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RESEARCH ARTICLE

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Interrelationships between circular economy and Industry 4.0: A research agenda for sustainable supply chains

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Abstract

The purpose of this article is to propose a novel classification of the interrelationships between Industry 4.0 (I4.0) technologies and circular economy (CE) principles that highlights the most conclusive findings and extant gaps in the relevant research. A systematic literature review has been developed to locate, select and evaluate relevant contributions made to CE interrelationships with I4.0 technologies. Studies have been analysed and classified according to the specific I4.0 technology and CE principle addressed (10Rs). The articles have been clustered into three main groups: (i) useful application of materials, (ii) extending the lifespan of products and their parts and (iii) smarter product use and manufacture. A mind map of the investigated articles has been used to establish the interrelationships between individual technologies and each CE principle at the supply chain level. Based on this classification, a focus group interview (FGI) was held with experts to dig deeper into the interrelationships between I4.0 technologies and CE principles. The FGI results have identified how each as yet unexplored I4.0 technology could be linked to each CE principle. A Fuzzy Delphi (FD) study was also applied to identify the most relevant I4.0 technologies for improving CE principles and closing gaps in the literature regarding the 10R CE principles. In addition, guidelines have been established to assist with practical applications and generate a research agenda on the interrelationships between I4.0 technologies and CE principles at the supply chain level. Implications for theory include the extension of view from the research gaps between I4.0 technologies and the 10Rs identified in the literature; also, an FGI and FD were performed based on the detected research gaps to identify future lines of research for academics and offer useful guidance to directors and managers on I4.0 technology interrelationships for improving at least one of the 10R CE principles. The contribution to practice aims to enable managers to easily identify which technology from the

Abbreviations: AI, artificial intelligence; AM, additive manufacturing; BDA, big data analytics; CE, circular economy; CPS, cyber–physical systems; FD, fuzzy Delphi; FGI, focus group interview; I4.0, Industry 4.0; IoT, Internet of Things; SDGs, Sustainable Development Goals; SLR, systematic literature review; SM, smart manufacturing; UN, United Nations; VR, virtual reality; WoS, Web of Science.

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I4.0 domain should be used to advance any given CE principle. Lastly, we provide useful guidance on the application of as-yet-unused technologies to improve CE principles.

KEYWORDS
circular economy, Fuzzy Delphi, I4.0 technologies, Industry 4.0 (I4.0), sustainable supply chains

1 | INTRODUCTION

The circular economy (CE) is a robust approach to promoting a change to sustainable practices in processes, technologies and people in society (Nascimento et al., 2019). CE proposes a transition from linear systems to circular production systems that reduce the need for mineral extraction, emissions, waste and contamination through a sustainable economy (Lopes de Sousa Jabbour et al., 2018). According to Caiado et al. (2022), the Sustainable Development Goals (SDGs) established by the United Nations (UN) are directly benefitted by CE, especially Goals 9 (build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation), 12 (ensure sustainable consumption and production patterns) and 13 (take urgent action to combat climate change and its impacts).

Several studies highlight the relevance and contribution of the interrelationships (i.e. a mutual relationship between the two concepts) between CE principles and Industry 4.0 (I4.0) technologies to accelerate the transition process towards circular production systems (Bag, Gupta, & Kumar, 2021; Lopes de Sousa Jabbour et al., 2018; Nascimento et al., 2019), for example, big data analytics (BDA) and CE in the flexible supply chain to improve sustainable manufacturing (Edwin Cheng et al., 2022). Kerin and Pham (2019) identified these interrelationships in a systematic review of I4.0 technologies such as the Internet of Things (IoT), virtual reality (VR) and augmented reality (AR) to support re-manufacturing. Also, circular business models that connect additive manufacturing (AM) and recycling practices in a digital sustainable supply chain have been found to achieve circularity (Nascimento et al., 2019). It is also important to mention blockchain technology, which revolutionises and securely digitises financial transactions and data exchange between companies in circular supply chains (Choi et al., 2020; Kouhizadeh et al., 2020).

The recent literature on CE has identified and improved strategies, principles and capabilities to transit from a linear to a CE (Bag, Gupta, & Kumar, 2021; Kirchherr et al., 2017; Potting et al., 2017). According to Kirchherr et al. (2017), there are 16 possible combinations of CE core principles in the 4Rs (Reduction, Reuse, Recycling and Recovery). However, the CE core principle that is most frequently used and most frequently cited as the most holistic is the 3R framework (Reduce, Reuse and Recycle) in the production, circulation and consumption process. It must be mentioned that some new principles and strategies have been derived from this definition, for example, the 9R framework proposed by Potting et al. (2017), which separates groupings of characteristics from linear to circular production systems into 10Rs: (i) useful application of materials (R9 Recover; R8 Recycle); (ii) extending the lifespan of products and their parts (R7 Repurpose; R6 Re-manufacture; R5 Re-furbish; R4 Repair; R3 Reuse); and (iii) smarter product use and manufacture (R2 Reduce; R1 Re-think; R0 Refuse).

In a literature review of the 10R principles and I4.0 in general, Bag, Gupta, and Kumar (2021) verified the degree to which I4.0 implementation enhances CE principles in mainly manufacturing companies and the causal relationships. However, the influence of specific I4.0 technologies on each of the 10R principles was not evaluated in either the literature or empirically. So, although specific I4.0 technologies can positively influence each of the CE principles, neither the relationships that are still unexplored in the literature nor how they can be extended to increase circularity in sustainable supply chains have been verified. This supports the problem statement to evaluate the interrelationships between these specific I4.0 technologies and 10R principles to create a research agenda for sustainable supply chains.

This work will undertake a systematic literature review (SLR) to identify the interrelationships between I4.0 technologies and 10R principles. A proposed classification of the interrelationships between individual I4.0 technologies and 10R principles will be used to create a CE-I4.0 mind map to evaluate these interrelationships with the literature. This is then used to categorise the 10R principles into three groups (useful application of materials, extending the lifespan of products and their parts and smarter product use and manufacture) and observe which I4.0 technologies influence each of these groups to deduce the most consistent interrelationships. The identification of the research gaps in the literature enables a focus group interview (FGI) and Fuzzy Delphi (FD) to evaluate, analyse and discuss some new interrelationships in which I4.0 technologies can influence CE principles to drive sustainable development. Based on the SLR, FGI and FD results, the objective is to create metacognitive mind maps and carry out qualitative analyses to establish some guidelines for implementing CE–I4.0 practices in sustainable supply chains. FGI and FD will enable researchers to determine the best directions in which to take their future research and managers to identify how they can exploit I4.0 technologies to advance the 10R principles.

The innovation for theory is provided by the results of an SLR that investigates works related to I4.0 technologies and CE principles to analyse, verify and identify conclusive relationships and research gaps in the literature. Based on the FGI and FD results, a research agenda is created of the interrelationships between some specific I4.0 technologies and 10R principles with an innovative classification of the literature that also allows to analyse the research gaps. Thus, a contribution is made to theory by indicating directions to guide future

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research on how underexplored I4.0 technologies could enhance CE principles in the short term.

For managers, this work will help to identify which I4.0 technologies they should use depending on the CE principle (R) that they want to advance. It also gives guidance on how newer technologies as yet unstudied in the literature could support each CE principle. The remainder of this paper is structured as follows: First, we provide a summary of the methodology used (Section 2). This is followed by the results (Section 3) and the discussion (Section 4). Finally, some conclusions (Section 5) are presented.

2 | MATERIAL AND METHODS

The research method is exploratory, with an SLR based on a central question that aims to investigate the main contributions that I4.0 technologies make to improving at least one of the 10R principles (Denyer & Tranfield, 2009). This research is mixed (Caiado et al., 2022) as it combines qualitative practices with the use of a rigorous process of evaluation, selection and reading to classify the relevant literature findings (Denyer & Tranfield, 2009), while new interrelationships are evaluated empirically through focus groups that address the identified research gaps (Nascimento et al., 2019). A quantitative approach is also used (Thomé et al., 2016) in the form of a descriptive analysis of the selected sample to determine the characteristics, frequency and distribution of the authors' institutions and the number of works that use the CE–I4.0 approach to support sustainable management systems (Garza-Reyes, 2015).

Note that this approach starts with an SLR with a rigorous literature selection and evaluation process (Denyer & Tranfield, 2009). This enables an innovative knowledge classification between CE and I4.0 that enables a mind map to be established that systematises these relationships (Saieg et al., 2018). In addition, an empirical approach is applied with an SLR PRISMA graph (Thomé et al., 2016), a FGI to discuss the implementation of CE–I4.0 interrelationships and FD to select from the FGI the most urgently required I4.0 technologies for improving CE principles, as shown in Figure 1.

An SLR has been developed to locate, select and evaluate the relevant contributions on I4.0 technologies and CE fields. The Denyer and Tranfield (2009) recommendations were followed to select and analyse the works and said authors' five-step methodology was applied. The validation and data coding step was included to guarantee the reliability of the systematic review process (Danese et al., 2018). Two further complementary steps were added based on the relationship gaps identified by the SLR: the focus group step for expert empirical verification (Nascimento et al., 2020). Thus, the seven research stages are (i) formulation of the research question; (ii) identification of the studies; (iii) selection and evaluation of studies; (iv) analysis and synthesis (Denyer & Tranfield, 2009); (v) validation and data code (Danese et al., 2018); (vi) focus group (Nascimento et al., 2020); (vii) FD (Garcia-Buendia et al., 2021); and (viii) presentation of results (Denyer & Tranfield, 2009).

2.1 | Question formulation

The initial step of an SLR is the formulation of the research question (Denyer & Tranfield, 2009). The central research question formulated to guide this study is: What interrelationships exist in the literature between I4.0 technologies and CE principles? Considering the central question, the secondary questions to segment the expected results of the present investigation are:

RQ1. What relationships exist in the literature between CE principles and I4.0 technologies?

RQ2. What research gaps between CE principles and I4.0 technologies can be identified in the literature?

RQ3. How can the research gaps between CE principles and I4.0 technologies identified in the literature be exploited to improve sustainable supply chains?

RQ4. What are the guidelines for increasing the maturity of the integration between I4.0 and CE in sustainable supply chains?

2.2 | Locating studies

The second step is to locate the relevant studies. Two decisions are essential at this stage: choice of search engine and formulation of search strings. Web of Science (WoS) was selected as the search engine as it offers exhaustive coverage of the field with high-quality international academic publications from influential publishers (Garcia-Buendia et al., 2021; Marín et al., 2021; Olawumi & Chan, 2018; Wamba & Queiroz, 2020). Authors agreed on a selection of search keywords based on the previous literature (Pagliosa et al., 2021). The search string was designed using Boolean operators as a combination of two-word groups, one group representing I4.0 technologies and the other representing CE principles. Table 1 presents the search string intended to ensure that the located articles contained at least one of the search keywords from each of the two groups in the document's title, abstract or keywords. This step retrieved a total of 551 documents.

2.3 | Study selection and evaluation

Inclusion and exclusion criteria are applied in this step. Only articles in English and published in journals with an impact index in Journal Citation Reports (JCR) and/or Scimago Journal Rank (SJR) were selected. Next, the article abstracts were meticulously read focusing on three main criteria: Are I4.0 technologies and CE addressed together in the article? Does the article have a management focus? Are CE or I4.0 technologies the main topic of the article? Each item had to meet all three criteria to be considered. The articles were then read in full to ensure that they complied with the study's objective. One hundred and seventy-two articles remained after this final assessment with one further article added after cross-referencing the selected literature (snowballing), giving a final sample of 173 articles.

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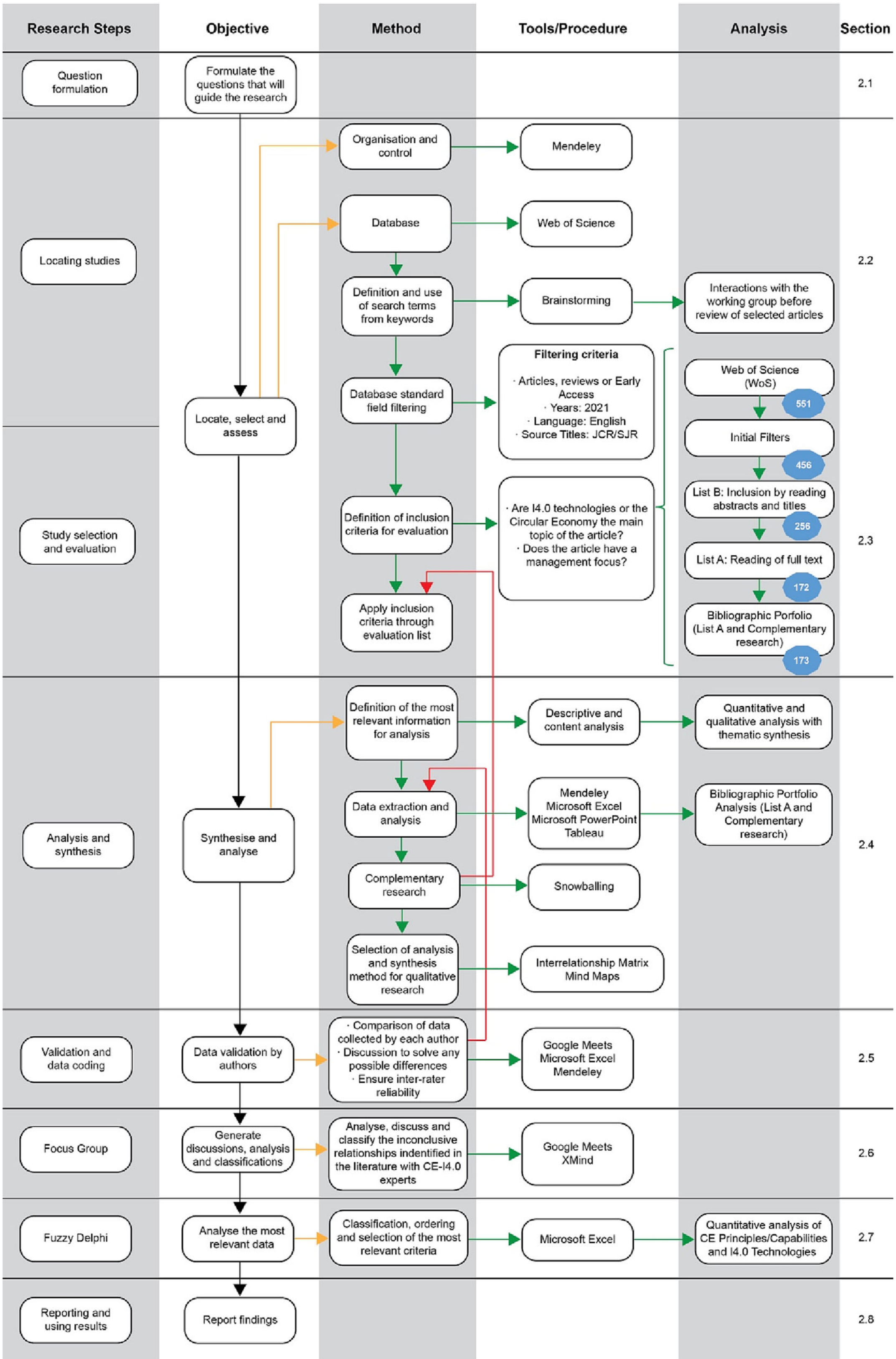

FIGURE 1 Research process, steps and procedures.

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TABLE 1 Research protocol for WoS database.

Search string	Group 1	TS = ("Circular Economy" OR "Industrial Ecology" OR "industrial symbiosis" OR "Closed loop supply chain" OR "reverse logistics")
	Group 2	AND TS = ("Big data" OR "Cloud Computing" OR "I4.0 Technolog*" OR "Artificial Intelligence" OR "Robotic" OR "Additive Manufacturing" OR "Augmented Reality" OR "Advanced manufacturing" OR "Blockchain" OR "Cyber?security" OR "Internet of Things" OR "Industrial simulation" OR "3d print*" OR "Industry 4.0" OR "Smart manufacturing" OR "Autonomous Robots" OR "Advanced robots")
Time horizon		No restriction
Search period		July 2021

2.4 | Analysis and synthesis

The method and definitions required to carry out the analysis and synthesis of the research had to be selected. Several methods that included thematic analysis/synthesis with metacognitive mind maps, qualitative comparative, meta-summary and content analysis were considered for the research synthesis (Barnett-Page & Thomas, 2009; Garza-Reyes, 2015; Thomas & Harden, 2008). Descriptive analysis was adopted for this research as it does not infer the human being and enables a variety of research data and statistics to be elaborated and demonstrated, thus providing a more quantitative view of the entire study (Marín et al., 2021). Content analysis, in which human inference occurs, was also used to provide a metacognitive analysis of the researched articles and a thematic synthesis that allows a comprehensive analysis of all the articles used in the research, such as benefits, barriers, category and research approach.

The results were entered into an Excel database to analyse the following data for each article: authors, title, journal/conference, year of publication, document source, findings, research category and approach, technologies addressed and used, description of how technologies were used, impact on and approach to CE and classification of benefits and barriers. At this stage, structures had to be pre-defined to collect the required information needed to explore each article's essential and relevant details (Denyer & Tranfield, 2009; Núñez-Merino et al., 2020; Thomé et al., 2016). Complementary research using the snowballing technique identified one further work that would add value to the study, and this was included in the bibliographic portfolio, yielding a final total of 173 articles (see appendices). Complementary research is essential and should extend beyond the keywords used (Greenhalgh et al., 2005).

2.5 | Validation and data code

The data validation and coding stage proposes that the review of articles be shared by the authors. This enables a comparison of the collected information and discussions to solve any possible differences, thus ensuring inter-evaluator reliability (Caiado et al., 2022; Danese et al., 2018). Each author analysed and read the articles and filled out the information sheet. After this step, the results were compared, and the differences were discussed in virtual meetings to generate greater consistency, validation and reliability of the processed data. This additional step allows for transparency in the analysis, minimises errors and evaluator bias and improves the quality and validation of the entire research process (Caiado et al., 2022).

2.6 | Focus group

In the analysis and synthesis stage, the documents are analysed and synthesised. Each study was analysed and classified according to the specific I4.0 technology and CE principle addressed. Based on this classification, which determined the interrelationships between I4.0 and CE principles, an assessment was made of the identified research gaps in an FGI with academic participants with research published in the three most cited JCR-indexed journals in WoS. New interrelationships were empirically established for theory-building (Voss et al., 2002). FGI data were collected via a recorded videoconference with FGI participants in line with the planned schedule. An agreement, disagreement and consensus-based qualitative approach produced a matrix table from the consensual interrelationships for guidelines for the CE–I4.0 interrelationship research agenda.

The general objective of this FGI protocol is to assess the interrelationships between I4.0 technologies and CE principles of research gaps identified in an SLR and, in addition, to extract new guidelines and best practices to support the interrelationships between I4.0 technologies and CE principles. Considering the need to analyse the interest group's perception of I4.0 technologies and 10R principles, theory-building explores the interaction between subject and object. Therefore, the purposes of the investigation are defined during this process (Voss et al., 2002). Below is an overview of the focus group discussion moderation guide:

Introductory question:

> From your perspective, describe how you perceive I4.0 technologies and circular economy integration can improve sustainable supply chains?

Main questions:

> How can blockchain technology improve the Repurpose and Refuse principles?
> How can additive manufacturing/3D printing technology improve the Repurpose principle?

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How can autonomous vehicle (AV) technology improve the Reuse, Re-manufacture, Repair, Re-furbish, Repurpose, Recycle, Recover and Refuse principles?
How can augmented reality technology improve the Reduce, Reuse, Re-think, Repair, Re-furbish, Repurpose, Recycle, Recover and Refuse principles?
How can virtual reality technology improve the Repurpose and Refuse principles?
How can cloud computing technology improve the Repurpose and Refuse principles?
How can advanced robotics technology improve the Re-think and Repurpose principles?
How can smart manufacturing/advanced manufacturing/cyber–physical systems technology improve the Repurpose principle?
How does quantum computing technology improve the Re-manufacture, Repair, Re-furbish, Repurpose, Recycle and Refuse principles?
How can drone technology improve the Reuse, Re-think, Re-manufacture, Repair, Repurpose, Recycle and Refuse principles?

Final questions:

What are the future directions, points of attention and goals for the implementation of integrated CE–I4.0 practices in sustainable supply chains?

The FGI participant selection criteria were: Participants had to have authored at least one of the three most cited works that integrate CE and I4.0 in the WoS database. The experts also had to be able to participate in the FGI via a videoconference. The authors selected the most cited researchers in CE–I4.0 interrelationships in WoS who met these requirements and agreed to participate in the FGI event on 27 September 2021 to discuss and define guidelines for a research agenda in the short term (Nascimento et al., 2020). FGI participants analysed the interrelationships between specific I4.0 technologies that aim to improve CE principles in sustainable supply chains (de Mattos Nascimento et al., 2018).

2.7 | Fuzzy Delphi

The FD method seeks to integrate the theory of the fuzzy set with the traditional Delphi method, with the objective of reducing uncertainties related to the specialists' preferences, thereby improving the quality of the results obtained in the research (Bouslama & Ichikawa, 1993). It was developed by Helmer and his associates as a long-term forecasting method that required repeated surveys of experts for the forecast values to converge (Bouslama & Ichikawa, 1993).

Based on the FGI results, a questionnaire was designed to collect the experts' opinions on the relevance of the CE principles for improving I4.0 technologies, which identified some gaps in the literature regarding the 10R CE principles and taking in account the CE–I4.0 interrelationships relevance discussed in the FGI. The questionnaire was separated into two stages. The first stage dealt with demographic information, and the second stage elicited responses from the participants. Fourteen specialists were selected using established criteria: a minimum of 6 years of experience in either sustainable operations, supply chain management, lean operations, operations management or I4.0 technologies, as shown in Table 2. This table lists the experts that participated in the research, including the FGI and FD stages. The first two experts participated in the FGI stage only. Interviews focused on explicit information in RQs and holding FGI sessions to discuss a topic raised by a skilled moderator and reporter are critical success factors for data collection. As reported in the study by Mishra et al. (2016), FGIs are carried out by two researchers, with one researcher facilitating the FGI content and process by assisting the participants while the other records the discussion with the prior authorisation of the participants and later prepares the transcripts. The expected duration of FGIs is approx. 60–90 min.

The corresponding triangular fuzzy numbers are given in Table 3.

Table 3 shows the triangular fuzzy numbers that correspond to the indicated linguistic terms. Tsai et al. (2020) and Lee et al. (2018) demonstrate an assumption that the significance value of an attribute b is rated by a respondent a as $j=(x_{ab},y_{ab},z_{ab})$, $a=1,2,3,\ldots,n$ and $b=1,2,3,\ldots,m$. Thus, the j_b weight of the b attribute is computed as $j_b=(x_b,y_b,z_b)$, where $x_b=min(x_{ab})$, $y_b=\left(\prod_1^n y_{ab}\right)^{1/n}$, and $z_b=max(z_{ab})$. According to Wu et al. (2016), the value of the convex combination D_b is generated using α cut, as in Equation (1).

$$u_b=z_b-\alpha(z_b-y_b), l_b=x_b-\alpha(y_b-x_b); \quad b=1,2,3,\ldots,m. \tag{1}$$

The α value adopted to represent a common situation is normally 0.5, but this value can be adjusted based on the experts' level of optimism or pessimism defined as 0 or 1 (Lee et al., 2018). The calculation of the value of the convex combination can be expressed as Equation (2).

$$D_b=\int(u_b,l_b)=[\lambda u_b+(1-\lambda)l_b] \tag{2}$$

where λ is used to express a decision maker's level of optimism and stabilise the expert group's radical judgments. Therefore, $\delta=\sum_{a=1}^{n}\frac{D_b}{n}$ is the filter threshold of the required attributes. If $D_b \geq \delta$, attribute b is accepted; otherwise, it must be rejected (Garcia-Buendia et al., 2022; Lee et al., 2018; Tsai et al., 2020).

2.8 | Reporting and using results

The last step is to report the results, with all the information extracted from the systematic review literature to a discussion of the results to identify any research gaps that can be used to determine guidelines for future research via the FGI and FD approaches (Denyer & Tranfield, 2009; Durach et al., 2017; Núñez-Merino et al., 2020; Okoli & Schabram, 2010). At this stage, the results are displayed

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TABLE 2 Expert panel profile.

Cod	Exp	Specialities	Role	Country	Expert	Social economic context	Applied method
A1	30 years	Sustainable management systems	Full professor	Brazil	Academic	Emerging	FGI
A2	7 years	Digital operations and supply chain management	Lecturer	Brazil	Academic	Emerging	FGI
A3	22 years	Lean supply chain management	Full professor	Brazil	Academic	Emerging	FGI/FD
A4	18 years	Technology and sustainable operations management	Lecturer	UK	Academic	Developed	FGI/FD
A5	24 years	Sustainable operations and supply chain management	Full professor	UK	Academic	Developed	FD
A6	26 years	Sustainable operations and supply chain management	Associate professor	Brazil	Academic	Emerging	FD
A7	6 years	Lean supply chain management	Lecturer	Spain	Academic	Developed	FD
A8	6 years	Sustainable operations and supply chain management	PhD student	Italy	Academic	Developed	FD
A9	15 years	Sustainable operations and supply chain management	Post-doctoral	Brazil	Academic	Emerging	FD
A10	11 years	Technology and operations management	Lecturer	Spain	Academic	Developed	FD
A11	25 years	Sustainable operations and supply chain management	Associate professor	Brazil	Academic	Emerging	FD
A12	7 years	Lean supply chain management	Lecturer	Spain	Academic	Developed	FD
A13	22 years	Operations management	Project manager	Brazil	Practitioner	Emerging	FD
A14	14 years	Operations management	Project engineer	Brazil	Practitioner	Emerging	FD
A15	27 years	Operations management	Project manager	Brazil	Practitioner	Emerging	FD
A16	35 years	Operations management	General manager	Brazil	Practitioner	Emerging	FD

TABLE 3 Corresponding triangular fuzzy numbers for relevance scale.

Scale	Linguistic term	Triangular fuzzy numbers (TFN)
1	No relevance (NR)	(0; 0; 0.25)
2	Low relevance (LR)	(0; 0.25; 0.50)
3	Moderate relevance (MR)	(0.25; 0.50; 0.75)
4	High relevance (HR)	(0.50; 0.75; 1.0)
5	Extreme relevance (ER)	(0.75; 1.0; 1.0)

quantitatively through descriptive and qualitative analysis using content analysis and thematic synthesis.

3 | RESULTS

The obtained results are presented in a descriptive analysis with graphs and tables to illustrate the contextual characteristics of the selected sample of 173 articles (see appendices). Content analysis is also presented with a mind map of the interrelationships between specific I4.0 technologies and CE principles at the supply chain level to enable an analysis of the interrelationships in the literature. Note that the study considers the 10R CE principles established by Potting et al. (2017): Reduce, Reuse, Re-think, Re-manufacture, Repair, Refurbish, Repurpose, Recycle, Recover and Refuse. Therefore, the research gaps identified in the literature enable the FGI and FD to generate discussions, analysis and results. These are represented as guidelines for future research in the novel research agenda that shows additional relationships with CE principles.

3.1 | Descriptive analysis

The distribution of publications by year is given in Figure 2. The first paper in the sample was published in 2005 and is a study of the use of artificial intelligence (AI) to simulate and evaluate the reverse logistics of containers in the automobile industry (Cheng & Yang, 2005). The I4.0 concept was coined at a later date, in 2011 (Kagermann, 2017), although some of the technologies included in the concept had begun to be developed previously. As can be observed, only three articles were found to have been published during the

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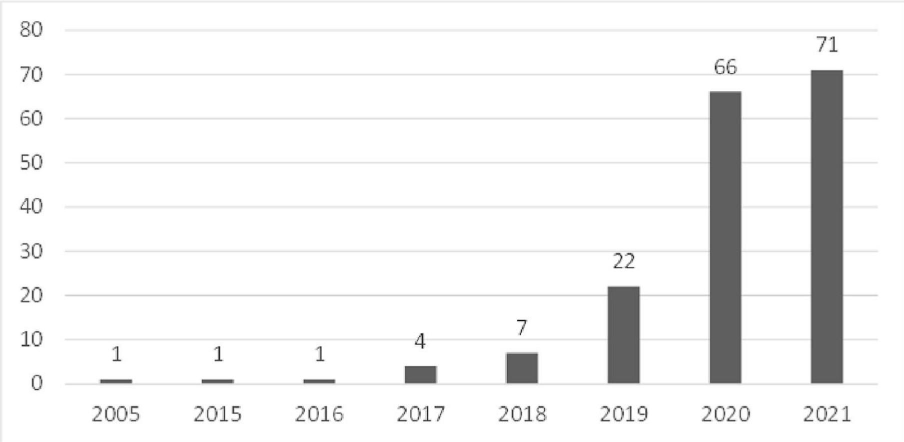

FIGURE 2 Number of publications per year.

TABLE 4 Publications by journal.

Journal	Papers
Journal of Cleaner Production	28
Sustainability	17
Resources, Conservation and Recycling	9
Technological Forecasting and Social Change	8
Applied Sciences	7
Business Strategy and Development	5
International Journal of Production Economics	4
Annals of Operations Research	3
Computers and Industrial Engineering	3
International Journal of Logistics Research and Applications	3
International Journal of Production Research	3
Johnson Matthey Technology Review	3
Journal of Industrial Ecology	3
Journal of Manufacturing Technology Management	3
Processes	3
Resources Policy	3
Sustainable Production and Consumption	3
Acta Agriculturae Scandinavica, Section B — Soil and Plant Science	2
California Management Review	2
Computers in Industry	2
Industrial Management and Data Systems	2
International Journal of Logistics Management	2
International Journal of Productivity and Performance Management	2
Journal of Intelligent Manufacturing	2
Metals	2
Production Planning and Control	2
Science of the Total Environment	2
Waste Management	2
Others (journals with one paper each)	43

2005–2016 period. However, from 2017, and especially from 2019 on, there was a steep rise in the number of articles to 22 in 2019, a figure that then more than tripled in 2021, when 71 publications were recorded. Two main points can help explain this enormous increase: Firstly, while the CE concept is not entirely new, the topic has undeniably found its way onto the agenda of policymakers in recent years. Some important examples are the EU's Circular Economy Action Plan (European Commission, 2015) and the Chinese Circular Economy Promotion Law (Geissdoerfer et al., 2017). Secondly, a steady increase in the maturity and applicability of I4.0 technologies is being seen (Jabbour et al., 2020), and they offer potential solutions that facilitate the transition to CE practices.

As mentioned in Section 2, we focused on high-quality peer-reviewed journals to ensure the quality of the data. The articles were spread over 71 different journals. The *Journal of Cleaner Production* (28 publications), *Sustainability* (17), *Resources, Conservation and Recycling* (9), *Technological Forecasting and Social Change* (8), *Applied Sciences* (7) and *Business Strategy and Development* (7) have the highest number of publications and together represent 43% of the total. Table 4 gives further details on the journals in which papers dealing simultaneously with CE and I4.0 technologies were located.

Regarding I4.0 technologies, most papers have adopted a general perspective (see Figure 3). More than one technology was discussed in some papers, which resulted in 213 technology references from 173 papers. The most singly addressed I4.0 technologies in papers were IoT, BDA, blockchain, AM and AI. Some of the technologies are at more advanced stages of maturity (e.g. cloud computing, BDA and IoT) in research and industry applications, while others such as quantum computing (Sarkis, 2021) are still in the early stages of development. Remarkably, although blockchain applications are only starting to be implemented in industry (Kouhizadeh et al., 2020), blockchain itself has already attracted considerable academic attention.

As can be observed in Figure 4, the literature has not devoted the same level of attention to all the principles. The most covered principles were Reduce, Recycle and Reuse, which is not surprising since these are the principles that make up the 3R framework (Khan

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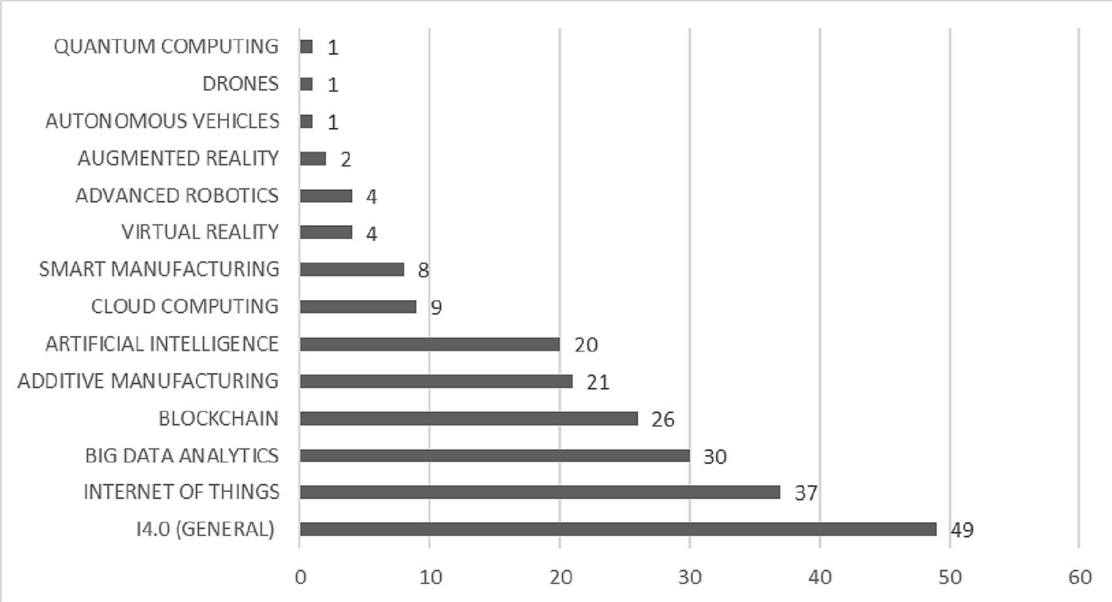
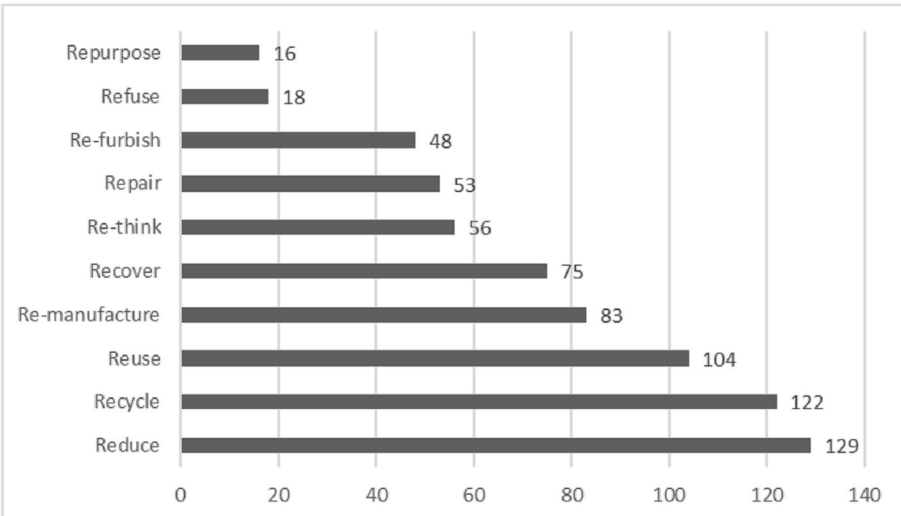


FIGURE 3 Specific I4.0 technologies by frequency.

FIGURE 4 CE principles by frequency.



et al., 2021). The least addressed principles were Repurpose and Refuse.

3.2 | Content analysis

3.2.1 | CE and I4.0 interrelationships at supply chain level

The literature review of CE principles and I4.0 technologies resulted in a metacognitive mind map with 140 possible interrelationships. Evidence of 100 of these was found. In addition, the works have been grouped into the three groups of Rs (useful application of materials; extending the lifespan of products and their parts; and smarter product use and manufacture). The most addressed interrelationships identified in the literature were between IoT and BDA use and the principles of reducing and recycling and a general perspective of Industry 4.0 associated with the principles of reducing, reusing, remanufacturing and recycling. In contrast, less use has been noted of I4.0 technologies in relation to the Refuse and Repurpose principles.

More specifically, in the literature on the use of IoT, smarter product use and manufacture are mainly addressed from the point of view of a reduction in waste generation, and the use of raw materials is one of the main topics covered (Garrido-Hidalgo et al., 2020). The use of IoT systems plays an important role by enabling efficient management of the use of resources, for example, energy management and water consumption (Ingemarsdotter et al., 2019; Rajput & Singh, 2020). Furthermore, some articles have associated IoT with the

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Re-think and Refuse principles. The use of IoT has been also extensively addressed to extend the lifespan of products and their parts (through the Reuse, Re-manufacture, Repair, Re-furbish and Repurpose principles) and to achieve the application of materials (via the Recycle and Recover principles). The literature on the use of BDA and CE mainly focuses on the principles of reduction and recycling. However, the use of BDA to enhance circularity ranges from supporting the conception of new business models (Xiang & Xu, 2019) to the extension of the life cycle of materials and products by using product use patterns and customer requirement data to carry out predictive maintenance (Edwin Cheng et al., 2022) and the useful application of end-of-life materials, which supports the management of urban recycling systems (Nobre & Tavares, 2017). Therefore, all 10 principles have been considered, although less attention has been paid to Repurpose and Refuse.

Regarding the use of blockchain, its ability to render information unalterable makes it an ideal technology to address the problem of data reliability. Therefore, together with other technologies such as IoT or big data, it supports product life cycle analysis to improve supply chains' performance in CE issues (Ajwani-Ramchandani et al., 2021; Chidepatil et al., 2020). In this sense, a variety of applications have been addressed to link the use of this technology and the development of solutions to extend the lifespan of products and their parts through the Reuse, Re-manufacture, Repair and Re-furbish principles. The useful application of materials was discussed regarding the Recycle and Recovery principles. Smarter product use and manufacture were mostly approached from the point of view of the principle of reduction. AM is another technology that has received considerable research attention. According to the reviewed literature, this technology can lead to the achievement of CE goals through smarter product use and manufacture by enabling designs that support the value cycle, for example, by minimising the types of materials present in a product (Colorado et al., 2020; Despeisse et al., 2017) and by enabling the manufacture of products and/or components in local locations, which reduces the CO^2 emissions associated with transport (Sauerwein et al., 2019). The literature also deals with issues related to the useful application of materials for both recycling and recovery. Regarding the extension of the lifespan of products/parts, AM enables the design of products that can be repaired or used to manufacture other products (Colorado et al., 2020; Despeisse et al., 2017).

Evidence was found for all groups and principles in the literature on AI and CE. In line with the previous technologies, the principles that were recurrently addressed were reducing and recycling. AI is often presented in conjunction with other technologies such as smart manufacturing/advanced manufacturing, advanced robotics, IoT and blockchain. AI's role is often associated with optimal decision-making and providing autonomy to systems pursuing CE objectives (Tozanlı et al., 2020; Wilts et al., 2021). In CE contexts, cloud computing is being used for the development of powerful platforms that enable collaboration and support the implementation of numerous sustainability-related projects (Wiedmann, 2017). Cloud computing is mainly associated with smarter product use and manufacture through the Re-think and Reduce principles. Solutions for extending the lifespan of products/parts (Reuse, Re-manufacture, Repair, Re-furbish) and the useful application of materials (Recycle and Recover) have also been addressed in the literature. Furthermore, this technology is often cited in conjunction with IoT devices for the analysis of the life cycle of products achieving, in conjunction with some specific cloud platforms, the efficient management of repair, reuse and recycling of products and/or their components, as is currently the case of electronic products and household appliances, for example (Conti & Orcioni, 2019).

Traditional manufacturing technologies are being transformed in the context of I4.0, giving rise to smart factories (Cioffi et al., 2020; Kerin & Pham, 2020). Applications of smart manufacturing/cyber–physical systems (SM/CPS) are being used to enhance product use and manufacturing, as well as to extend and manage the product life cycle. In this sense, by using CPS in conjunction with a variety of I4.0 enabling technologies, smart manufacturing is primarily enabling materials reduction and product repair, reuse, re-manufacturing, recycling and recovery (Kerin & Pham, 2019; Nascimento et al., 2019). Therefore, the literature on SM/CPS and CE is not as extensive as on the previously mentioned technologies, although it has covered almost all principles (with the sole exception of repurposing).

Furthermore, technologies such as VR, AR and advanced robotics have been addressed, albeit in a small number of papers. Even so, VR is being used in the simulation of systems for CE objectives, for example, by simulating the automated sequence of product disassembly in robotics systems (Kerin & Pham, 2019; Rocca et al., 2020). Despite the small number of papers that have addressed this technology, the use of VR was also related to the three groups of principles. Similarly, advanced robotics applications were associated with all three groups. Among other objectives, this technology aims to automatically separate recyclable and reusable components and classify all components and waste for subsequent management (Sarc et al., 2019). Conversely, AR was associated with only one group of principles—extending the lifespan of products/parts—specifically with Re-manufacturing. Its main application in CE contexts is to facilitate work by tagging information to physical products and providing precise information on tasks and the sequence in which they should be performed (Kerin & Pham, 2020).

Finally, drones, AV and quantum computing technologies were addressed in one article each. According to the literature, drones can be linked to principles from each of the three groups: Reduce, Refurbish and Recovery activities (Mahroof et al., 2021). AV was associated with smarter product use and manufacture (Re-think and Reduce) (Prideaux & Yin, 2019), and future applications of quantum computing could be used to improve product use and manufacture (Re-think and Reduce) to extend the lifespan of products/parts (Reuse) and to improve the application of materials (Recovery) by dynamic route optimisation and simulation to maximise product usability, reusability and life cycle (Sarkis, 2021). The results are summarised in Figure 5 and detailed in the appendices.

3.3 | Focus group outcomes

Based on the gaps identified in the systematic review, focus groups were held to analyse and discuss the potential contributions of CE

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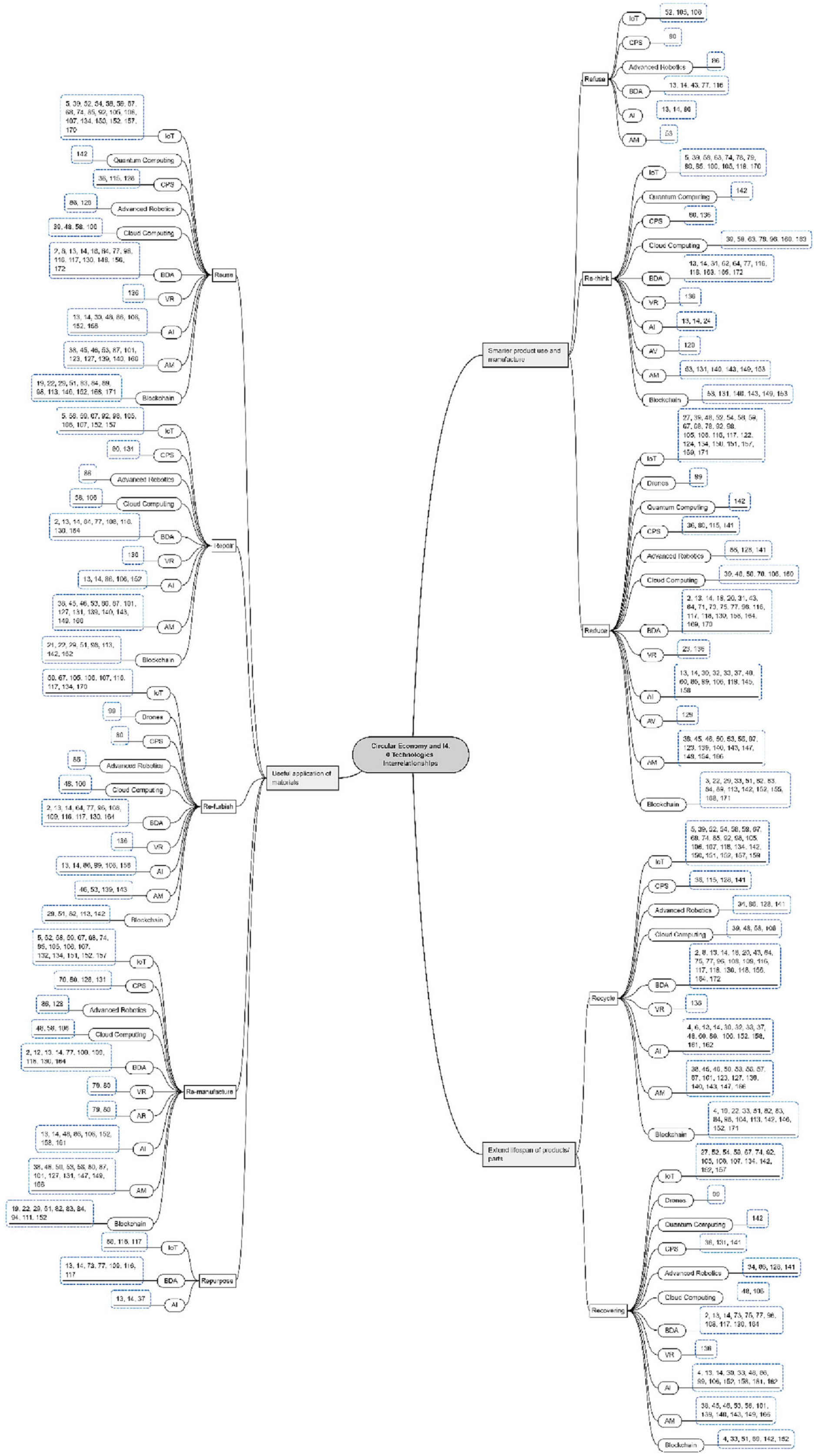

FIGURE 5 Mind map of CE–I4.0 interrelationships.

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TABLE 5 Fuzzy Delphi responses.

Expert	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
A3	4	3	3	4	4	4	4	4	4	4
A4	2	3	4	4	4	4	3	4	4	5
A5	3	4	3	4	2	2	3	4	3	3
A6	4	5	2	3	4	5	5	4	2	3
A7	4	3	3	4	4	3	4	4	4	3
A8	4	5	3	4	5	5	5	5	3	3
A9	4	4	4	3	3	3	4	4	3	2
A10	3	5	2	3	4	5	3	4	3	4
A11	4	5	3	4	4	4	3	5	3	4
A12	2	5	4	4	4	4	4	5	1	2
A13	2	5	3	4	4	4	4	4	3	2
A14	4	3	5	3	3	4	4	5	4	3
A15	4	5	3	4	4	5	4	4	4	3
A16	3	5	3	4	5	5	4	5	3	2

principles to improving I4.0 technologies not identified in the literature. The appendices present the core questions that the focus group addresses regarding research gaps, focus group discussions and research lines in the agenda on CE–I4.0 interrelationships.

The results presented in the appendices describe how, according to the iterations in the focus group, CE principles can improve I4.0 technologies through interrelationships not identified in the literature. It should be noted that AM was identified as one of the technologies most cited as relevant for enabling redesign, repurposing, remanufacturing and re-thinking in sustainable supply chains. In contrast, quantum computing and advanced robotics technologies were perceived to have few short-term benefits and/or applicability for improving at least one of the CE principles with no interrelationships identified in the literature. According to the FGI results, 16 guidelines were established with research lines to extend the literature with new theory and practical works to better explore CE–I4.0 interrelationships.

The points of attention and future goals are related to best CE–I4.0 implementation and what is still missing for this integration to happen. According to Expert A4 and Expert A1, the lack of governance, communication and reliability among actors in the value chain stands out. What is required above all is the support of top management and organisational culture (Expert A3) to generate confidence in the supply chain for innovation and continuous improvement (Expert A4). It is worth noting that one challenge is the replacement of the workforce, which today depends on high-quality industrial jobs (Expert A1).

To verify the most critical and urgent I4.0 technologies to improve CE capabilities, and given that the FGI discussed no CE–I4.0 interrelationships identified in the literature, FD study rounds were performed both to determine priority CE–I4.0 interrelationships and also identify CE–I4.0 interrelationship guidelines for a research agenda generated by multiple theoretical and empirical methodological procedures (SLR, FGI and FD) to support continuous and incremental improvements in SDGs 9, 12 and 13.

3.4 | FD results

An FD study was applied with Equations (1) and (2) to identify the most relevant CE principles for improving I4.0 technologies. The values adopted for α and λ were 0.5 and 1, respectively (Chang et al., 2000). The FD was carried out in two rounds, the first exploratory and the second confirmatory (Garcia-Buendia et al., 2022), with the answers of experts who responded to the two stages of the questionnaire accepted as valid (Tsai et al., 2020). This also allowed to reflect on their responses and confirm their assessment in this process of evaluating the I4.0 technologies that can most contribute to CE principles for which no CE–I4.0 interrelationship exists in the literature. The experts who participated in the research are listed in Table 2; of the 14 participants, 71.43% hold PhD, 7.14% MSc and 21.43% BSc. 57.14% of the participants reside in Brazil, with the remainder residing in Spain (21.42%), the United Kingdom (14.28%) and Italy (7.14%). The experts responded on a 5-point Likert scale from 1 = *irrelevant* to 5 = *extremely relevant*, as described in Table 3. FD responses are presented in Table 5.

The experts' responses on the relevance of the I4.0 technologies for improving CE principles are given in Table 5, where T1 is blockchain technology, T2 is additive manufacturing, T3 is autonomous vehicles, T4 is augmented reality, T5 is virtual reality, T6 is cloud computing, T7 is advanced robotics, T8 is smart manufacturing/advanced manufacturing/cyber–physical systems (CPS), T9 is quantum computing, and T10 is drone technology.

The calculated threshold (δ) value was 0.796, and all the criteria whose convex combination values were lower than δ were rejected, as can be observed in Table 6. The ability of four of the 10 I4.0 technologies to improve CE principles was rejected, namely, blockchain, autonomous vehicles, quantum computing and drone technologies. The most relevant I4.0 technology for improving CE principles was smart manufacturing/advanced manufacturing/CPS, which 64.3% of

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TABLE 6 Results after screening.

Criteria	μb	lb	Db	Decision
T1: Blockchain to improve CE principles	0.772	−0.272	0.772	Rejected
T2: Additive Manufacturing to improve CE principles	0.894	−0.019	0.894	Accepted
T3: Autonomous Vehicles to improve CE principles	0.760	−0.260	0.760	Rejected
T4: Augmented Reality to improve CE principles	0.834	0.041	0.834	Accepted
T5: Virtual Reality to improve CE principles	0.841	−0.341	0.841	Accepted
T6: Cloud Computing to improve CE principles	0.863	−0.363	0.863	Accepted
T7: Advanced Robotics to improve CE principles	0.848	0.027	0.848	Accepted
T8: Smart Manufacturing/Advanced Manufacturing/Cyber-Physical Systems (CPS) to improve CE principles	0.916	0.334	0.916	Accepted
T9: Quantum Computing to improve CE principles	0.500	0.000	0.500	Rejected
T10: Drone technology to improve CE principles	0.735	−0.235	0.735	Rejected

the experts considered highly relevant and 35.7% considered extremely relevant.

4 | DISCUSSION

SLR, FGI and FD triangulation culminated in the guidelines for the research agenda and discussions that aimed to contrast the results obtained with state-of-the-art literature to generate innovative knowledge (de Mattos Nascimento et al., 2022; Tortorella et al., 2020). Triangulation showed that the most analysed technologies in the literature were IoT (Rajput & Singh, 2020), BDA (Xiang & Xu, 2019), blockchain (Choi et al., 2020), AM (Colorado et al., 2020) and AI (Wilts et al., 2021). The least cited were quantum computing (Sarkis, 2021), drones (Mahroof et al., 2021), AV (Prideaux & Yin, 2019), AR (Kerin & Pham, 2020) and advanced robotics (Tozanlı et al., 2020). The intermediaries with a respective frequency of 9 and 8 were cloud computing and smart manufacturing. Regarding the CE principles, the most analysed were Reduce, Recycle and Reuse. The I4.0 technologies that most contribute to each of the 10Rs were also identified, with Refuse, Re-furbish, and Repurpose most associated with BDA; Re-think, Reduce, Reuse, Re-manufacture, Recycle and Recover with IoT; and Repair with AM.

From the two rounds of the FD, four I4.0 technologies and their consequent interrelations with CE principles were rejected. This generated an order of priority, with the I4.0 technologies from the FGI that were prioritised and evaluated as most relevant included in the research agenda. An SLR with a matrix of interrelationships and mind maps, FGIs with discussions and conclusions on CE–I4.0 interrelationships and FD were also performed to prioritise the research agenda. The guidelines for the research agenda were established based on the results of the FGI and FD; these iterations analysed how I4.0 technologies could be used to close the existing research gaps in the literature and propose best practices, points of attention and/or guidelines for each I4.0 technology and the respective 10R principles (Nascimento et al., 2020). A research agenda (see Figure 6) was then generated based on these priorities to achieve the guidelines categorised as very urgent, urgent and not very urgent.

Figure 6 shows that, based on the guidelines generated through the FGI results, the categorisation is made with the most frequent I4.0 technologies and the corresponding highest value of the convex combination in the FD, which generates a sense of urgency for the guidelines by using a weighted sum calculation to order the research agenda. Note that the guidelines were created from the FGI discussions that evaluated how each I4.0 technology could improve the implementation of each respective R when no interrelationships were identified in the literature. So, the guidelines for the research agenda are separated into a short-term view of the efforts made for future CE–I4.0 theory-building (Voss et al., 2002).

Based on the research agenda presented in Figure 6, which summarises and classifies the guidelines established through FGI discussions and FD rounds, Repurposing is considered the CE principle with the highest frequency of non-interrelation and, therefore, identified as a research gap. The research gaps identified were repurposing with drones, quantum computing, smart/advanced manufacturing/CPS, advanced robotics, AV, AM/3D printing, blockchain, virtual reality, AR and cloud computing. However, from the systematic review, positive CE–I4.0 interrelationships were also identified in terms of both approach and useful Repurposing with some I4.0 technologies such as IoT (Ingemarsdotter et al., 2019; Nobre & Tavares, 2020b), BDA (Bag & Pretorius, 2022; Jabbour et al., 2020; Kazancoglu et al., 2021; Nobre & Tavares, 2020a, 2020b) and AI (Bag, Pretorius, et al., 2021; Colla et al., 2020). High-priority BDA, AM/3D printing and cloud computing technologies were defined as very urgent for iteration with the 10R research gaps. I4.0 technologies designated as an urgent priority were smart manufacturing, advanced robotics, and AI. Lastly, VR and AV were placed in the not very urgent priority category for generating positive interrelationships with CE in the short-term CE–I4.0 research agenda.

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5 | CONCLUSIONS

5.1 | Implications for theory

Research gaps between 10R principles and I4.0 technologies identified in the literature (Nascimento et al., 2018; Voss et al., 2002) were used in the FGI and FD to analyse, discuss and propose interrelationships with I4.0 technologies for improving at least one of the 10R principles. Thus, a novel literature classification is provided that enables to identify the interrelationships between each I4.0 technology and each CE principle grouped by purpose (see metacognitive mind map in Figure 5) used to create mind maps with the state-of-the-art CE-I4.0 literature. Furthermore, guidelines are provided based on the FGI and FD to guide future research on the as-yet-unstudied I4.0 technologies that must be investigated to analyse their impact on CE principles.

The present work differs from earlier research studies in the adaptation and rigour of the proposed methodology, which combines an SLR, FGI and FD to generate guidelines for the CE–I4.0 interrelationship research agenda for improving sustainable supply chains. The methodology used combines theoretical and empirical approaches and qualitative and quantitative categories (Caiado et al., 2022). It is worth noting that the results identified and presented in metacognitive mind maps are innovative for the literature as they find relationships in the approach or applications of CE–I4.0 to assist researchers or companies in their planning and empirical validations. A further novelty of the present work that distinguishes it from previous studies is that it identifies research gaps in the form of relationships that do not exist in the prior literature, which can be used to extend theory and propose recommendations and guidelines for the development of new works focused on unexploited opportunities for theory-building (Voss et al., 2002).

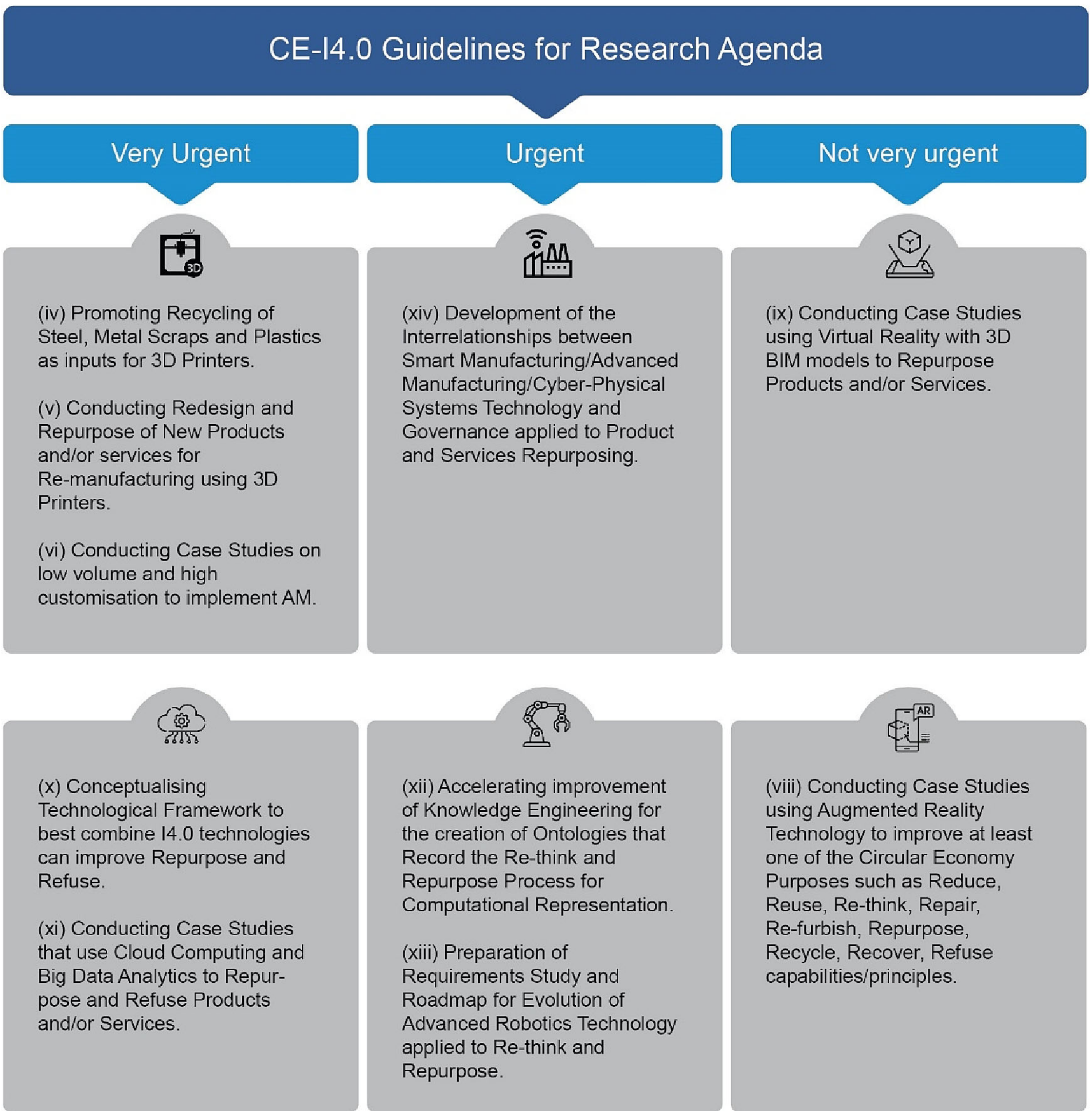

FIGURE 6 CE–I4.0 guidelines for a research agenda for sustainable supply chains.

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5.2 | Implications for practice

The contribution to practice aims to establish the I4.0 technologies that influence and support incremental improvements to CE principles by considering the SLR's content analysis results, which find conclusive relationships between every I4.0 technology and CE principle. Based on the 40 identified research gaps, an FGI and FD were performed to discuss and propose potential new conclusive relationships between I4.0 technologies and CE principles with guidelines for the research agenda and also best practices, recommendations and/or barriers. As a result, companies and applied research can analyse and design I4.0 technology applications with case studies that perform empirical validations in sustainable supply chains. The suite of I4.0 technologies can be combined and adapted either completely or consistently for continuous and incremental adoption to increase the maturity of the 10R principles. Furthermore, with the results of the guidelines for the research agenda, managers will be able to analyse how they can use I4.0 technologies to fully achieve their CE–I4.0 interrelationship goals.

5.3 | Limitation and future works

The limitation of our work is related to the selection of the articles: Only peer-reviewed high-impact articles in the WoS database have been reviewed. Although WoS is a highly reliable and comprehensive academic database, it may not contain every publication that complies with the research focus. Furthermore, the study was also limited to the selection and availability of FGI experts on CE–I4.0 interrelationships who have published articles recently and are among the top three most cited authors of papers on the topic in Scopus and WoS. Despite this, the sample selection criterion is robust, but it is worth noting this limitation caused by the scarcity of experts on CE–I4.0 interrelationships. However, this was mitigated with rigour in the criterion and sample selection from both the literature and empirical studies by the FGI and FD rounds, which is a point of attention for stating the limits and scope of the present research work.

Therefore, a future, deeper analysis of the effect of I4.0 technologies in CE contexts is required. In addition, autonomous vehicles have received scarce attention in the literature, although their potential impact in CE contexts is robust as they provide efficient transport for multiple routes. For example, smart transport system use would facilitate route optimisation by considering the demand location, efficient parking location and optimum fuel consumption.

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APPENDIX A: CE–I4.0 INTERRELATIONSHIPS MATRIX

Emerging IT of I4.0	Circular economy capabilities/principles									
	Smarter product use and manufacture			Extend lifespan of products/parts					Useful application of materials	
	R0: Refuse	R1: Re-think	R2: Reduce	R3: Reuse	R4: Repair	R5: Re-furbish	R6: Re-manufacture	R7: Repurpose	R8: Recycle	R9: Recovering
Internet of things (IoT)	52, 105, 106	5, 39, 58, 63, 74, 78, 79, 80, 85, 100, 105, 118, 170	27, 39, 48, 52, 54, 58, 59, 67, 68, 78, 92, 98,105, 106, 116, 117, 122, 124,134, 150, 151, 157, 159, 171	5, 39, 52, 54, 58, 59, 67, 68, 74, 85, 92, 105106, 107, 134, 150, 152, 157,170	5, 58, 59, 67, 92, 98, 105, 106, 107, 152,157	59, 67, 105, 106, 107, 116, 117, 134, 170	5, 52, 58, 59, 67, 68, 74, 85, 105, 106, 107,132, 134, 151, 152, 157	68, 116, 117	5, 39, 52, 54, 58, 59, 67, 68, 74, 85, 92, 98,105, 106, 107, 118, 134, 142,150, 151, 152, 157, 159	27, 52, 54, 59, 67, 74, 92, 105,106, 107, 134, 142, 152, 157
Drones			99			99				99
Quantum computing		142	142	142						142
Smart/advanced manufacturing/ CPS	80	80, 136	36, 80, 115, 141,	36, 115, 128	80, 131	80	79, 80, 128,131		36, 115, 128, 141	36, 131, 141
Advanced robotic	86		86, 128, 141	86, 128	86	86	86, 128		34, 86, 128,141	34, 86, 128,141
Cloud computing		39, 58, 63, 78, 96, 160, 163	39, 48, 58, 78, 106, 160	39, 48, 58, 106,	58, 106	48, 106	48, 58, 106		39, 48, 58, 106	48, 106
Big data analytics	13, 14, 43, 77, 116	13, 14, 31, 62, 64, 77, 116, 118, 163, 165, 172	2, 13, 14, 18, 20, 31, 43, 64, 71, 73, 75, 77, 96, 116, 117, 118, 130, 156, 164, 169, 170	2, 8, 13, 14, 18, 64, 77, 96, 116, 117, 130, 148, 156, 172	2, 13, 14, 64, 77, 108, 116, 130, 164	2, 13, 14, 64, 77, 96, 108, 109, 116, 117, 130, 164	2, 12, 13, 14, 77, 108, 109, 116, 130, 164	13, 14, 73, 77109, 116, 117	2, 8, 13, 14, 18, 20, 43, 64, 75, 77, 96, 108, 109, 116, 117, 118, 130, 148, 156, 164, 172	2, 13, 14, 73, 75, 77, 96, 108, 117, 130, 164
Virtual reality		136	23, 136	136	136	136	79, 80		136	136
Augmented reality							79, 80			
Artificial intelligence	13, 14, 86	13, 14, 24	13, 14, 30, 32, 33, 37, 48, 60, 86, 99, 106, 119, 145, 158	13, 14, 30, 48, 86, 106, 152, 158	13, 14, 86, 106, 152	13, 14, 86, 99, 106, 158	13, 14, 48, 86, 106, 152, 158, 161	13, 14, 37	4, 6, 13, 14, 30, 32, 33, 37, 48, 60, 86, 106, 152, 158, 161, 162	4, 13, 14, 30, 33, 48, 86, 99, 106, 152, 158, 161, 162
Autonomous vehicles		129	129							

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Emerging IT of I4.0	Circular economy capabilities/principles: Smarter product use and manufacture			Extend lifespan of products/parts					Useful application of materials	
	R0: Refuse	R1: Re-think	R2: Reduce	R3: Reuse	R4: Repair	R5: Re-furbish	R6: Re-manufacture	R7: Repurpose	R8: Recycle	R9: Recovering
Additive manufacturing/ 3D printing	53	53, 131, 140, 143, 149, 153	38, 45, 46, 50, 53, 56, 87, 123, 139, 140, 143, 147, 149, 154, 166	38, 45, 46, 53, 87, 101, 123, 127, 139, 140, 166	38, 45, 46, 53, 80, 87, 101, 127, 131, 139, 140, 143, 149, 166	46, 53, 139, 143	38, 46, 50, 53, 56, 80, 87, 101, 127, 131, 147, 149, 166		38, 45, 46, 50, 53, 56, 57, 87, 101, 123, 127, 139, 140, 143, 147, 166	38, 45, 46, 53, 56, 101, 139, 140, 143, 149, 166
Blockchain		3, 51, 84, 88, 98, 110	3, 22, 29, 33, 51, 82, 83, 84, 89, 113, 142, 152, 155, 168, 171	19, 22, 29, 51, 83, 84, 89, 98, 113, 146, 152, 168, 171	21, 22, 29, 51, 98, 113, 142, 152	29, 51, 82, 113, 142	19, 22, 29, 51, 82, 83, 84, 94, 111, 152		4, 19, 22, 3351, 82, 83, 84, 98, 104, 113, 142, 146, 152, 171	4, 33, 51, 89142, 152
General proxy about I4.0	7, 11, 40, 90, 93, 120, 135	7, 11, 25, 26, 35, 40, 42, 44, 49, 76, 90, 93, 100, 120, 125, 133	1, 7, 9, 10, 11, 16, 17, 25, 26, 28, 35, 40, 41, 42, 44, 47, 49, 55, 65, 66, 69, 70, 72, 76, 81, 90, 93, 97, 102,103, 112, 114, 115, 120, 125, 126, 135, 138, 144, 173	1, 7, 9, 10, 11, 15, 16, 17, 25, 26, 28, 35, 40, 41, 42, 44, 47, 49, 55, 61, 65, 66, 69, 72, 76, 90, 91, 93, 97, 102, 103, 112, 114, 115, 120, 121, 125, 135, 138, 144	7, 9, 10, 11, 40,44, 69, 90, 93, 120, 135	7, 11, 17, 28, 40, 44, 65, 70, 90, 93, 120, 121, 135, 138	1, 7, 9, 10, 11, 17, 25, 26, 28, 35, 40, 44, 47, 49, 55, 61, 65, 69, 72, 76, 90, 97, 103, 120, 121, 135, 137, 167, 173	7, 11, 28, 44, 65, 90, 120	1, 7, 9, 10, 11, 15, 16, 17, 25, 26, 28, 35, 40, 41, 42, 44, 47, 49, 55, 61, 65, 66, 69, 72, 90, 91, 95, 97, 112, 115, 120, 121, 135, 137, 138, 144	1, 7, 9, 11, 17, 40, 42, 44, 47, 49, 55, 69, 70, 90, 93, 102, 120, 121, 135, 138, 144, 173

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APPENDIX B: GUIDELINES FOR RESEARCH AGENDA

Core questions in the focus group	Focus group discussions	Guidelines for research agenda
How can blockchain technology improve repurpose and Refuse capabilities/principles?	Blockchain is a protocol that promotes security and end-to-end integration of information and is widely used in cryptocurrencies (Expert 4). It can also be used to repurpose if the technology is applied in a supply chain. This has to involve several actors: One designer in one country and the other designer in another country and marketing and product people in a third country. Thus, secure communication protocols are possible between different countries and different actors, and, for example, payments can be made to these people in cryptocurrencies, thus promoting digital culture and communication through these blocks (Expert 4). So, digital blockchains can facilitate transactions, not only of a digital product (Expert 3) but also to re-propose a service or a business model, for example, servitisation (Expert 2). I believe that there will be a need to create a safety chain between these companies in the production chain, such as rules of trust to increase cooperation between actors at the digital supply chain level (Expert 1)	(i) Digital workflow for better communication and transactions to repurpose products and/or services (ii) Technological framework to implement a management system with blockchain for repurposing products and/or services at sustainable supply chain level (iii) Case study to repurpose products or services using blockchain, IoT, cloud computing and big data analytics
How can additive manufacturing/3D printing technology improve Repurpose capabilities/principles?	AM is a real possibility for manufacturing and perfectly replicating a variety of machines that can be sold with a service. So, 3D printing is a very viable option: You print whatever you want, you make a 3D project and print it. This generates tremendous freedom (Expert 4). The primary way to implement circularity is by recycling steel and plastic, to transform waste into inputs for 3D printers (Expert 4). Regarding the potential interrelationship between repurposing and 3D printing, the challenge is to take a product that already has a purpose and find a new function or adapt it to a new function (Expert 2). Nowadays, if I think about taking a product apart and making a new product if this is the re-proposal that we are talking about, then yes, I agree with you (Expert 2). I agree with what (Expert 2) said; it would be like taking a product apart and using it to make a powder for a 3D printer to make another product that could be used in the same way as this product or for something else (Expert 3). Most importantly, you must make it simple, simple because complex is questionable (Expert 1). If it is not viable on a large scale, it is practically just for show (Expert 1). I do not know if I would say for show, but low volume and high customisation are the best practices for AM implementation (Expert 4)	(iv) Recycling steel, metal scraps and plastics as inputs for 3D printers (v) Redesign and repurpose new products and/or services for re-manufacturing using 3D printers (vi) Case studies on low volume and high customisation to implement AM
How can autonomous vehicle technology improve Reuse, Re-manufacture, Repair, Re-furbish, Repurpose, Recycle, Recover and Refuse capabilities/principles?	I do not see much maturity in this; I even believe that it will be more applied in internal logistics (Expert 4). Another problem is that when they leave university, professionals do not receive	(vii) Autonomous vehicle technology can improve the capabilities/principles of Reuse, Re-manufacture, Repair, Re-furbish, Repurpose, Recycle, Recover and Refuse

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	much information about I4.0, about how information and ideas are programmed that have to be transformed into information decisions (Expert 1). I agree with you, but updating and searching for new skills for new professionals (Expert 3). Yes, in autonomous vehicles, it is even more difficult, even more, because they are limited to internal logistics; it is much more difficult to see this (Expert 2)	
How can augmented reality technology improve Reduce, Reuse, Re-think, Repair, Re-furbish, Repurpose, Recycle, Recover, Refuse capabilities/principles?	I imagine for re-thinking; if you have virtual and augmented reality, you can look and think about making other things, incremental improvements (Expert 4). It is also a matter of training and empowering (Expert 3). This technology is widely used for safety in the industrial environment, maintenance and maintenance training. So I imagine that it could be used in the same way for re-education in the circular economy (Expert 3). For me, this is re-thinking (Expert 4)	(viii) Case studies using augmented reality technology to improve at least one of the circular economy purposes, such as, Reduce, Reuse, Re-think, Repair, Re-furbish, Repurpose, Recycle, Recover and Refuse capabilities/principles
How can virtual reality technology improve Repurpose and Refuse capabilities/principles?	It is more applicable to repurposing because you can have a virtual 3D model, using the virtual world to repurpose something, have an idea, assemble and disassemble until the objective is accomplished to continuous improvement of products and services toward circularity (Expert 4). Refuse, I cannot see anything (Expert 4). It can also be used for simulation, using different scenarios there, and proposing new functions (Expert 3). In this sense, I think it is helpful to try to anticipate problems and visualise situations (Expert 2). Predictions and simulations. Also, with augmented reality, you can buy a product using your cell phone; you already have this with QR codes nowadays, and you can also see the entire sustainable history (Expert 3)	(ix) Case studies using virtual reality with 3D BIM models to repurpose products and/or services
How can cloud computing technology improve Repurpose and Refuse capabilities/principles?	I think indirectly. These technologies end up working indirectly. Where there are more data and more information, you can make more effective decisions that will eventually culminate in aligned things, but it's indirect (Expert 2). Yes, and what (Expert 1) commented on the principle, having information, indirectly or directly helps you to have communication (Expert 4). So, cloud computing alone may make such an important contribution, but cloud computing and big data together will magnify the contribution (Expert 2). It is also a contradiction because, for example, there is a lot of talk about big data, but very little about what you need to use big data; you can work with different databases without the need for big data (Expert 4). When talking about big data, there is the 3V (variety, velocity and volume), there is the issue of volume, but there is the issue of structured and unstructured data; you combine these data, different databases, not only by volume but also for the variety of information (Expert 3)	(x) Technological framework to best combine I4.0 technologies can improve repurpose and refuse (xi) Case studies that use cloud computing and big data analytics to repurpose and refuse products and/or services

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How can advanced robotics technology improve Re-think and Repurpose capabilities/principles?	I find its application difficult because you will not re-think using robots or repurposing unless the robot is intelligent enough to do it on its own (Expert 4). Regarding this question of repurposing, I think I agree with the issue that you mentioned, which I find difficult. However, re-thinking the concept is trying to make more intensive use of the product (Expert 3). I cannot identify relationships because to repurpose something and to re-think everything depends on human beings, and they can only be replaced when the robot has full artificial intelligence. This is unthinkable today (Expert 4). I agree that the robotics issue would have to be linked to the analytics issue. A robust AI algorithm to help make decisions based on what has been learned from human data, at least if it is to be achieved in a short time (Expert 3)	(xii) Knowledge engineering for the creation of ontologies that record the re-think and repurpose process for computational representation (xiii) Requirements study and roadmap for evolution of advanced robotics technology applied to re-think and repurpose
How can smart manufacturing/advanced manufacturing/cyber–physical systems technology improve Repurpose capability/principle?	All this discussion, all these possibilities depend on the well-established governance system (Expert 1). Because without effective governance that knows or approaches the base of the pyramid to collect reliable information and make a decision (Expert 1). Besides, you can an attempt to make at the management level, which is to resolve the error as quickly as possible, so work is essential of governance that will hold back this attempt to get quality information (Expert 1). So all this change in the circular economy implies having strategic intelligence focused by the organisation to map the problems and seek solutions and paths to make the circular economy viable (Expert 1). I agree that this stimulus is top-down because there will be change, and there must be support (Expert 3)	(xiv) Interrelationships between smart manufacturing/advanced manufacturing/cyber–physical systems technology and governance applied to repurposing products and services
How does quantum computing technology Re-manufacture, Repair, Re-furbish, Repurpose, Recycle and Refuse?	It is even a step even up from the supercomputer, it would be a super ultra-computer (Expert 4). More agile decisions, maybe more agile decisions in the chain. But there is the matter of the trade-off, of what the cost is for you to have this operating. There will be the expense of energy and resources (Expert 3). In relation to mining, I emphasise that energy expenditure is not sustainable (Expert 4)	(xv) Circular business model that integrates quantum computing technology and CE principles (xvi) Benefits, barriers and challenges related to application of quantum computing technology in CE context
How can drone technology improve Reuse, Re-think, Re-manufacture, Repair, Repurpose, Recycle and Refuse capabilities/principles?	Drones can be used for deliveries (Expert 2). I think this drone issue is more to monitor, control or deliver, as (Expert 2) commented earlier (Expert 3). Would a drone be used to collect waste for recycling? (Expert 4). I have heard about the police using lots of drones to monitor border areas, for example (Expert 3). I know that agribusiness is now using drones for crop monitoring, and I saw another company that mapped a steelyard to make an inventory of steel (Expert 2)	(xv) Circular business model that integrates drone technology and CE principles (xvi) Benefits, barriers and challenges related to application of drone technology in CE context

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