EXACTA Engenharia de Produção eISSN 1983-9308

Editor: Dr. Luiz Fernando Rodrigues Pinto,
Universidade Nove de Julho, Uninove / São Paulo - SP, Brasil
Submissões para este periódico

ADVANCING SUSTAINABLE MANUFACTURING IN PRODUCTION ENGINEERING: CASE STUDY ON INDUSTRY 4.0 AND CIRCULAR ECONOMY IN THE INDUSTRIAL SECTOR

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Versão do autor aceita publicada online: 02 set. 2024

Publicado online: 10 out. 2024

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Como citar esse artigo - American Psychological Association (APA):

Vido, M., Pacchini, A. P. T., Lucato, W. C., Oliveira Neto, G. C., & Bezerra, F. E. (2024, artigo aceito online). Advancing sustainable manufacturing in production engineering: case study on Industry 4.0 and circular economy in the industrial sector. *Exacta*, artigo aceito online. https://doi.org/10.5585/2024.27304

Notas dos Autores

Os autores declaram que não há conflitos de interesses.

Abstract

Traditionally, manufacturing relied on a linear economy, taking, making, using, and disposing of resources, pushing the planet toward resource exhaustion. Industry 4.0 introduces enabling technologies that can foster circular strategies, addressing the challenge of reducing non-renewable resource usage. This study models a conceptual framework applying digital technologies to a circular economy, systematically reviewing specific literature using the PRISMA methodology. Data was collected through case studies involving four automotive, electronics, and footwear companies. The findings confirm IoT and Big Data as crucial technologies for circular economy applications. The successful integration of these technologies in Industry 4.0 is poised to enhance industrial sustainability across various manufacturing sectors.

Keywords: circular economy, Industry 4.0, sustainable manufacturing

Avançando a manufatura sustentável em engenharia de produção: estudo de caso sobre Indústria 4.0 e economia circular no setor industrial

Resumo

Tradicionalmente, a manufatura se baseava em uma economia linear, extraindo, fabricando, utilizando e descartando recursos, levando o planeta em direção à exaustão dos recursos. A Indústria 4.0 introduz tecnologias habilitadoras que podem promover estratégias circulares, enfrentando o desafio de reduzir o uso de recursos não renováveis. Este estudo modela um framework conceitual aplicando tecnologias digitais a uma economia circular, revisando sistematicamente a literatura específica utilizando a metodologia PRISMA. Os dados foram coletados por meio de estudos de caso envolvendo quatro empresas dos setores automotivo, eletrônico e de calçados. Os resultados confirmam a Internet das Coisas (IoT) e o Big Data como tecnologias cruciais para aplicações da economia circular. A integração bem-sucedida dessas tecnologias na Indústria 4.0 está prestes a melhorar a sustentabilidade industrial em vários setores de manufatura.

Palavras-chave: economia circular, Indústria 4.0, manufatura sustentável, indústria; produção

1. Introduction

In recent years, the world has faced numerous environmental problems caused by accelerated growth. That is larger motivated by the fact that, since the beginning of industrialization, a business model called Linear Economy has been used. That concept of "taking, making, using, and disposing of" is prevalent. In this way, the products of manufacturing companies, when they become obsolete or reach the end of their useful life, are easily discarded (Rajput and Singh, 2019). Furthermore, the linear model leads to relevant economic losses and negative externalities such as pollution, poor management of resources, and deforestation, among many other negative impacts on the environment. However, this picture has been changing. In addition to consumers starting to prefer sustainable products, organizations and governments are devoting more attention to solving environmental problems to grow with a long-term redesign, rebuilding strategies, and creating new business opportunities and sustainable processes (Camilleri et al., 2023; Roca et al., 2020).

In this regard, Linear Economy has been losing ground to the Circular Economy (CE), which focuses on maximizing resources, considering the entire production life cycle, from the extraction of raw materials to the disposal of the product after its use. The goal is to extract maximum value by designing successive cycles of use and thinking about the product strategy since its initial conception. CE is not just about simply changing a product or recycling materials. It is, rather, related to a change in the business model and culture of the interconnected companies in the supply chain, in an intersectoral collaboration with effective policies and business strategies (Morseletto et al., 2023; Masi et al., 2018). At the same time, Industry 4.0 (I 4.0) brings a new paradigm for manufacturing companies, which is based on information and communication technologies and takes them to a new level of performance and digital integration (Pacchini et al., 2019). It is a digitalization process that allows, among other advantages, to make decisions in real-time through the convergence of information and communication technologies with operating technologies (Villas-Boas et al., 2023; Kang et al., 2016).

Lasi et al. (2014) stated that the fundamental platform of I4.0 is the interconnectivity between intelligent machines. It allows the manufacture of customized products, using enabling technologies, which consist of Cyber-Physical Systems (CPS), the Internet of Things, Big Data, and Artificial Intelligence (AI), among others. Thus, the manufacturing industries, generators of technological agents, and innovations could support CE initiatives not related to increasing productivity in manufacturing but also from design to the end of the product's life cycle (Chioffi et al., 2020; Kamble et al., 2018).

Therefore, the CE business model supported by digital technologies and its connectivity represents a potential opportunity to meet market needs such as durability, ease of maintenance, the usability of recyclable materials, and even preparing these products allowing them to be remanufactured or recovered (Ellen MacArthur Foundation, 2020). Indeed, I 4.0's digital technologies are opening new perspectives to drive the development of CE, both in new services or emerging products and in new business models (Yang, 2018). That results in a relevant potential for the creation of intelligent processes with high sustainable value (Kamble et al., 2018; Bressanelli et al., 2018). The expansion of such concepts generates a sustainable environment in the three known dimensions of sustainability: economic, social, and environmental. The result is the efficient use of resources in a continuous cycle, minimizing the amount of waste and adding value for as long as possible (Stock et al., 2018; Urbinati et al., 2017).

Despite the advantages and the importance of connectivity between the CE and I4.0 to boost a new sustainable business model, the finds gathered from the extensive literature review indicate that an investigation comprising a set of I 4.0 enabler technologies applied to CE to improve manufacturing sustainability remains unexplored. Therefore, such finds compose a research gap that the present study seeks to fill (Jabbour et al., 2018). Consequently, the proposed study should contribute to the knowledge by identifying which enabling technologies of I 4.0 applied to CE could foster a path towards sustainable manufacturing. As a result, the following research question has been placed: What are the enabling technologies of Industry 4.0 applied in the Circular Economy that contribute to sustainable manufacturing?

Due to the lack of specific frameworks that offer an adequate explanation for the question explored in this study, exploratory multiple case studies were selected as the methodological approach for this research (Yin, 2017). Furthermore, case studies allow the exploration of areas with little preexisting literature and support in the development of frameworks using data collected through direct interaction with subjects of interest (Bryman, 2016).

2. Theoretical background

This chapter encompasses the literature review to support the current study. Moreover, this chapter is comprised of three subsections. First, a conceptualization of the Circular

Economy is described, followed by the contextualization of Industry 4.0. Finally, enabler technologies related to CE are discussed.

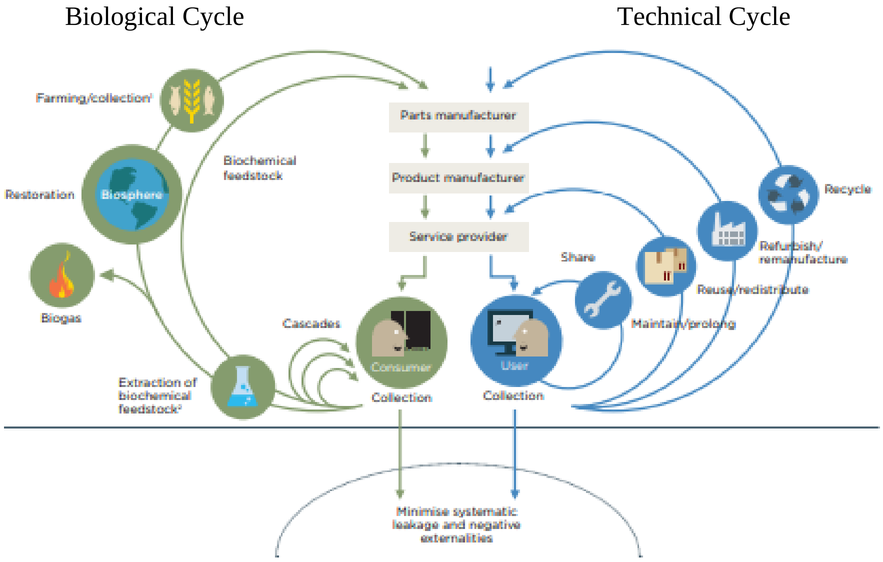
2.1 Circular Economy

Humanity is currently facing the challenges of poverty, inequality, climate change, environmental degradation, violence, and injustice (UN, 2020). CE is a concept that seeks to balance human consumption with the ability to supply Earth's resources and focus on closing the environmental cycle of industrial networks through business models that encourage the improvement of companies' sustainability (Nuñes-Castro et al., 2018). Both concepts of CE and sustainability are overlapping and mutually supportive (Geissdoerfer et al., 2017). This relationship is linked to the fact that the traditional business model known as Linear Economy has the meaning of "get-use-dispose" which generates an imbalance between demand, consumption, and natural resources. In addition to affecting the environment and socioeconomic conditions (Elliot, 2011).

Notwithstanding, the Ellen MacArthur Foundation (2020) indicated two distinct industrial cycles in the CE: the biological cycle that uses ingredients obtained from vegetal material that return their value as biological nutrients for the soil because they are biodegradable. Moreover, the technical cycle uses materials that are not continuously produced by the biosphere, i.e., they are not renewable and should be used in a way that circulates in closed industrial cycles according to CE principles. This work will deal with the technical cycle, as shown in Figure 1.

Figure 1

Circular Economy cycles



Source: Ellen Macarthur Foundation, 2023.

Merli et al. (2018) and Lacy and Rutqvist (2016) report that CE was introduced in academic literature in 1990, together with the 3R principle, which comprises "Reduce", "Reuse" and "Recycle". The CE theme has become popular in China from the perspective of economic growth and the limitations of natural resources (Su et al., 2013). Since then, CE has gained relevance at the political, industrial, and academic levels. From an academic perspective, it has been investigated as a paradigm strongly related to sustainability (Okorie et al., 2018).

The transition from a linear to a circular business model concept offers opportunities to manage waste production (Garcia-Muiña et al., 2019). The main objective of the CE is to obtain support for the recycling of materials and balance economic and environmental growth (Winans et al., 2017). The CE allows for economic growth from finite resource constraints, providing opportunities for companies on new concepts of value creation, revenue generation, cost reduction, resilience, and creation of legitimacy (Manninen et al., 2018).

There are several possibilities for defining CE. This could be due to its complexity and transdisciplinary nature (Sauvé et al., 2017). However, the definition most often cited is that indicated by the Ellen MacArthur Foundation (2020): "a global economic model for minimizing the consumption of finite resources, focus on the intelligent design of materials, products, and systems." Such a concept has achieved greater attention among the academic and industrial sectors since it is pointed out as a promising approach to promoting sustainable economic development. However, even with evident benefits, CE still shows little adoption by companies, which need to face several challenges to adopt this model (Bressanelli et al., 2018). One of them can mention the business model, the bureaucratic and legal obstacles that hinder changes, and the rigidity of consumer behavior (Phan et al., 2019).

Despite these challenges, the importance of ending the product's life cycle, and transforming it, in fact, into a cycle of reuse, repair, reform, and recycling, is a fundamental strategy to achieve competitive growth. Moreover, it reduces costs and can be useful in creating new business models and job opportunities (Kalmykova et al., 2018).

2.2 Industry 4.0

The I4.0 concept emerged in Germany to ensure that German industries could maintain their leadership in the global market for equipment manufacturers, integrating information and communication technologies (ICTs) to become a leading supplier of intelligent manufacturing technologies (Kagermann et al., 2013). I4.0 results from the incorporation and development of a set of digitally-based technologies. This set may vary in the perception of different analysts. However, among the most relevant technologies, we can mention sensors and actuators, the internet of things (IoT), big data, cloud computing, artificial intelligence, wireless communication technologies, integrated management systems, robotics, additive manufacturing, and new materials (Vido et al., 2024).

Digital technology is the fundamental driving force for industry 4.0 (Ferreira et al., 2023; Gouping et al., 2017). The focus of I 4.0 is on industrial production processes but is not limited to it. All this digital transformation can be applied to the value chain both, in manufacturing companies and other sectors of the economy (Ustundag et al., 2018). By connecting resources, materials, and control systems, it is possible to create smart networks along the entire value chain, increasing the quality of decisions in real-time, in addition to the possibility of autonomous control (Kopacek, 2015). All this connection and integration of the physical and the virtual world through IoT is carried out in cyber-physical systems, that is embedded systems and networks that monitor and control physical processes. This is usually done in a closed loop, in which the physical processes affect the calculations made by the algorithms that are in embedded systems and vice versa (Hermann et al., 2016).

The concepts of I4.0 currently challenge industrial companies in several sectors. However, companies have different levels of maturity concerning new technologies, processes, and organizational aspects, which requires a systematic approach to knowing these levels and implementing I4.0 strategies (Pessl et al., 2017). In addition, the promise of I4.0 becomes a reality as long as companies are mature enough to adopt it and create comprehensive transition strategies. Companies cannot ignore all the processes involved, investing only in digitization. In addition, not all organizations are ready to achieve a complete digital transformation (Ghobakhloo, 2018). In this context, developing countries find it more demanding to implement I4.0. For example, in Brazil, few industries are aware of technologies related to I4.0, but not half of them know at least one of the technologies that support I 4.0 (Lucato et al., 2019). However, smart factories with the ability to self-plan and adapt using networked cyber-physical systems are an essential condition for the successful development of new business models and the management of the entire value chain (Witkowski, 2017).

3. Methods

The research design was comprised of three phases: the first consisted of a bibliographic study to verify which are the enabler technologies of I 4.0 applied to CE, that are generating a path for sustainable manufacturing. The second stage indicates the most mentioned I 4.0 enabling technologies were selected, creating a conceptual framework. Finally, in the third phase multiple case studies were carried out in four industrial companies. The case studies were conducted through semi-structured interviews to verify the adequacy of the proposed framework in real-life situations.

3.1 Criteria for Literature Review

A systematic literature search on digital databases was conducted to identify and evaluate prior scientific works (Dresch et al., 2015, Tranfield et al., 2003), to investigate the related findings to the research question. The literature search was carried out in the following databases: Scopus, Web of Science, and Science Direct due to their relevance to the theme and research area (Rosa et al., 2020; Pessôa and Becker, 2020; Liao et al., 2017). Moreover, literature search in academic databases was limited to the key terms to avoid a large volume of data (Eisenhardt and Graebner, 2007). Following the authors, the keywords used for the research were: Industry 4.0, Circular Economy, Technologies, and Sustainable Manufacturing, in their various combinations. The documents not related to the topic of interest of this research, those not related to peer-reviewed articles in journals and not written in English were excluded from the research (Fahimnia, et al., 2015). There was no date delimitation for the articles searched.

Therefore, the document selection criteria were based on the following search protocol aspects: 1. Explicit discussion of digital technologies implemented in an industrial organization supporting CE;

2. Articles in which the key terms match the title and or abstract or keywords.

3. Academic journal articles;

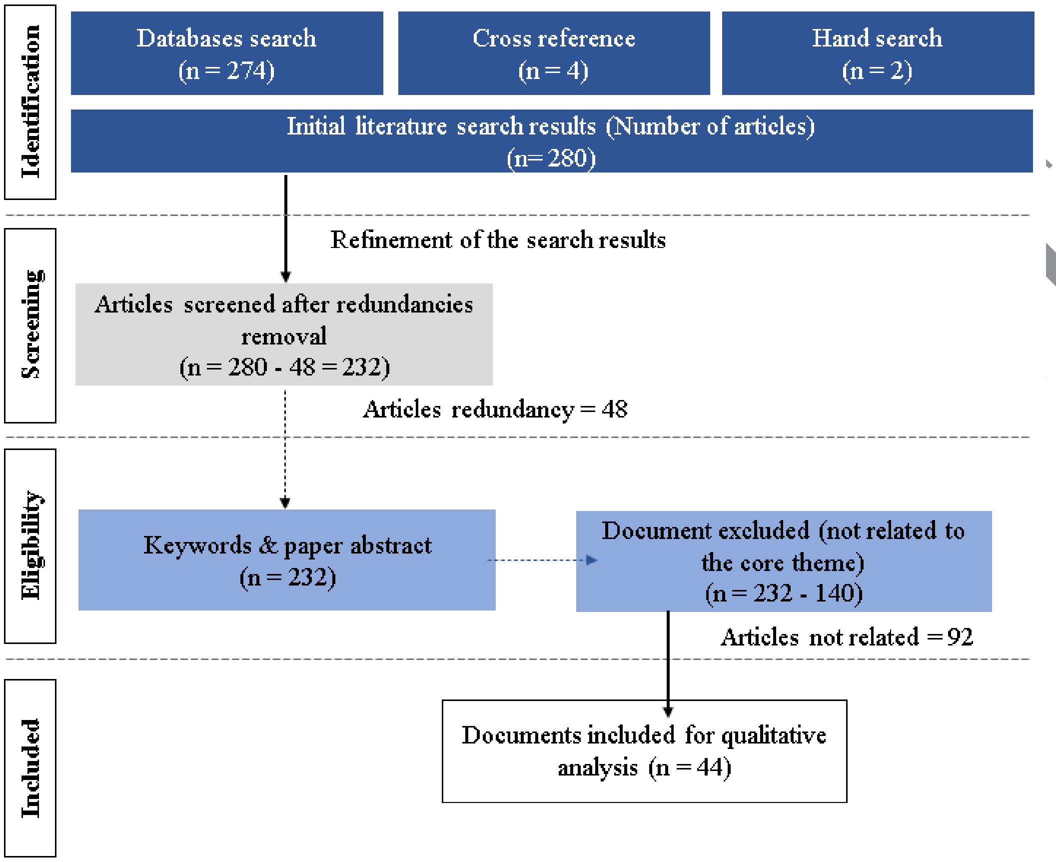
4. English language;

5. Databases. Delimitations: all documents non-refereed as scientific documents (journal articles), such as conferences, books, and magazines were excluded from the initial search in the scientific database (Fahimnia et al., 2015).

The document selection process of the systematic review to carry out the literature search performed in this study followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) proposed by Moher et al. (2015). It was selected to perform the analysis of the documents and applied to conduct different phases of the literature review in a systematic process model. Moreover, the eligibility criteria for selecting documents, including the content analysis of the research articles are reported in the stages of the PRISMA flow diagram shown in Figure 2.

Figure 2

Reporting items for the systematic review based on PRISMA



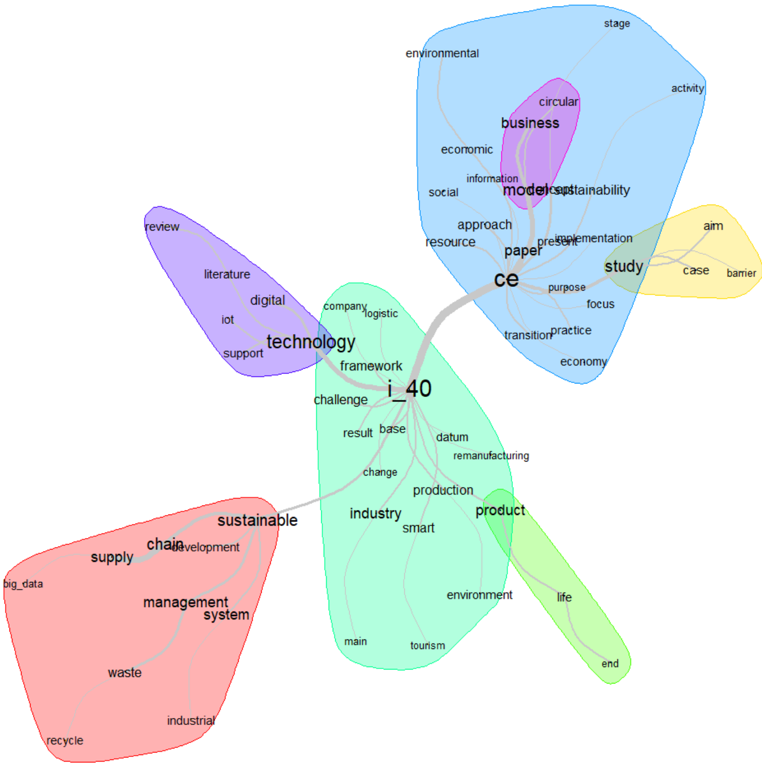
Source: Adapted from Moher et al., 2015.

Based on the PRISMA stages for identification, screening, eligibility and final document selection reported in Figure 2, the initial screening, 280 articles were obtained, of which, in a first review, 48 were removed because they were duplicated in the various databases. In a second stage, 140 articles that did not belong to the manufacturing sector were eliminated. Within this context, from the 92 remaining articles, 48 were excluded since they did not show a specific relationship between I 4.0 technologies, and CE. Therefore, 44 relevant articles remained that were used to support this work. The PRISMA checklist content adapted from Page et al. (2021) is applied to this work as a support to perform the literature review (see details in Appendix A).

As previously stated, the research builds upon the work across the selection of enabler technologies applied to CE to contribute to sustainable manufacturing, presenting the required literature as a basis for this research. While explaining how the literature search was conducted and aligned with the PRISMA flow diagram (Moher et al., 2015), an amount of 44 academic articles were selected to answer the research question. To analyze the textual links of the searched keywords and the text structure with the proposed theme, Iramuteq textual analysis software was applied to cache the quality of the 44 selected documents. The result is shown in Figure 3. The main themes of I 4.0 and the CE present a strong correlation in the selected texts and the relationship between I 4.0 technologies, CE, and sustainability in a second plan, indicating that the selected documents are consistent with the proposed theme.

Figure 3

Keywords Similarity Chart



Source: Obtained by the authors with the Iramuteq software

3.2 Case Studies

For this type of research, the case study is indicated, as it makes it possible to obtain facts from the recent and current past, extracted from various sources of objective evidence, both through direct observations and through semi-structured interviews (Yin, 2017).

According to Bryman (2016), in a semi-structured interview, the researcher must prepare a script containing the questions he intends to address during the interview. However, this script is only a guide for the researcher to be sure to cover relevant aspects of his research - he is free to develop the topic in the direction he finds most convenient. It is almost an informal conversation between the interviewee and researcher in which questions relevant to the research are developed as the interview flows naturally. For the selection of companies to be included in the case studies, the following criteria were established by the researchers as follows:

a. The company should have implemented the most relevant practices in I 4.0;

b. They should also use CE practices effectively;

c. Belong to different industrial sectors to have great coverage of the research.

For this work, as for the number of companies to be researched, it was decided to use the strategy of theoretical replication according to Yin (2017). It is assumed that the results of the cases may be different, even before carrying them out. To perform this study, more than 04 cases were necessary, and to satisfy this decision, 07 companies were invited to participate in this research that met the three selection criteria previously mentioned. From this amount, a total of 04 companies from the industrial sector agreed to participate in the research, as follows:

a. two companies from the automobile sector; a truck manufacturer, which has been guiding the development of the CE since 2016 with the application of I 4.0 enabling technologies. Moreover, another car manufacturer, which started in 2013 the implementation of I4.0 with many CE practices were selected;

b. one company from the footwear sector, which accounts for 18,000 worldwide, including around 2,300 employees in Brazil. The company has processes focused on the CE with the use of I4.0 technologies, and, in 2019, started launching products with the concepts of the CE;

c. a company in the electronics sector with 10,000 employees in Brazil and 160,000 worldwide. One of its subsidiaries in Brazil is dedicated entirely to CE and has exported this concept to other branches around the world.

3.3 Interview Protocol

A qualitative approach has been chosen to conduct this subsection, and a semi-structured set of interviews has been conducted. As this study aimed to perform semi-structured interviews, a dialog was conducted between the respondents and researchers. All relevant questions to the research were approached by the researchers as the interview flowed naturally. Bryman (2016) highlights that it is relevant for the researcher to produce an aide-mémoire to ensure that none of the important questions are forgotten, even if the semi-structured interview does not require the prior preparation of a questionnaire.

The interview protocol was written in Portuguese and all interviews were conducted in that language. The introductory section of the interview protocol presented to the respondents the purpose of this work, covering its topics, including the research question and primary objective. In addition, to keep the original content of the model, a flowchart explaining the entire concept of the proposed model prior to the interview question was shown. During each interview, the researcher spent between 10 to 15 minutes making the protocol content presentation, including details of the research. As interviews are means of collecting data, this tool is assumed in this work in order to conduct qualitative research to allow the researcher to collect opinions, experiences, processes, or behaviors from interviewees (Döringer, 2020).

Following Rowley (2012), to allow the researcher to conduct interviews and collect the necessary data in a minimum amount of time, the length of each interview took between 35 and 60 minutes. Based on such assumption, the issues considered relevant to performing the interviews were:

1. What kind of I 4.0 technologies did the company use in their internal manufacturing process?

2. What is the level of awareness of employees regarding CE and its practices?

3. What is the impact of Industry 4.0 technologies on the development of CE practices?

4. What did the company first implement in its process? Was Industry 4.0 first, or did the CE concept come first? What kind of barriers were identified?

5. Did any I 4.0 technologies adopted by the company contribute to the development of CE?

Furthermore, respondents which belong to the manufacturing sector were selected to bring relevant skills and experiences to the research based on the following core competence criteria:

a) CE initiatives;

b) Enabler technologies applications;

c) Brazilian industrial leaders.

4. Results

This work provides insights gathered from the literature related to enabling technologies and offers academics and practitioners opportunities to explore the synergy between I 4.0 and CE to answer the research question RQ: What are the enabling technologies of Industry 4.0 applied in the Circular Economy that contribute to sustainable manufacturing?

This section summarizes the results gathered from the literature review and the case studies performed in the industrial sector.

4.1 Sustainable manufacturing and I 4.0 enabling technologies applied to CE

Several enabling technologies of I 4.0 related to CE are being implemented worldwide. Nevertheless, the results exploring this connection towards sustainable manufacturing remain not much discussed in the literature (Kamble et al., 2018). The enabling technologies of I4.0 can support sustainable manufacturing in the supply chain with a focus on the CE, aiming at reductions in the use of resources, mitigating the environmental impact, and supporting companies in the transition from the linear model to the CE (Singh, S.P. and Singh, R.K., 2019). Rosa et al. (2020) indicated that I 4.0 technologies can be used to make CE feasible. They concluded that the adoption of digital technologies could help organizations improve their circular business model, involving customers and suppliers. Similarly, Jabbour et al. (2020) point to the benefits of the relationship between I4.0 and the CE, with the potential contribution of enabling technologies to the strengthening of circular models.

The enabling technologies of I4.0 applied to CE, can be a channel to promote a sustainable manufacturing environment, defining new paths for a transition from traditional manufacturing processes to digital sustainable ones to support a circular business model (Pham et al., 2019; Jensen and Remmen, 2017). In the literature review carried out to support this work, and whose details are shown in the Methods section, 44 papers were selected as can be seen in Table 1. These articles allowed the identification of 18 enabling technologies of I 4.0 applied to CE. However, it can be seen in Table 1 that not all of them are related to sustainable manufacturing.

Table 1

Enabling Technologies of I 4.0 applied in CE

		Industry 4.0 Enabling Technologies																			
#	**Papers**	Internet of Things	Big Data	Cyber Physical Systems	Cloud Computing	RFID	Artificial Intelligence	Additive Manufacturing	Augmented Reality	Collaborative Robots	Vertical Integration	Intelligent Materials	Simulation	Cybersecurity	Autonomous Vehicles	Internet of Services	Blockchain	M2M	Mobile technology
1	Ardito et al. (2019)		x		x									x					
2	Abdul-Hamid et al. (2020)	x	x	x	x	x	x						x	x					
3	Bag et al. (2020a)	x	x		x		x	x											
4	Bag et al. (2020b)	x	x	x	x	x	x		x	x	x				x				
5	Belaud et al. (2019)		x																
6	Bressanelli et al. (2018)	x	x																
7	Cezarino et al. (2019)	x	x	x	x		x	x	x		x			x		x			
8	Chauhan et al. (2019)	x	x		x		x	x					x						
9	Cioffi et al. (2020)	x		x															
10	Daú et al. (2019)	x																	
11	De Sousa Jabbour et al. (2018)	x		x	x			x											
12	Dev et al. (2020)	x	x		x	x		x					x						
13	Fatimah et al. (2020)	x	x		x	x				x									
14	Fischer et al. (2020)	x	x		x														
15	Garcia-Muiña et al. (2018)	x																	

		Industry 4.0 Enabling Technologies																	
16	Garcia-Muiña et al. (2019)	x																	
17	Garrido-Hidalgo et al. (2019)	x			x	x													
18	Ivascu (2020)	x	x	x	x	x	x	x	x	x			x	x				x	x
19	Jabborur et al. (2020)	x	x		x	x	x			x							x		
20	Jabbour et al. (2020)	x	x		x		x				x					x			
21	Jayakumar et al. (2020)	x	x	x	x	x	x	x		x							x		
22	Kamble et al. (2018)	x	x					x	x										
23	Kerdlap et al. (2019)	x																	
24	Kerin et al. (2019)	x	x	x	x	x	x	x	x	x	x		x		x	x			
25	Kouhizadeh et al. (2019)	x															x		
26	Limba et al. (2020)	x	x	x	x						x						x		x
27	Lu et al. (2020)		x				x			x					x				
28	Manavalan and Jayakrishna (2019)	x	x																
29	Martín-Gómez et al. (2019)	x	x	x	x	x				x	x							x	
30	Nascimento et al. (2019)			x				x											
31	Okorie et al. (2018)	x		x				x											
32	Ozkan-Ozen et al. (2020)	x	x											x			x		
33	Pham et al. (2019)	x	x	x	x		x												
34	Rajput and Singh (2019a)	x			x		x												

		Industry 4.0 Enabling Technologies																	
35	Rajput and Singh (2019b)	x		x															
36	Ramakrishna et al. (2020)	x					x	x				x					x		
37	Rejikumaret al. (2019)	x		x												x			
38	Rocca et al. (2020)	x		x						x			x						
39	Rosa et al. (2020)	x	x					x					x	x					
40	Sanchez et al. (2020)							x											
41	Tomiyama et al. (2019)		x	x			x	x											
42	Turner et al. (2019)							x											
43	Yadav et al. (2020)			x															
44	Yang et al. (2018)			x															
Total		**35**	**25**	**20**	**20**	**10**	**15**	**16**	**5**	**9**	**6**	**1**	**7**	**6**	**3**	**4**	**6**	**2**	**2**

Therefore, in the 44 researched articles, those most cited technologies were considered relevant for this work. Thus, from the 18 mentioned in the selected articles, 08 were selected, as shown in Table 2. They are the Internet of Things, big data, cyber-physical systems, cloud computing, additive manufacturing, artificial intelligence, Radio-frequency identification (RFID), and collaborative robots (cobots). The selection criteria for these technologies are described in the Methods section.

Table 2

Percentages of the number of citations in the 44 selected articles

Technologies	Freq.	% of papers
Internet of Things	35	79,5
Big Data	25	56,8
Cyber-Physical System	20	45,5
Cloud Computing	20	45,5
Additive Manufacturing	16	36,4
Artificial Intelligence	15	34,1
RFID	10	22,7
Collaborative Robots	9	20,5

Source: Authors

These enabling technologies provide increased capacity to interconnect and cooperate with productive resources, that is, physical assets, people, and information, both within the factory and along the value chain, making the manufacturing process sustainable due to the increased efficiency, innovation, employment, and well-being (Lucato et al., 2019). Bressanelli et al. (2018) stated that the Internet of Things and big data have an expressive contribution to the establishment of a circular economy, as shown in Table 3. These are two technologies that, from the point of view of product design, support the transition to a circular economy with a focus on increasing the efficiency of resources and extending their useful life.

Table 3

Characteristics of IoT and Big Data applied in CE

Business model functionality	IoT	Big Data	Empirical results
Improving product design	x	x	Respond better to customer needs by collecting usage data through IoT.
Attracting target customers	x	x	Improve marketing activities through IoT regarding how customers are using products.
Monitoring and tracking product activity	x		Through IoT, manufacturers may monitor the product conditions, status, location, and usage level.
Providing technical support	x	x	The analysis of Big Data collected through IoT in order to improve the provision of technical support and services such as repair, assistance, spare parts management
Providing preventive and predictive maintenance	x	x	The analysis of Big Data collected through IoT by appropriate analytics entails the provision of preventive and predictive maintenance.
Optimizing the product usage	x	x	provide their customers personalized advice to optimize the usage phase through an analysis of the Big Data collected by the IoT sensors.
Upgrading the product	x		Replace only digital elements, such as the product firmware or software, thus enhancing the feasibility of upgrading in a remote way.
Enhancing renovation and end-of-life activities (execute collection, refurbishment, remanufacturing, and recycling)	x	x	Based on IoT, manufacturers can access real-time product information, e.g., geo-localization and condition.

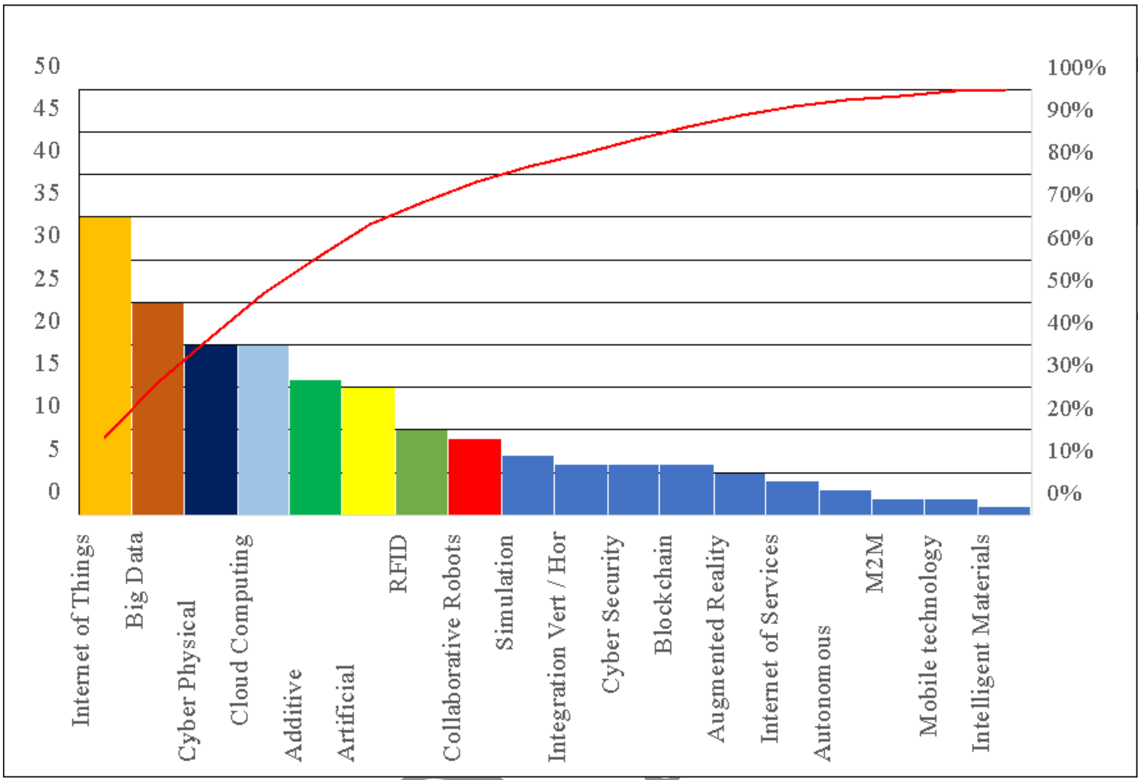
Source: Adapted from Bressanelli et al., 2018.

4.2 Conceptual Framework

The Pareto analysis, which was developed by the Italian economist Vilfredo Pareto is defined as one of the most used classification methods to identify relevant activities and recognize relevant priorities for the management decision (Cebi and Kahraman, 2012). This method is widely used both by academics and practitioners to classify different information. In these cases, the most relevant items were classified with up to 80% incidence (Juran, 1992). The Pareto classification criteria distinguish a few activities having high importance from many activities having no importance (Jacobs et al., 2005). It has been used as a managerial tool to determine the called curve ABC, or the "A" class, "B" class, and "C" class according to the item's relevance, cost-effectiveness, storage sequence, or usage (Ballou and Srivastava, 2007). The Pareto diagram is shown in Figure 4.

Figure 4

Pareto diagram applied for the selection of relevant technologies.



Source: Authors

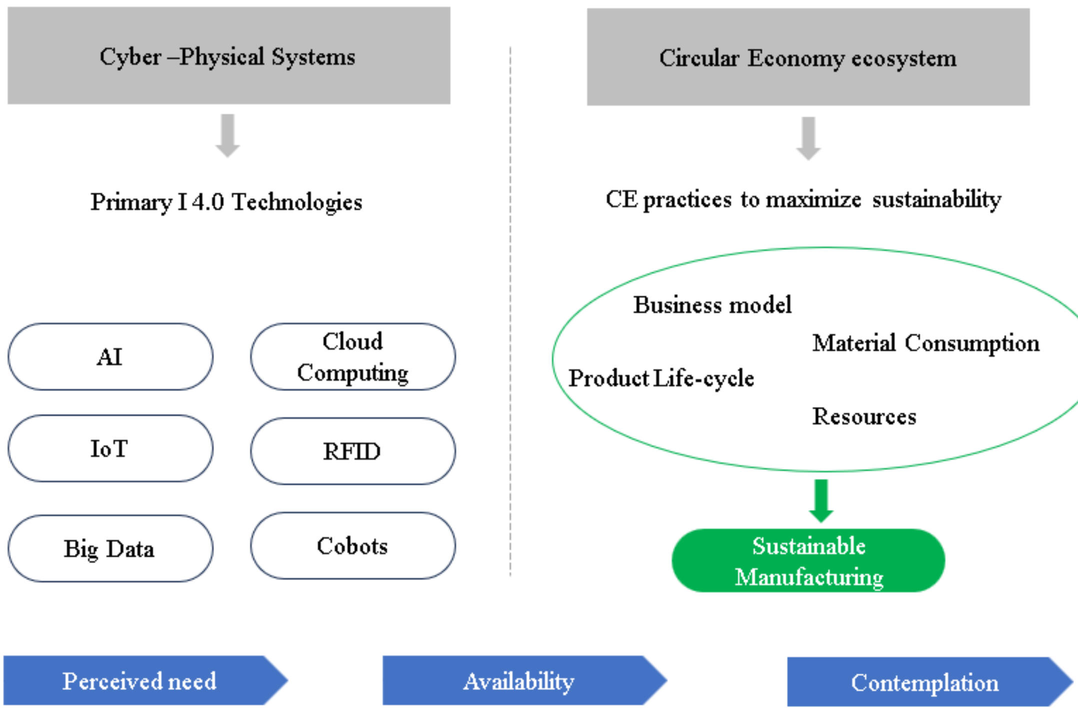
Because of this screening process, the eight most cited I 4.0 enabling technologies were identified, which comprise the proposed conceptual framework and are shown in Table 4. The Pareto diagram selects the most important technologies applied to CE to enable sustainable manufacturing. According to Figure 4, the most cited I 4.0 enabling technologies were identified as:

1. Internet of Things
2. Big Data
3. Cyber-Physical-System (CPS)
4. Cloud Computing
5. Additive Manufacturing
6. Artificial Intelligence
7. RFID
8. Collaborative Robots

The main results obtained from the systematic literature review indicated efforts by academic researchers to investigate issues related to the Industry 4.0 enabling technologies used in the CE environment. In the 44 articles analyzed, an amount of 18 documents including I4.0 technologies related to CE were identified, with a total of 192 citations. To model the generic framework only the highly cited technologies shown in Figure 4 were considered Moreover, the architecture of the proposed framework to integrate enabler technologies to CE practices to boost sustainable manufacturing is shown in Figure 5.

Figure 5

Conceptual framework of digital technologies applied to CE



Source: Authors

The Conceptual framework shown in Figure 5 consists of two related and depending pillars. The Cyber-Physical Systems Pillar element describes the primary enabler Technologies of I 4.0. Therefore, the IoT, big data, and cloud computing are related to the cyber side of I4.0 Technologies. RFID and cobots are associated with the physical side of technologies of I 4.0. The second pillar is related to the CE element, which comprises sustainable practices implemented by organizations to boost a sustainable manufacturing ecosystem. The ground framework contemplates the perception needs of organizations to empower CE, followed by the technology available in the organization ecosystem to incorporate I 4.0 into CE practices which is fundamental for contemplation of a suitable sustainable manufacturing environment.

4.3 Research interviews

Through semi-structured interviews, it was possible to analyze the respondent's perception of the influence of enabling technologies of I 4.0 in the CE, comparing the results obtained with the proposed conceptual framework. In general, the researcher and respondents had an open and informal conversation to generate more in-depth responses regarding sensitive topics. In summary, all respondents of this study work for industries in the private sector. The majority of respondents were senior executives with engineering degrees and additional Master's degrees. During the interviews, the researcher had the opportunity to get beliefs through open-ended questions to obtain insights based on the issues introduced to the experts. Moreover, the names of the participants were not identifiable to ensure anonymity between participants.

4.3.1. Case Study 1

The company is a car manufacturer with headquarters in Germany, with 10,000 employees in Brazil. The respondent has a position as Digital Factory Specialist. According to the interviewee, the enabling technologies associated with CE practices allowed a great boost to the sustainability of manufacturing. The concepts were implemented simultaneously, but as the listed technologies were implemented there was a great advance in the development of the circular economy. The company does a continuous work of acculturation of the employees, concerning the new trends and has obtained excellent results.

4.3.2. Case Study 2

The company is one of the world's largest truck manufacturers, accounting for 3,000 employees in Brazil. The company uses the 5R's, applying the concept of zero waste disposition to landfills. There is a high level of employee awareness, and the company is currently at a very high stage in terms of EC practices. The respondent is a senior executive, accumulating 18 years working for the company, and holds the position of Sustainability Manager. With the adoption of the enabling technologies of I 4.0, there was a significant improvement in the company's sustainability, since the company can get faster responses, which reflects in more concise EC actions.

4.3.3. Case Study 3

The company is a Brazilian footwear manufacturer, accounting for 20,000 employees in Brazil. Moreover, the company has a global footprint, including 110 countries accounting for 19,000 employees. The respondent holds the position of Sustainability Manager. The enabler technologies of I 4.0 adopted by the company have made actions possible in reducing waste and rework in production. Big data and IoT have made it possible to meet consumer needs, eliminating the inventory of produced and unsold products, for instance. As the product is stored in retail stores, they opted for the Beacon technology instead of RFID, so that they could be used Bluetooth from the store or the customer.

4.3.4. Case Study 4

This is a multinational company from the electronics sector, accounting for 10,000 employees in Brazil. Moreover, the company has a global footprint, accounting for 160,000 workers. The respondent holds a position as Innovation Director. The group organization in Brazil is comprised of three companies. The first one produces injected parts, using mainly recycled raw material. Such material is provided by the second company, which has been practicing the EC for years, reusing electronic waste and scrap, in general. That company even serves as a business model for the remaining companies in the group. The third company focuses on research, mainly in the field of digital technology, which has brought a huge increase in the introduction of I4.0 technologies inside the company. The company is improving the process of selection and separation of resins, making it possible to obtain recycled material with properties similar to the raw material. Table 4 summarizes the results of case studies indicating the practical contributions of I 4.0 technologies to CE in the industrial field.

Table 4

Practical contributions of I 4.0 technologies to CE

I4.0 enabling technologies	Case study 1	Case study 2	Case study 3	Case study 4
Internet of Things	The company is waiting for 5G sources. Nevertheless, it has been used with some restrictions due to the speed limit to receive information related to the stock to eliminate waste.	The company is applying IoT technology to monitor the energy consumption and the traceability of chemical products used in production processes.	IoT is applied to analyze the level of residues and scraps generated by the machines on the shop floor, through sensors connected to the industrial park. In addition, IoT provides real-time energy consumption monitoring of the machines.	The company collects information from dumpsters equipped with sensors, which are strategically located, to allow the collection of material for recycling and products for remanufacturing.
Big Data	Such technology is applied to develop manufacturing systems following matrix standards from the headquarters in Europe, seeking to develop products according to the market's needs.	Data analysis has been used as a support tool for product development based on the Eco-design concept, once currently 90% of the truck's parts are recycled	Data analytics has been used in the analysis of market data to avoid waste in production	Data analytics has been used to support marketing to obtain consumer experience propose product improvements and monitor the product life cycle.
Cyber-Physical System	CPS has been used in new product development, once the focus is concentrated on the projects designed to reduce the waste of raw material (scraps) during the stamping process of components.	CPS has been used to optimize resources during the production processes.	CPS supports data analytics platforms to better interact with the final consumer to allow the production line to personalize the products.	Not applicable or not available.
Cloud Computing	Used to obtain data in real-time, but it is currently working based on a private cloud inside the company.	The data of the storage areas are concentrated in a cloud to streamline the inventory control, which is located normally in another facility.	The company makes data available in the cloud on a specific platform to guide recyclers (contractors) outside the company.	Not applicable or not available.

I4.0 enabling technologies	Case study 1	Case study 2	Case study 3	Case study 4
		Moreover, the cloud is a tool to have access to stored goods.		
Additive Mfg.	Applied for complex body parts, car prototypes, and stamping molds, focusing on reducing waste during the production process.	Additive manufacturing begins to be used in production by adding material and decreasing the residue.	Additive manufacturing is applied as the filament of recycled material by the company itself to develop new prototypes.	Used to produce components of the final product and manufactured with a focus on zero waste.
Artificial Intelligence	In new developments, the projects are designed to reduce the waste of raw material (scraps) during the process of stamping components, in addition to being present in vehicles improving fuel consumption and CO2 emissions	The artificial intelligence systems installed in the trucks are used in fuel management and support to obtain maximum efficiency in cargo transportation solutions.	Artificial Intelligence works in conjunction with Big Data to identify consumer needs when the company is developing new products.	Artificial Intelligence works in conjunction with collaborative robots.
RFID	Used for traceability of packages and identification of their useful life during the logistics cycle of the components (pilot phase project).	To manage the stock control of harmful material and waste mapping, besides the control of the stock of material with health impacts.	Not applicable or not available	Sensors installed on products and dumps
Collaborative Robots (cobots)	The cobot use is not associated with Circular Economy	It begins to be used in the analysis of production processes, minimizing unnecessary disposal.	Used in production processes focusing on energy monitoring.	The company applies this technology to obtain cost savings in the sorting and separation of materials received for recycling.
Other Technologies	Development of products and processes within the concepts of Circular Economy.	Not mentioned	The company chose to use Beacons instead of RFID, equipping its products with these sensors to track them and track their useful life	Not applicable or not available

The practical contributions of this study lay in the application of I 4.0 digital technologies enhancing CE practices across the manufacturing field. Moreover, the finds in Table 5 shown the practical contribution of digital technologies gathered from the finds in the literature search of this work. The results of the case studies analysis clearly indicate that I 4.0 digital technologies might contribute to achieving CE in the industrial field. Information and communication technologies such as IoT and Big Data are a booster of CE initiatives and encourage its adoption by organizations from the industrial field.

5. Discussion

This study provided a practical scenario that encompasses the adoption of enabler technologies of I 4.0 applied in the CE that contribute to sustainable manufacturing while adding knowledge to the body of the literature. The purpose of the qualitative interviews developed in this study was to verify the adequacy of digital technologies based on the literature to foster a new CE business model. According to the information collected from the respondents, the analyzes of the case studies was performed in two steps. Initially, an internal comparison of case studies was made, followed by a cross-case analysis, followed by a cross-case analysis.

5.1 Internal case comparison

After analyzing the four case studies there is a consensus as to the fact that the I 4.0 enablers technologies when applied to CE bring positive results for the sustainability of the manufacturing process. Likewise, the predominance of digital technologies is important for developing the sustainability of the manufacturing process and adding value as recommended by Bressanelli et al. (2018). Therefore, based on the responses of the interviewees of the four case studies, the results shown in Table 5 show that I4.0 enables technologies that drive the CE the most, as a path for sustainable manufacturing. As noted, the Internet of things, artificial intelligence, big data, and additive manufacturing were cited as being relevant to the contribution to the CE in all companies surveyed.

Table 5

Internal comparison of case studies

	Industry 4.0 Enabling Technologies							
	Internet of Things	Artificial Intelligence	Big Data	Additive Manufacturing	Cyber-Physical Systems	RFID	Cobots	Cloud Computing
Company 1	x	x	x	x	x	x		x
Company 1	x	x	x	x	x	x	x	x
Company 1	x	x	x	x	x		x	x
Company 1	x	x	x	x		x	x	
Total	**4**	**4**	**4**	**4**	**3**	**3**	**3**	**3**

Source: Authors

5.2 Cross-case analysis

The purpose here is to make a cross-analysis of the four case studies to systematize and compare data from qualitative research to arrive at some common findings (Leonard-Barton, 1990). The four studies presented here are included and sought to answer, as much as possible, through the case studies the question proposed in their real-world configurations, as shown in Table 6. It is noted that common sense is the use of IoT and Big Data technologies, according to Bressanelli et al. (2018), have an expressive contribution to the establishment of a circular economy. Even in the case of companies from different sectors, they all agree with the importance of the enabling technologies of I 4.0 applied in the EC are important to generate a path for sustainable manufacturing.

Table 6

Cross case analysis

	Company 1	Company 2	Company 3	Company 4
Enabling technologies are important for sustainable manufacturing.	x	x	x	x
Enabling technologies are important for the CE.	x	x	x	x
Enabling technologies and CE are both important for sustainable manufacturing.	x	x	x	x
The company has sought to develop sustainable manufacturing.	x	x	x	x
Which technologies have been used the most?	IoT, Big Data, AI	IoT, Big Data, RFID	IoT, Big Data, Cloud	Iot, Big Data, AM

Source: Authors

In the case studies, it was noted that regardless of the sector the researched companies are involved in the process of implementing the CE, using various I 4.0 enabling technologies to support them in the transition from the linear to the circular model, seeking to enhance the sustainability of their respective manufacturing processes as suggested by Singh et al., (2019). Interviews with sustainability specialists focused on innovation show that companies are looking for innovative solutions, with a growing concern for increasingly sustainable processes. This trend can be observed by the framework proposed by this research and confirmed by all four companies studied, which were the same technologies selected in the literature. It was also observed that their order of importance was not relevant, but there was a unanimous use of all the technologies mentioned.

It is noteworthy the lack of unanimity in the use of Cloud Computing. The companies that adopted this technology showed a clear preference for a private cloud, as evidenced in the interviews. This confirms that still exists in the country to externalize the storage of sensitive information, confirming the findings of Pacchini et al. (2019). Another relevant fact is the use of Artificial Intelligence by all the companies surveyed. This shows the utilization of said technology for the CE in sustainable manufacturing, with the growth of machine learning utilization. Cobots are similarly used by all companies surveyed, but one of them did not associate its use with CE practices. Therefore, it was not considered a technology used to generate a path to sustainable manufacturing (Kamble et al., 2018).

Except for the order of use of the technologies, it can be observed that the conceptual framework shown in Figure 5 was confirmed in the research since during the interviews they were made spontaneously; that is, the technologies of the conceptual framework were not presented to the respondents. Moreover, after conducting field research, the interviews confirmed the relevance of the adoption of enabler technologies to the implementation of a new CE business model.

In summary, the findings are aligned with what was identified in the literature review, and the results provided directions for the selected digital technologies, including the proper use of the Internet of Things (IoT) and Artificial Intelligence (AI) represent the most proper application supporting CE practices. Indeed, the use of digital technologies brings positive perspectives to improve the development and implementation of Circular Economy practices, accelerating the sustainable manufacturing process across the industrial sector.

6. Conclusions

This work led to the conclusion that the I4.0 technologies referenced in the conceptual framework proposed in Figure 5 have boosted an evolution in the implementation of CE practices. That evolution is mainly encouraged by technologies and the digitization of production processes and customer services. Moreover, this work, when investigating the key technologies that impact on the implementation of CE brings contributions to theory, practice, and society. For the CE and I 4.0 field of knowledge, the results fill a gap in the literature and answer the research question by showing the main enabling technologies of I 4.0, used in the traditional CE practices aligned with the sustainable manufacturing environment. Like all research, it also has limitations.

Based on only four case studies, the results obtained cannot be generalized. Therefore, it is suggested for future studies to expand the research through a wide survey considering a larger universe of companies. Another limitation concerns the place of its execution. As only companies located in Brazil were considered, there is no way to guarantee that the same results will be obtained in other industrial realities. Therefore, there is also a recommendation for future analyses to replicate this research in other locations.

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APPENDIX A - PRISMA item checklist

Section and topic	Nr.	Checklist item	Manuscript
ABSTRACT Abstract	1	Provide a summary of the results.	In Abstract
INTRODUCTION Objectives	2	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Page 2
METHODS Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Page 7
Information sources	4	Specify all databases, registers, websites, organizations, reference lists, and other sources searched or consulted to identify studies.	Page 7
Search strategy	5	Present the full search strategies for all databases, registers, and websites, including any filters and limits used.	Page 8
Data collection process	6	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Page 8
RESULTS Results of individual studies	7	For all outcomes, present, for each study	Page 12
	7.a	Present results of analyses conducted to assess the robustness of the synthesized results	Page 13
DISCUSSION Discussion	8.a	Provide a general interpretation of the results in the context of other evidence.	Page 24
	8.b	Discuss any limitations of the evidence included in the review	Page 27
	8.d	Discuss the implications of the results for practice, policy, and future research.	Page 27
Competing interests	9	Declare any competing interests of review authors.	Page 27

Source: Adapted from Page et al., 2021.