. The key general objectives were described, as well as research limitations and recommendations for future studies. Based on this analysis, the study's key conclusion is that new paths and challenges are still necessary, both at theoretical and managerial levels. To fill that gap, five propositions are suggested as propositions for new studies: verify the applicability of I4.0 technologies to foster clean production, analyze I4.0 technology utilization in circular supply chains, assess the additive manufacturing adoption impact on CE, seek to understand how I4.0 can support CE in the stakeholders' view and understand the driving and hindering factors for I4.0 and CE adoption in the supply chain.

As this study's theoretical contribution, we mention the interrelations between the two theoretical fields, which despite being still considered developing themes in academia, present a broad framework able to generate new interdisciplinary study fields like digital CE, Circular I4.0 (Rosa *et al.*, 2019) or even smart CE (Kristoffersen *et al.*, 2020). We can also highlight as a contribution the presentation of these themes' interrelations based on the analyzed articles, like their interfaces and the potential CE advancements supported by I4.0.

The practical contributions of this study traverse the applicability of the raised assumptions to several industry sectors. However, as verified by some studies, small- and medium-sized companies need closer attention, as they lack financial capital for the application of the techniques, as mentioned by Kumar *et al.* (2020) and Lu *et al.* (2020).

As managerial implications, we may suggest a transition agenda towards CE, using I4.0 technologies for operational, tactical and strategic level personnel in the organizations, as well as potential utilization strategies in specific field studies, like supply chain management and product manufacturing per se.

This study also has limitations. For instance, although consistent, the study sample basis is still recent, missing greater research depth. Also, research strings may have minimized the number of selected studies – the sample could have been bigger. The majority of the selected studies consisted in bibliographical research, which corroborates this being an embryonic theme, which needs more empirical research. Finally, researcher biases should be considered.

On top of the five propositions already listed, we also suggest the following ideas for future studies, based on the systematic literature review papers: replicate already conducted studies changing the research approach from qualitative to quantitative (Del Giudice *et al.*, 2020; Kristoffersen *et al.*, 2020; Lardo *et al.*, 2020; Yadav *et al.*, 2020; Zhang *et al.*, 2019) or use the same approach, yet perfecting the data collection mechanism (Fatimah *et al.*, 2020); using the interface between the theoretical fields, focusing on the sustainability social context (Ma *et al.*, 2020; Sharma *et al.*, 2020); describing and analyzing the transition from a traditional factory towards one that adopts CE and I4.0 (Erro-Garcés, 2019); applying the theoretical model proposed in the study onto the practical field (Gan *et al.*, 2020; Kerin & Pham, 2020; Kristoffersen *et al.*, 2020); proposing closer relationship between university and industry to promote the symbiosis between CE and I4.0 (Ramakrishna, Ngowi, Jager, & Awuzie, 2020) and finally the replication of the study into another country's context (Sandvik & Stubbs, 2019).

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