# How do different Industry 4.0 technologies support certain Circular Economy practices

## Abstract

**Purpose**

Uncovering the relationship between Industry 4.0 (I4.0) technologies and circular economy (CE) practices is critical not only for implementing CE but also for leveraging I4.0 to achieve sustainable development goals. However, the potential connection between them—especially how different I4.0 technologies may influence various CE practices—remains inadequately researched. The purpose of this study was to quantitatively explore the impacts of various I4.0 technologies on CE practices.

**Design/Methodology/approach**

A mixed method consisting of a systematic literature review, content analysis, and social network analysis was adopted. First, 266 articles were selected and mined for contents of I4.0 technologies and CE practices; 27 I4.0 technologies and 21 CE practices were identified. Second, 62 articles were found that prove the positive influence of I4.0 technologies on CE practices, and 124 relationships were identified. Third, based on evidence supporting the link between I4.0 technologies and CE practices, a two-mode network and two one-mode networks were constructed and their network density and degree centrality indicators were analyzed.

**Findings**

I4.0 technologies have a low application scope and degree for promoting CE. The adoption of a single I4.0 technology has limited effect on CE practices, and wider benefits can be realized through integrating I4.0 technologies. The Internet of Things, additive manufacturing, big data and analytics, and artificial intelligence are among the top technologies promoting CE implementation and reduction and recycling were identified as the main mechanism. The integration of these technologies is the most popular and effective. Twelve CE practices were identified to be the most widely implemented and supported by I4.0 technologies.

**Research limitations/implications**

First, only journal articles, reviews, and online publications written in English were selected, excluding articles published in other languages. Therefore, the results obtained only represent a specific group of scholars, which may be fragmented to a certain extent. Second, because the extraction of the impact of I4.0 on CE mainly relies on a manual literature review, this paper only provides the statistics of the number of publications involving relationships, while lacking the weight measurement of relationships.

**Originality**

A comprehensive, quantitative, and visual analysis method was employed to unveil the current implementation levels of I4.0 technologies and CE practices. Further, it was explored how different I4.0 technologies can affect various CE aspects, how different I4.0 technologies are integrated to promote CE realization, and how various CE practices are implemented simultaneously by I4.0 technologies.

**Keywords:** Industry 4.0 technologies, Technology adoption, Circular economy practices, Social network analysis.

## 1. Introduction

Sustainable development, which was proposed and defined by the World Commission on Environment and Development in 1987, has finally reached a consensus in many countries after discussion for nearly 35 years. In 2015, 17 sustainable development goals (SDGs) were proposed by the member states of the United Nations (UN) in the 2030 Agenda to guide all countries towards seeking sustainability (Salvia *et al.*, 2019). Research has begun to explore how to achieve these 17 SDGs. In particular, studies related to circular economy (CE) and Industry 4.0 (I4.0) technologies show that a considerable number of SDG targets can be directly attained by using CE practices, I4.0 technologies, or a combination of both (Schroeder *et al.*, 2019; Wali *et al.*, 2021; Belmonte-Urea *et al.*, 2021; Bai *et al.*, 2022; Dantas *et al.*, 2021). I4.0 technologies can help underpin CE practices (De Sousa Jabbour *et al.*, 2018) and CE practices can connect I4.0 technologies and SDGs (Bai *et al.*, 2022). It has been claimed that the incorporation of I4.0 and CE can achieve sustainability (Rajput and Singh, 2019; Zhou *et al.*, 2020; Yadav *et al.*, 2020; Dantas *et al.*, 2021). Therefore, the CE-I4.0 relationship is critical for attempts to achieve SDGs (Dantas *et al.*, 2021). It is thus of top importance to uncover the complex interactions between different I4.0 technologies and CE practices to facilitate their adoption, integration, and combination (Zhou *et al.*, 2020; De Sousa Jabbour *et al.*, 2018).

Several studies have explored the relationships between I4.0 and CE, including the impacts of I4.0 on CE and mutual actions between them (Piscitelli *et al.*, 2020; Garcia-Muiña *et al.*, 2018; Dantas *et al.*, 2021). For instance, Kouhizadeh *et al.* (2019) focused on a single I4.0 technology and its impact on CE. De Sousa Jabbour *et al.* (2018) and Laskurain-Iturbe *et al.* (2021) extended this stream of research by including additional I4.0 technologies. Clearly, the majority of studies have taken a qualitative approach when exploring how I4.0 technologies may affect CE. Despite valuable contributions achieved by this approach, scientific, structured, and quantitative interpretations of the actual relationships between various I4.0 technologies and CE practices (Blömeke *et al.*, 2020) as well as possible integration paths of I4.0 technologies remain unknown. In fact, most companies still have not fully embraced CE practices because of various challenges they face, which is further complicated in the era of I4.0. Meanwhile, the integration of I4.0 and CE is still in its primary stage, and also facing many challenges. A systematic understanding of the application status of I4.0 technologies in CE can provide a basis and pathway for expanding the depth and breadth of the application of I4.0 technologies. Moreover, understanding the current reality of CE practices can also provide solutions for enterprises to expand the scope of CE with I4.0 support. To achieve these benefits, the following questions need to be answered urgently:

(1) How many (and which) I4.0 technologies have been applied to how many (and which) CE practices?

(2) How are different I4.0 technologies supporting and promoting the realization of CE, and in what way (e.g., a single or an integrated way)?

(3) Which CE behaviors can be simultaneously realized and promoted by one specific I4.0 technology to save costs for enterprises?

Previous research has not yet provided holistic, systematic, global, and quantitative answers to these questions. To fill this gap in the literature, in this study, a systematic literature review on the I4.0 technologies and CE practices and their relationships was conducted. In particular, the positive impact of I4.0 technologies on CE practices was assessed to study how different I4.0 technologies support the implementation of CE practices. Furthermore, social network analysis (SNA) was used to visualize and analyze the relationships between I4.0 technologies and CE practices through a two-mode network and two one-mode networks. The impacts of I4.0 technologies on CE, the integration of I4.0 technologies, and the implementation of various CE practices are thus quantitatively and visually disclosed.

This study adds to the literature in several important ways: First, a systematic and comprehensive literature review was conducted to uncover the promoting effects various I4.0 technologies have on the implementation of CE. Second, a comprehensive, quantitative, and visual analysis method was employed to unveil the current implementation levels of I4.0 technologies and CE practices, and to explore how different technologies can affect various aspects of CE. The remainder of this paper is organized as follows: Section 2 reviews existing studies on I4.0 technologies, CE practices, and their relationships. In Section 3, the methodology of this study is introduced, including the identification and selection of publications, the extraction of I4.0 technologies and CE practices as well as their relationships, and the method for visualizing and analyzing relationships. Section 4 shows the analysis and results, which is followed by Section 5, which presents the key findings, a pertinent discussion, and conclusions.

## 2. Literature Review

### 2.1 I4.0 technologies

I4.0—also known as the “Fourth Industrial Revolution”—was derived from the German federal government in 2011. I4.0 was defined as “*a German strategic initiative to take a pioneering role in industries which are currently revolutionising the manufacturing sector*.” (Xu L D *et al*., 2018). I4.0 emphasizes the improvement of industrial capabilities through reinforcing industry with technological applications and digitalization (Luthra *et al*., 2020). A consensus has yet to be established in the literature on how to categorize technologies related to I4.0 (Laskurain-Iturbe *et al*., 2021).

Wortmann and Flüchter (2015) emphasized the Internet of Things (IoT) as a subset of I4.0 because IoT-based solutions are often applied by the smart industry, which is widely discussed in the context of I4.0. IoT was further subdivided into Industrial Internet of Things (IIoT) and Consumer Internet of Things (CIoT) (Sarc *et al*., 2019). Rajput and Singh (2019) argued that I4.0 is a combination of cyber-physical systems (CPS), IoT, and cognitive computing (CoC). Blömeke *et al.* (2020) pointed out that CPS form one technical core of I4.0. Dantas *et al*. (2021)

stated that technologies related to I4.0 include CPS, IoT, big data and analytics (BD(A)), additive manufacturing (AM), the Internet of Services (IoS), cloud computing (ClC), augmented reality (AR), systems integration (SI), simulation (SIM), cybersecurity (CS), and autonomous robots. In addition, digitalization (Dig) and intelligent robotics (Rob) are also considered as new I4.0 approaches, which have been used to develop waste management towards CE (Sarc *et al*., 2019). Gubbi *et al*. (2013) stated that the IoT essentially consists of radio frequency identification (RFID) systems and wireless sensor networks (WSNs).

## 2.2 CE practices

The concept of CE, which is widely considered as an important means to sustainable development, attempts to bring environment protection and economic growth into equilibrium. Its role is increasingly stressed in the context of I4.0 where a multiplicity of novel technologies is created and adopted (Zhou *et al*., 2020). CE has been defined by various means in literature. Kirchherr *et al*. (2017) gathered and analyzed 114 CE definitions proposed by various scholars. To better understand the concept, definition, and implementation of CE, CE is usually translated into concrete practices, actions, or elements. Accordingly, various “R” frameworks, also known as CE principles, have been used to interpret these practices. For instance, the 3R framework (i.e., reduce, reuse, and recycle), the 4R framework, the 6R framework, the 9R framework, and the 10R framework (Bag *et al*., 2021; Kirchherr *et al*., 2017). To avoid confusion caused by terminology, in this paper, CE practices refers to CE principles, CE actions, and CE elements.

With the deepening of CE, several of the actions of these R frameworks were further subdivided. Blömeke *et al*. (2020) identified nine operations in remanufacturing and recycling. Steinhilper and Weiland (2015) claimed that remanufacturing includes the five critical processes of disassembly; cleaning; inspection, diagnosis, and sorting; reconditioning; and reassembly. Laskurain-Iturbe *et al*. (2021) considered reduce as reduce input consumption (RIC) and reduce waste and emissions (RWE), where RIC was divided into RIC-material, RIC-energy, RIC-water, and RWE is divided into RWE-waste and RWE-emissions. In addition, the Ellen MacArthur Foundation put forward the ReSOLVE framework to show organizations how to implement CE practices (De Sousa Jabbour *et al*., 2018). The ReSOLVE framework includes six business actions, namely, regenerate, share, optimize, loop, virtualize, and exchange. Kouhizadeh *et al*. (2019) connected the blockchain application to these six actions of CE (ReSOLVE model) to explore how blockchain technology can transform and advance CE implementation.

Furthermore, other practices or activities are also involved and were considered in CE. Prominent examples are industrial symbiosis (Brondi *et al*., 2018), waste-to-energy (Khan and Kabir, 2020), composting (Filippini *et al*., 2019), eMaintenance (Turner *et al*., 2020), predictive maintenance (Turner *et al*., 2020), and zero waste manufacturing (Kerdlap *et al*., 2019). eMaintenance arises from the utilization of digital technologies in maintenance and can be advanced by the utilization of I4.0 technologies. Predictive maintenance is one form of eMaintenance that can achieve the goal of sustainable maintenance which is an application of CE thinking (Turner *et al*., 2020). Zero waste manufacturing is another concept of CE to support countries in their transition to CE through reuse and recycling (Kerdlap *et al*., 2019).

### 2.3 The relationships between I4.0 technologies and CE practices

Currently, two main streams of literature address the relationships between I4.0 technologies and CE. The first stream of literature focuses on unilateral relationships, i.e., the influence technologies related to I4.0 have on CE, while the second concentrates on the mutual relationships between I4.0 and CE, emphasizing the integration of technologies and CE practices towards achieving sustainability.

The first stream of literature, i.e., studies on the effects of I4.0 technologies on CE, illustrates the impact of certain I4.0 technologies on CE. For instance, Kouhizadeh *et al*. (2019) studied the influence of blockchain on the transformation of organizations towards CE. De Sousa Jabbour *et al*. (2018) showed how different I4.0 technologies, including IoT, cloud manufacturing (CM), CPS, and AM, underpin CE strategies of an organization. Taking a wider scope, Laskurain-Iturbe *et al*. (2021) explored the influence of AM, artificial intelligence (AI), artificial vision (AV), BD(A), CS, IoT, Rob, and virtual and augmented reality (VAR) on certain CE practices, through an investigation of 120 project managers and in-depth case studies of 27 projects. Piscitelli *et al*. (2020) presented a systematic literature review of 78 studies on the connection between CE and I4.0 and provided insights on how different I4.0 technologies could brace CE strategies. Other studies, such as Shayganmehr *et al*. (2021) and Mastos *et al*. (2021), attempted to analyze the impacts of I4.0 technologies on CE from a macro perspective. They found I4.0 technologies as enablers and key driving factors for the successful development of CE, contributing to the digitalization of CE practices. Bag *et al*. (2021) further found that firms with a high level of I4.0 implementation tend to develop higher 10R advanced manufacturing capabilities. The empirical study by Tang *et al*. (2022) on private companies involved in supply chain operations demonstrated the significant impact of Blockchain on all components of CE. Ertz *et al*. (2022) published a literature review that explored how I4.0 technologies prolong product lifetimes (which is considered a way to conserve resources in CE), and found that AM, AI, IoT, and BD(A) are four key constitutive I4.0 technologies.

In the second stream of literature, i.e., that on the mutual relations between I4.0 technologies and CE, I4.0 and CE are understood as two sides of the same coin (Garcia-Muiña *et al*., 2018). Cezarino *et al*. (2019) studied how I4.0 and CE could relate to each other. Rosa *et al*. (2020) developed a framework where I4.0 and CE are inter-connected. In their systematic literature review, Dantas *et al*. (2021) showed that the incorporation of CE practices and I4.0 technologies could achieve SDGs. Zhou *et al*. (2020) assessed the joint implication of I4.0 and CE from the perspective of technology progress and structural change. Spaltini *et al*. (2021) put forward a framework to analyze the mutual relationships between different CE strategies and I4.0 technologies, and identified CM and AM as the most important enabling technologies of CE strategies including reduce, redesign, recycling, and remanufacturing. Rajput and Singh (2019) identified the enablers and obstacles of I4.0 and established the connection between CE and I4.0 by identifying cause and effect relationships among these enablers and obstacles. However, the direct relationship between CE and I4.0 in terms of multiple technologies and practices was not established in their study. Bai *et al*. (2022) explored the impacts of I4.0 technologies on SDGs, stating that CE plays a critical role in connecting I4.0 and SDGs. Belhadi *et al*. (2022) developed a self-assessment model to explore the link between CE and I4.0 and quantify the level of CE-I4.0 integration.

In summary, despite significant contributions made by existing studies on how I4.0 technologies might support CE, this body of literature further benefits from a more holistic perspective. For instance, numerous studies focused on a single I4.0 technology and its impact on CE, while others extended the scope and assessed several I4.0 technologies. Moreover, most existing studies have taken qualitative approaches and generated in-depth but relatively narrow insights, that often lack scientific, structured, and quantitative interpretations of actual promoting effects of all

I4.0 technologies on CE practices or actions. Therefore, studies that systematically explore the relationships of each individual I4.0 technology on each CE practice from a comprehensive perspective are urgently needed (Esmaeilian *et al*., 2020; Dubey *et al*., 2019; Laskurain-Iturbe *et al*., 2021).

## 3. Research Method

A mixed method, consisting of a systematic literature review, content analysis, and SNA, was adopted in this study. Relevant literature was reviewed and analyzed using content analysis to identify I4.0 technologies and CE practices or actions, and to extract the impacts of various I4.0 technologies on CE practices. Then, a two-mode network and two one-mode networks were constructed and analyzed. Several network indicators were employed to characterize how I4.0 technologies affect CE practices from a holistic perspective. How different I4.0 technologies are integrated to promote the realization of CE and how various CE practices are implemented simultaneously by I4.0 technologies was also explored. The research method is depicted in Figure 1.

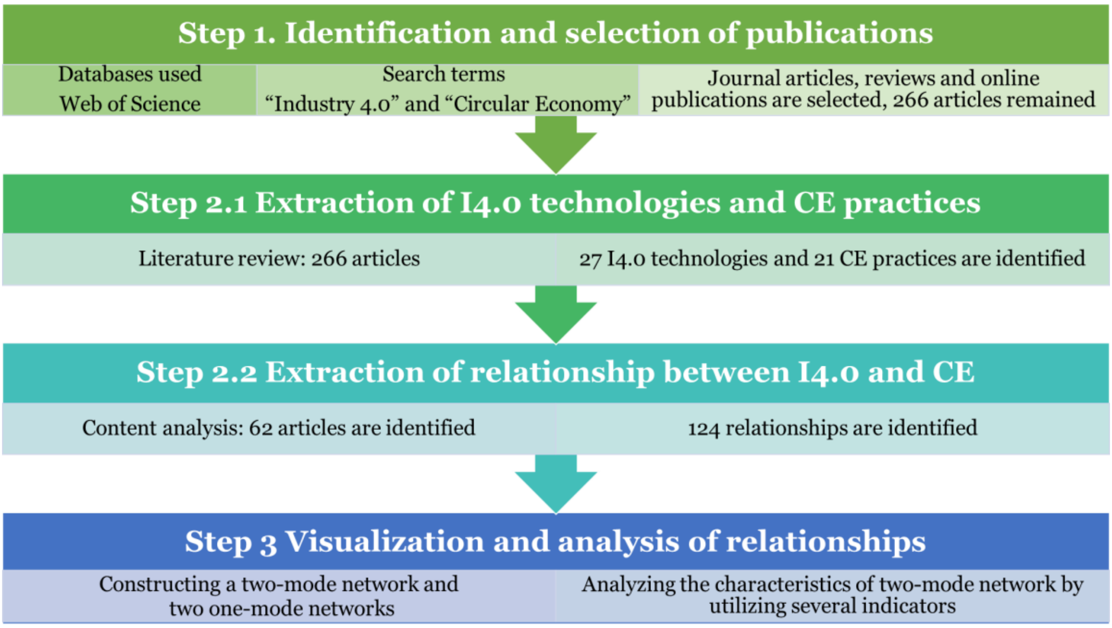


**Figure 1.** The research method

### 3.1 Step1: Identification and selection of publications

To identify technologies related to I4.0, CE practices or actions, as well as the impacts of I4.0 on CE, the Web of Science databases were used to collect published works between 2011 (when the concept of CE was coined) and 2021. To accurately position I4.0 and CE, these publications were filtered based on an initial review of the subject using the following query and Boolean operators: SUBJECT = ("Industry 4.0") AND SUBJECT = ("Circular Economy"). It is worth making a point that although

"Industry 4.0" and "Circular Economy" have several similar terms, such as fourth industrial revolution, intelligent manufacturing, recycling economy, etc., the search strategy of "Industry 4.0" and "Circular Economy" yielded the greatest number these two terms were kept in article search. The initial search returned 286 publications with I4.0 and CE in their titles, keywords, or abstracts, including journal articles, review papers, conference papers, online publication, meeting protocols, data sets, and editorial materials. To ensure a high quality of identified relationships, only journal articles, reviews, and online publications written in English were selected, and 266 papers remained to identify the contents of I4.0 technologies and CE practices. Another round of manual selection was imposed on these articles, which left a final sample of 62 publications that can provide clear evidence on the positive influence of I4.0 on CE. The time span of these 266 and 62 articles was only from 2017 to December 2021, as shown in Figure 2. The first article involving both CE and I4.0 technologies appeared in 2017 and was titled "Enabling circular economy through product stewardship".

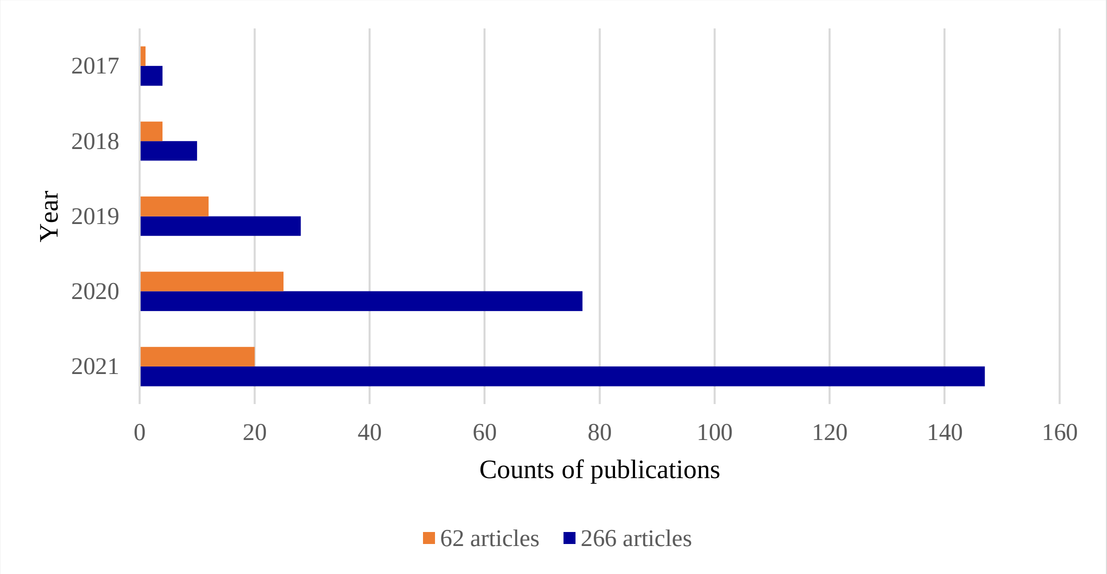


**Figure 2.** Annual distribution of selected publications

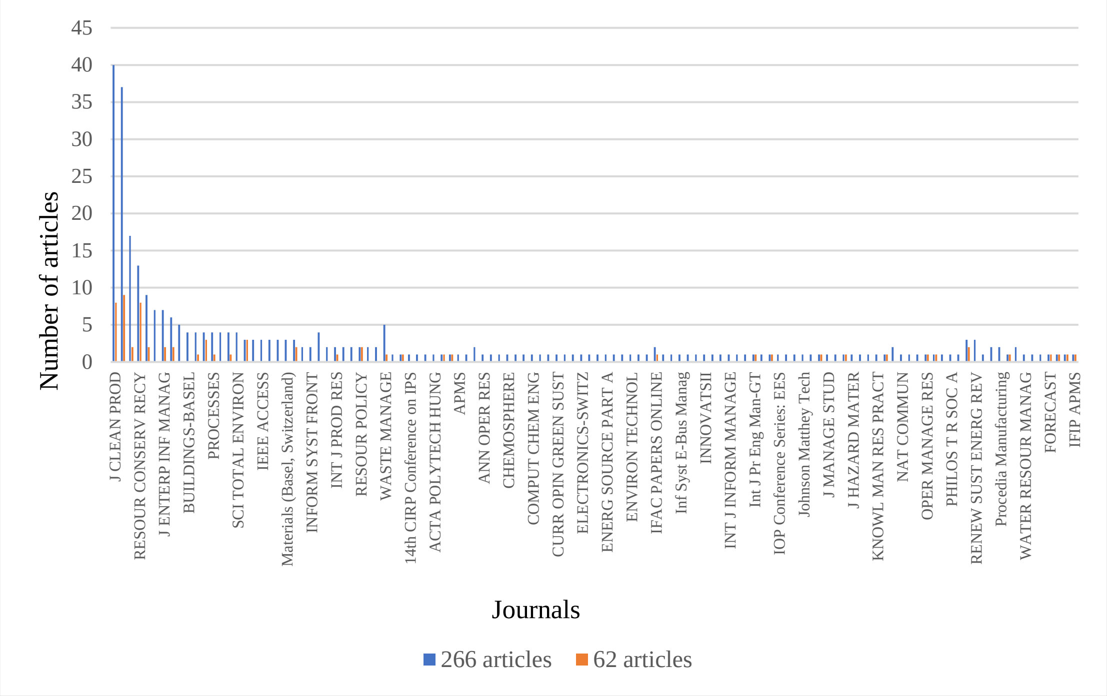


**Figure 3.** Journal distribution of selected papers

Figure 3 shows the distribution of articles obtained by journal classification. Data presented in both Figure 2 and Figure 3 include all relevant studies (266) and 62 selected studies with potential relationships. Literature related to I4.0 and CE began to emerge in 2017, and the number of publications followed an increasing trend ever since, indicating the growing interest for I4.0 and CE among researchers. In terms of the outlet for publications, most articles were published in JOURNAL OF CLEANER PRODUCTION, SUSTAINABILITY, PRODUCTION PLANNING CONTROL, RESOURCES CONSERVATION AND RECYCLING, and BUSINESS STRATEGY AND THE ENVIRONMENT.

## 3.2 Step 2: Extraction of I4.0 technologies, CE practices, and their relationships from publications

After determining the final publications for analysis, key information was extracted and systematized through content analysis, consisting of the following categories:

- CE practices related to the involvement of CE practices.
- I4.0 technologies related to the involvement of I4.0 technologies applied in CE.
- Promoting effects of technologies related to I4.0 on different CE practices, which focuses on the evidence each paper provides on how adopting technologies related to I4.0 has positively affected CE practices.

This step therefore grants theoretical support for the quantitative analysis of the impacts of I4.0 on CE. In contrast to studies on mutual relationships between I4.0 and CE, this paper focuses on how a certain I4.0 technology might promote the implementation of a certain CE practice.

## 3.3 Step 3: Visualization and analysis of relationships

### 3.3.1 Construction of networks related to I4.0 and CE

To directly describe the impacts of I4.0 technologies on CE practices, a two-mode network was constructed, denoted as $G_{I4.0-CE}$, as follows:

$$G_{I4.0-CE} = (V_{I4.0}, V_{CE}, E_{I4.0-CE}) \tag{1}$$

where $V_{I4.0}$ represents the set of I4.0 technologies identified by scholars, $V_{I4.0} = \{v_i^{I4.0}, i = 1, \cdots, N_{I4.0}\}$; $N_{I4.0}$ is the total number of I4.0 technologies; $V_{CE}$ indicates the set of CE practices, $V_{CE} = \{v_j^{CE}, j = 1, \cdots, N_{CE}\}$; $N_{CE}$ is the total number of CE practices; $E_{I4.0-CE}$ represents the set of the effect of I4.0 technologies on CE, $E_{I4.0-CE} = \{e_{ij} | i = 1, \cdots, N_{I4.0}; j = 1, \cdots, N_{CE}\}$, where $e_{ij} = 1$ if I4.0 technology $v_i^{I4.0}$ has a positive impact on the CE practice $v_j^{CE}$, otherwise, $e_{ij} = 0$. These positive impacts were obtained through Section 3.2 in which the effects of I4.0 technologies on CE practices were identified from publications.

To further analyze the role of the integration of different I4.0 technologies for promoting CE implementation, as well as the relationships among CE practices at the realization level, two one-mode networks (i.e., a technical integration network and a CE practice association network) were constructed. The technical integration network is denoted as $G_{I4.0}$, as follows:

$$G_{I4.0} = (V_{I4.0}, E_{I4.0-I4.0}). \tag{2}$$

where $E_{I4.0-I4.0}$ represents the set of integration relationships among I4.0 technologies for promoting the implementation of CE, $E_{I4.0-I4.0} = \{e_{ik} | i = 1, \cdots, N_{I4.0}; k = i + 1, \cdots, N_{I4.0}\}$, and $e_{ik} = 1$ if I4.0 technology $v_i^{I4.0}$ and $v_k^{I4.0}$ work together in a CE practice, otherwise, $e_{ik} = 0$. The CE practice association network is denoted as $G_{CE}$, as follows:

$$G_{CE} = (V_{CE}, E_{CE-CE}). \tag{3}$$

where $E_{CE-CE}$ represents the set of association relationship among CE practices, $E_{CE-CE} = \{e_{jq} | j = 1, \cdots, N_{CE}; q = j + 1, \cdots, N_{CE}\}$, and $e_{jq} = 1$ if two CE practices

$v_j^{CE}$ and $v_q^{CE}$ can be implemented by the same I4.0 technology, otherwise, $e_{jq} = 0$.

### 3.3.2 Analysis indicators of networks related to I4.0 and CE

Once the networks $G_{I4.0-CE}$, $G_{I4.0}$, and $G_{CE}$ were constructed, based on evidence obtained from publications, density, and degree centrality were used to analyze the characteristics of the impacts of I4.0 technologies on CE, the incorporation of I4.0 technologies, and the implementation of various CE practices.

**(1) Density**

The density of the network $G_{I4.0-CE}$ was used to characterize the scope and extent of the impacts I4.0 technologies have on CE practices recorded in the selected publications. The tightness and sparsity of the influencing relation among I4.0 and CE in the network were measured, denoted as $D(G_{I4.0-CE})$, as follows:

$$D(G_{I4.0-CE}) = M_1/(N_{I4.0}N_{CE}). \tag{4}$$

Similarly, the density of network $G_{I4.0}$ and $G_{CE}$ can be calculated as follows:

$$D(G_{I4.0}) = M_2/[(N_{I4.0})(N_{I4.0} - 1)], \tag{5}$$

$$D(G_{CE}) = M_3/[(N_{CE})(N_{CE} - 1)]. \tag{6}$$

where $M_1$, $M_2$, and $M_3$ are the number of actual links between various I4.0 technologies and CE practices, the number of links among technologies related to I4.0, and the number of links among CE practices, respectively.

**(2) Degree Centrality**

In the network $G_{I4.0-CE}$, degree includes both in-degree and out-degree. The out-degree of the I4.0 technology node $v_i^{I4.0}$, denoted as $k_{v_i^{I4.0}}(G_{I4.0-CE})$, refers to the number of CE practices that can be implemented by the $i$th I4.0 technology. The in-degree of the CE practice node $v_j^{CE}$, denoted as $k_{v_j^{CE}}(G_{I4.0-CE})$, refers to the number of I4.0 technologies that can be used to promote the implementation of the $j$th CE practice. The following formula was used to normalize the degree centrality according to the SNA method:

$$k^*_{v_i^{I4.0}}(G_{I4.0-CE}) = \frac{k_{v_i^{I4.0}}(G_{I4.0-CE})}{N_{CE}} \tag{7}$$

$$k^*_{v_j^{CE}}(G_{I4.0-CE}) = \frac{k_{v_j^{CE}}(G_{I4.0-CE})}{N_{I4.0}} \tag{8}$$

In the networks $G_{I4.0}$ and $G_{CE}$, degree centralities are denoted as $k_{v_i^{I4.0}}(G_{I4.0})$

and $k_{v_j^{CE}}(G_{CE})$, which are the number of edges connected to the nodes $v_i^{I4.0}$ and $v_j^{CE}$, respectively.

Degree centrality can be used to identify important nodes in the network. In the network $G_{I4.0-CE}$, a I4.0 technology node with a highly normalized degree centrality implies that this technology promotes the realization of CE in more aspects, i.e., it can be applied more extensively and deeply in CE. A CE practice node with a highly normalized degree centrality indicates that this CE practice can be achieved by utilizing more I4.0 technologies; in other words, it can be more easily fused with different I4.0 technologies. In the network $G_{I4.0}$, a I4.0 technology with higher degree of centrality indicates that this is the most basic and most widely used technology in the integration application of various I4.0 technologies in the process of promoting CE practices. At present, the realization of CE is based on either individual I4.0 technologies or the integration of various I4.0 technologies; therefore, technologies with a high degree centrality are regarded as the most important and essential technologies to advance the realization of all aspects of CE. In the network $G_{CE}$, a CE practice with higher degree centrality means that this CE practice was promoted most by I4.0 technologies, receives the most attention by scholars at present, and can be most easily realized by I4.0 technologies.

# 4. Results

## 4.1 Identification of technologies, practices, and their relationships

This paper extends the work of Dantas *et al.* (2021) by incorporating more I4.0 technologies and CE practices. Through content analysis of 266 publications, 27 I4.0 technologies and 21 CE practices were identified, as shown in **Appendix 1** and **Appendix 2**. Similarly, 124 relationships were identified and extracted from the 62 selected articles, as shown in **Appendix 3**. The overall condition of the 62 selected articles and the methods used for obtaining and verifying relationships in the articles are listed in Table 1.

According to **Appendix 1** and **Appendix 2**, the top 10 I4.0 technologies that are most frequently mentioned by scholars are IoT, BD(A), CPS, AI, WSNs, AM, ClC, Rob, Dig, and VAR; the top 10 CE practices are recycle, reduce, reuse, remanufacture, recover, optimize, loop, repair, maintenance, and waste management. Regarding the extraction of relationships, it is worth noting that this study builds on the findings of other scholars (that are, 62 selected articles). Once a positive relationship was confirmed and found in the literature, it was identified, collected, and recorded. To meet the research purpose of this paper, the analysis only focused on positive impacts. The specific effects of each I4.0 technologies on CE practices are shown in **Appendix 3**. After deleting duplicate relationships, 124 relationships were finally retained.

**Table 1 Summary of relationships and methods from 62 selected publications**

| Year | Number of relationships identified | Number of Corresponding Publications | Grounded theory | Case study | Literature review | Framework analysis | Empirical research | Model evaluation | Content and thematic analysis |
|---|---|---|---|---|---|---|---|---|---|
| 2017 | 2 | 1 | | √ | | | | | |
| 2018 | 24 | 4 | | √ | √ | | | | |
| 2019 | 44 | 12 | √ | √ | √ | √ | √ | | |
| 2020 | 95 | 25 | | √ | √ | √ | √ | √ | √ |
| 2021 | 84 | 20 | | √ | √ | √ | √ | √ | |
| Total | 249<br>(including repeated relationships) | 62 | | | | | | | |

## 4.2 Visualization of relationships related to I4.0 and CE

According to the method described in Section 3.3.1 and data obtained in Section 4.1, a two-mode network and two one-mode networks were constructed, as shown in Figures 4, 5, and 6. Isolated nodes can be found in all three networks.

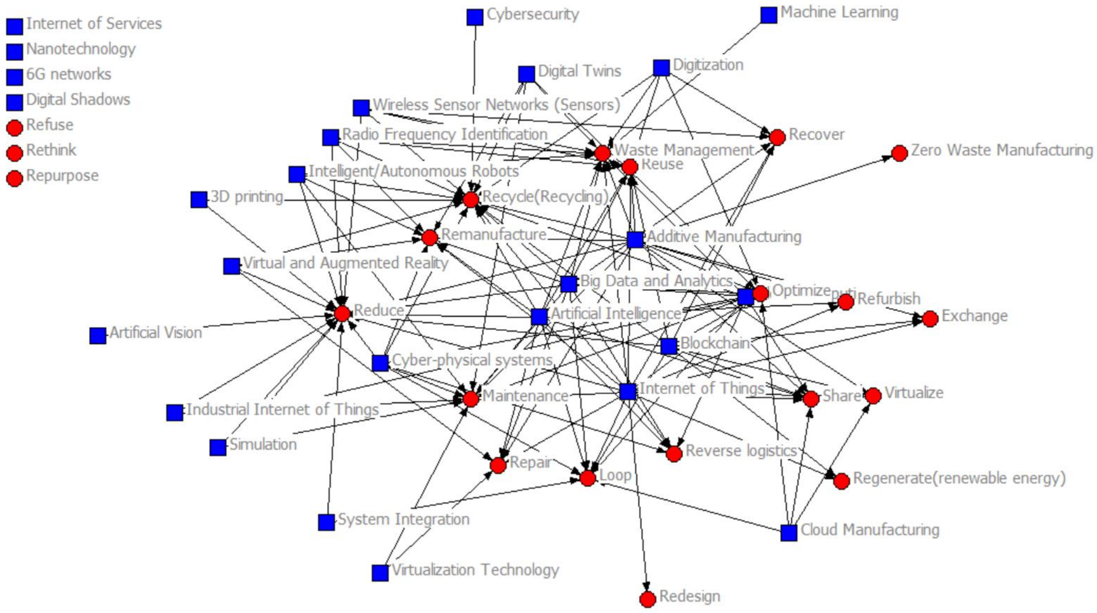


**Figure 4.** The two-mode network $G_{I4.0-CE}$

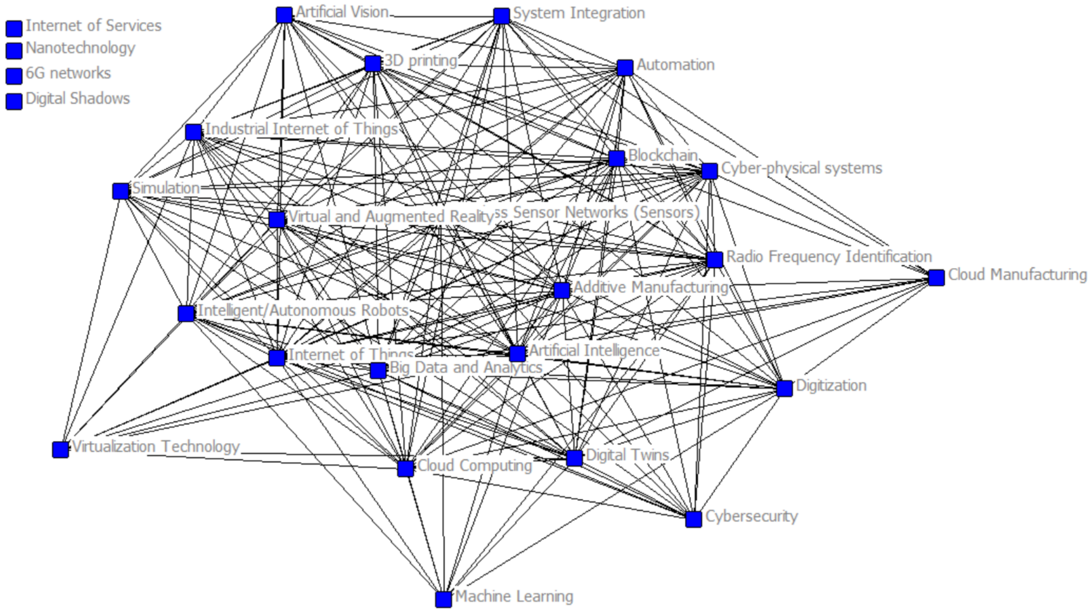


**Figure 5**. The one-mode network $G_{I4.0}$

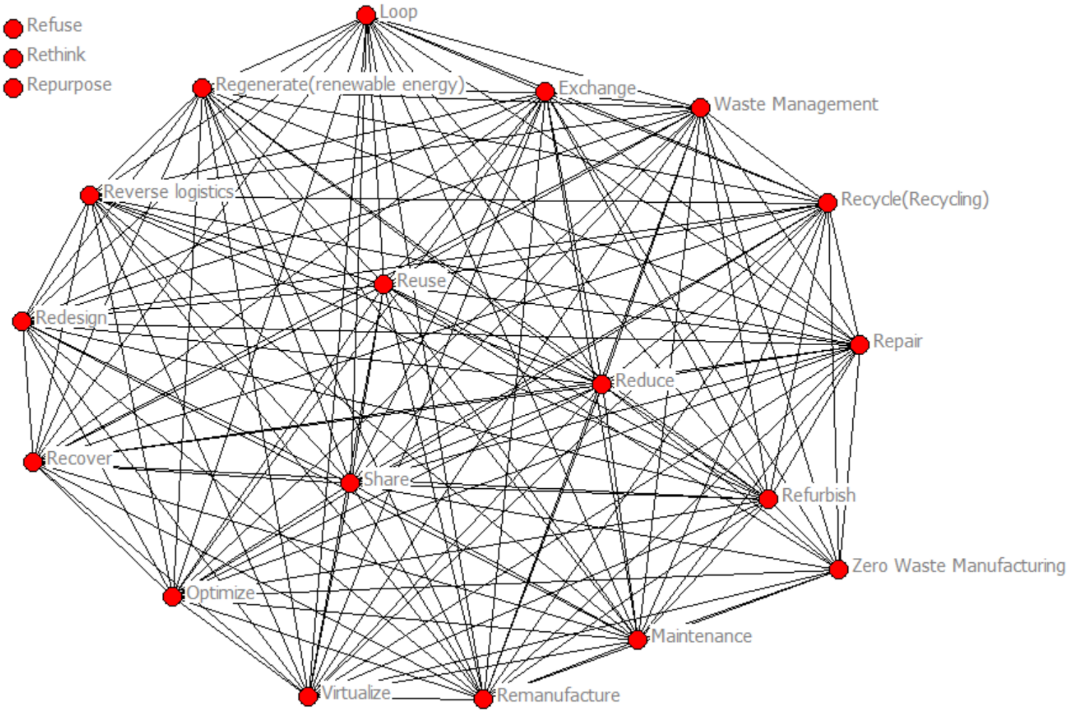


**Figure 6.** The one-mode network $G_{CE}$

## 4.3 Characteristics of relationships between and among I4.0 and CE

### 4.3.1 Analysis of network density and characteristics

The density of the two-mode network $G_{I4.0-CE}$ is 0.219. The density values of technical integration network $G_{I4.0}$ and CE practice association network $G_{CE}$ are 0.295 and 0.352, respectively.

**Table 2** Density of networks

| Network | Number of Nodes (N) | Actual links (M) | Density (D) |
|---|---|---|---|
| $G_{I4.0-CE}$ | 48 | 124 | 0.219 |
| $G_{I4.0}$ | 27 | 207 | 0.295 |
| $G_{CE}$ | 21 | 148 | 0.352 |

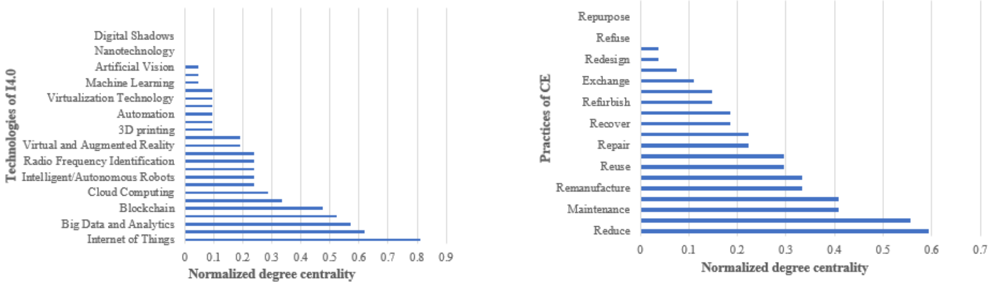
As shown in Table 2, the densities of all three networks are low. The low density of network $G_{I4.0-CE}$ indicates that at present, I4.0 technology has a low application scope and degree for promoting various aspects of CE implementation. The low density of network $G_{I4.0}$ indicates that the adoption of various I4.0 technologies in CE mainly focused on the application of a single technology, while technology integration is generally low. The low density of network $G_{CE}$ indicates that the realization of CE practices identified by scholars requires a corresponding promotion of various I4.0 technologies; in other words, a single I4.0 technology cannot realize all CE practices.

In addition, the existence of isolated nodes in the network further indicates that the network density is low. In the network $G_{I4.0-CE}$, there are four isolated nodes related to I4.0 technologies, and three related CE practices. This shows that in the 62 selected articles, whether these four technologies of I4.0 can promote the implementation of CE practices could not be proved. Similarly, whether these three practices of CE can be realized by I4.0 technologies could also not be proved. In other words, these isolated nodes indicate that scholars merely recognized these concepts, but their relationships need further research.

Isolated nodes in $G_{I4.0}$ imply that there is no evidence that these technologies can contribute to CE, neither together nor in combination with other technologies. Isolated nodes in $G_{CE}$ imply that there is no evidence to support that these CE practices can be implemented along with other CE practices by simultaneously adopting one or more I4.0 technologies.

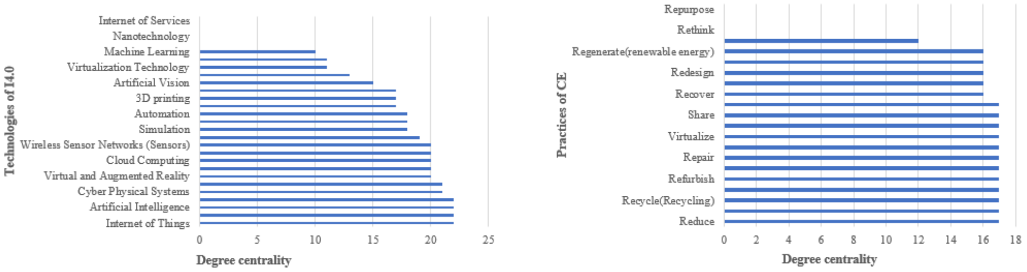
### 4.3.2 Analysis of degree centrality and key nodes

The ranks of normalized degree centrality of 27 I4.0 technologies and 21 CE practices are shown in Figure 7. The top I4.0 technologies are IoT, AM, BD(A), and AI, as their normalized degree centralities are higher than those of other technologies. The top four CE practices are reduce, recycle, maintenance, and waste management, of which, maintenance has the same centrality than waste management. These results show that scholars have widely recognized that IoT, AM, BD(A), and AI can effectively promote the realization of CE in terms of reduce, recycle, maintenance, and waste management. Therefore, IoT, AM, BD(A), and AI can be considered as basic technologies that are applied most extensively and deeply in CE, especially IoT whose normalized degree centrality is 0.81. Moreover, among CE practices, reduce, recycle, maintenance, and waste management are best implemented through adopting I4.0 technologies, especially reduce with a normalized degree centrality of 0.593.



(a) Normalized degree centrality of 29 technologies of I4.0 in network $G_{I4.0-CE}$ (b) Normalized degree centrality of 21 practices of CE in network $G_{I4.0-CE}$

**Figure 7** Normalized degree centrality of nodes in network $G_{I4.0-CE}$



(a) Degree centrality of 29 technologies of I4.0 in the network $G_{I4.0}$ (b) Degree centrality of 21 practices of CE in the network $G_{CE}$

**Figure 8** Degree centrality of nodes in network $G_{I4.0}$ and $G_{CE}$

The rankings of the degree centralities of 27 I4.0 technologies in network $G_{I4.0}$ and 21 CE practices in network $G_{CE}$ are shown in Figure 8. The top ranks of degree centrality in network $G_{I4.0}$ are IoT, BD(A), AI, and AM, all of which have the same degree centrality of 22. Therefore, IoT, BD(A), AI, and AM can be considered the most essential technologies to advance the realization of all aspects of CE. In the network $G_{CE}$, the top degree centrality is 17, which includes reduce, reuse, recycle, optimize, refurbish, remanufacture, repair, maintenance, virtualize, waste management, share, and exchange, the degree centralities of which are identical. Therefore, these can be considered as CE practices that are best braced by I4.0 technologies.

## 5. Conclusions and Discussion

### 5.1 Main conclusions and discussion

The purpose of this study is to quantitatively explore the impacts of various I4.0 technologies on CE practices from the perspective of multiple I4.0 technologies and CE practices. A mix of methods consisting of systematic literature review, content analysis, and SNA was adopted. First, 266 articles were selected and mined for contents of I4.0 technologies and CE practices, and 27 I4.0 technologies as well as 21 CE practices or actions were identified. Second, 62 articles were identified that proved the positive influence of I4.0 technologies on CE practices, and 124 relationships were identified. Third, based on evidence supporting the link between different I4.0 technologies and different CE practices, a two-mode network and two one-mode networks were constructed. Network density and degree centrality were used to analyze the characteristics of networks and key nodes. The main conclusions are summarized as follows and are compared with previous papers in Table 3.

(1) In 266 articles published during 2017 and 2021, scholars identified 27 I4.0 technologies and 21 CE practices. Twenty-three I4.0 technologies have been found to have a promoting effect on 18 types of CE practices.

(2) At present, I4.0 technology has a low application scope and degree for promoting various aspects of CE. Moreover, a single I4.0 technology cannot realize all CE practices, and different I4.0 technologies must be integrated. However, the integration of I4.0 technologies is generally low. This conclusion is consistent with the views of Cagno, E. *et al*. (2021), Rocca *et al*. (2020) and Paladini, S. *et al*. (2021) who claimed that the integration of different I4.0 technologies enables a better study of their role in CE transformation.

(3) IoT, AM, BD(A), and AI are generally considered as the I4.0 technologies that can most promote the realization of CE. Most scholars chose to promote the realization of CE from aspects such as reduce and recycle. This result supports certain findings of previous studies. For instance, Rosa *et al*. (2019) and Khan, S. *et al*. (2021b) pointed out that AM, BD(A), AI, and IoT are the I4.0 technologies that are most often described as CE enablers. Ćwiklicki *et al*. (2020) and Laskurain-Iturbe *et al*. (2021) argued that IoT and BD(A) are the most common I4.0 technologies that connect CE.

(4) With respect to the integration of I4.0 technologies to facilitate CE implementation, scholars agree that the integration of IoT, BD(A), AI, and AM is most significant. Regarding the implementation of CE practices, reduce, reuse, recycle, optimize, refurbish, remanufacture, repair, maintenance, virtualize, waste management, share, and exchange are the CE practices that are currently most implemented through I4.0 technologies.

(5) The existence of isolated nodes in Figures 4, 5, and 6 implies that I4.0 technologies, such as IoS, nanotechnology (NT), 6G networks (6G), and digital shadows (DS) have not been applied to CE. Furthermore, CE practices, such as refuse, rethink, and repurpose have not yet been realized by currently available I4.0

technologies. Therefore, new research directions may include exploring the feasibility of the application of these isolated I4.0 technologies in CE, and the technical path for realizing these isolated CE practices.

**Table 3** Comparison of the main conclusions by this paper with those of previous papers

| Articles | Conclusion (1) | Conclusion (2) | Conclusion (3) | Conclusion (4) | Conclusion (5) |
|---|---|---|---|---|---|
| This study | √ | √ | √ | √ | √ |
| Rosa et al. (2019) | | | √ | | |
| Ćwiklicki et al. (2020) | | | √ | | |
| Rocca et al. (2020) | | √ | | | |
| Laskurain-Iturbe et al. (2021) | | | √ | | |
| Ortega-Gras et al. (2021) | | | √ | | |
| Cagno, E., et al. (2021) | | √ | | | |
| Paladini, S., et al. (2021) | | √ | | | |

## 5.2 Theoretical and managerial implications

This study offers important theoretical and practical implications. With regard to theory, this paper explores a broad range of technologies and CE actions, including 27 technologies and 21 CE actions. The influencing relationships are intuitively given in terms of networks. This study therefore enriches and expands the literature on the impacts of I4.0 technologies on CE by systematically summarizing, quantitatively analyzing, implementing network visualization, and interpreting previous work from the perspective of multiple technologies and various CE practices. The results of this study provide feasible and valuable suggestions for future research. For instance, the results show that most scholars have focused on the application of IoT on reduce and recycle. However, the role of other I4.0 technologies such as NT, DS, 6G, and IoS in promoting the implementation of CE should be further explored and studied. In addition, the findings of this study show that a single I4.0 technology cannot achieve all CE practices, and the integration degree of I4.0 technologies is low. Therefore, more attention should be directed to the integration of different I4.0 technologies, including prerequisites of their integration, integration methods, and integration stages. At the same time, the findings of this study show that scholars' understanding of the contents and actions of CE is constantly expanding. Scholars are working towards effectively realizing CE from many aspects. In addition, the findings of this study also show that existing methods of relationship recognition mainly focus on methods of qualitative analysis, including literature review, case study, content and thematic analysis, and framework analysis; however, there are few quantitative analysis methods such as empirical studies and model evaluations. Therefore, more quantitative studies should be conducted in the future.

With regard to management practice, the cost of technology adoption is an important factor for small and medium-sized enterprises when adopting I4.0 technologies. In general, these enterprises cannot achieve full I4.0 technology coverage and can only choose one or few technologies within a certain cost range to promote the CE practice. Therefore, enterprises can effectively control the technology cost through the relationship between various CE practices. For instance, enterprises can choose interlinked CE practices based on their business characteristics, while ensuring that the chosen CE practices can be implemented through the same I4.0 technology. In this way, as long as one I4.0 technology is introduced, two or three aspects of corporate CE can be realized, and the operating costs of enterprises can be effectively lowered.

## 5.3 Limitations and future work

Because of the limited number of selected articles and manual judgment, as well as the selection and extraction of the impact of I4.0 technologies on CE, this study has several limitations: First, only journal articles, reviews, and online publications written in English were selected, while studies published in other language are not covered. Therefore, the results only represent a defined group of scholars, which may be fragmented to a certain extent. Second, as the extraction of the impact of I4.0 technologies on CE mainly relies on a manual process of reviewing the selected literature, this paper only provides the statistics of the number of publications involving relationships, while lacking a weight measurement of these relationships.

Future studies are encouraged to explore the magnitude of the impact of I4.0 technologies on CE from an empirical perspective.

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## Appendix 1: Identified I4.0 technologies from 266 publications

| No. | I4.0 Technologies | Abbreviation | Description | Number of sources |
|---|---|---|---|---|
| 1 | Internet of Things | IoT | The IoT is based on modern wireless communication network, which realizes the technology of data collection, transmission and exchange among people, equipment and objects. | IoT was involved in 113 articles |
| 2 | Big Data and Analytics | BD(A) | A technology for analyzing structured and unstructured data with high volume, high velocity and high variety. | BD(A) was involved in 90 articles |
| 3 | Cyber-physical systems | CPS | A complex computer system that integrates calculation analysis, network and precise control. | CPS was involved in 64 articles |
| 4 | Artificial Intelligence | AI | Using computer systems to simulate human intelligence | AI was involved in 58 articles |
| 5 | Wireless Sensor Networks (Sensors) | WSNs | A technique that senses the environment or a particular substance. | WSNs was involved in 55 articles |
| 6 | Additive Manufacturing | AM | The technology of manufacturing product parts by continuously adding materials. | AM was involved in 54 articles |
| 7 | Cloud Computing | ClC | Digital infrastructure for storing, managing and processing data in remote servers via the Internet. | ClC was involved in 50 articles |
| 8 | Intelligent/Autonomous Robots | Rob | A mechanical system that can adapt to changes and complete various tasks without human help. | Rob was involved in 45 articles |
| 9 | Digitization | Dig | The process of converting complex and diverse information into measurable numbers. | Dig was involved in 39 articles |
| 10 | Virtual and Augmented Reality | VAR | AR: Technology that combines virtual information with physical space.<br>VR: A fully virtual world that allow interaction with the environment. | VAR was involved in 34 articles |
| 11 | Radio Frequency Identification | RFID | Technology to achieve the purpose of identification and data exchange through radio frequency. | RFID was involved in 34 articles |
| 12 | Blockchain | Block | Blockchain technology refers to the connection of data, which helps to strengthen the sharing of product and process information in the supply chain. | Block was involved in 32 articles |
| 13 | 3D printing | 3D | A technology to produce small batches and complex products with lower cost, less materials and less waste | 3D was involved in 28 articles |

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| 14 | Machine Learning | ML | A computational techniques for learning from data and improving specific computer algorithms. | ML was involved in 26 articles |
| 15 | Simulation | SIM | A virtual replica of a process or system running, which evaluates its changes under different conditions through modeling. | SIM was involved in 24 articles |
| 16 | Automation | Auto | The process of using machines to achieve the expected goals according to human requirements with the direct participation of no or few people. | Auto was involved in 24 articles |
| 17 | Industrial Internet of Things | IIoT | Devices that integrate and connect to the Internet and industrial applications through network sensors. | IIoT was involved in 17 articles |
| 18 | Digital Twins | DT | The process of simulating the system through physical model, sensor update, operation history and other data. | DT was involved in 17 articles |
| 19 | Cybersecurity | CS | Ensuring secure and reliable communication between systems, preventing damage, change, or leakage. | CS was involved in 15 articles |
| 20 | Cloud Manufacturing | CM | It is a virtual portal to create a shared network of manufacturing resources and capabilities provided as services. | CM was involved in 14 articles |
| 21 | Internet of Services | IoS | Internet of Services can transform applications into interoperable services, and use semantics to understand and process data and information. | IoS was involved in 12 articles |
| 22 | Virtualization Technology | VT | Building a hybrid reality by mixing digital content with the physical industry. | VT was involved in 8 articles |
| 23 | Nanotechnology | NT | Use biomolecules to make substances | NT was involved in 4 articles |
| 24 | System Integration | SI | The horizontal combination of multiple systems and the vertical combination of system components. | SI was involved in 2 articles |
| 25 | 6G networks | 6G | The 6th generation of mobile networks that interconnects not only people but also devices and objects. | 6G was involved in 1 articles |
| 26 | Digital Shadows | DS | A mode of mapping the real world in virtual space. | DS was involved in 1 articles |
| 27 | Artificial Vision | AV | Extracting the data of digital image or video in industrial process, analyze and evaluate them, and finally make corresponding decisions. | AV was involved in 1 articles |

## Appendix 2: Identified CE practices from 266 publications

| No. | Practices | Definition | Number of sources |
|---|---|---|---|
| 1 | Reduce | Improving the efficiency of manufacturing, use and consumption of products by consuming fewer resources and materials. | Reduce was involved in 98 articles |
| 2 | Reuse | Reuse refers to the process of continuing to use all or part of waste without treatment. | Reuse was involved in 98 articles |
| 3 | Recycle(Recycling) | Reprocessing waste products into new materials or products. | Recycle was involved in 116 articles |
| 4 | Recover | Collecting energy at the end of product use for continued utilization in the next life cycle products. | Recover was involved in 60 articles |
| 5 | Redesign | Using recycled materials and resources to design new products. | Redesign was involved in 13 articles |
| 6 | Remanufacture | It refers to a method of prolonging the service life of products. Recycle, inspect, repair or assemble the waste products to maintain the original value and specifications. | Remanufacture was involved in 71 articles |
| 7 | Repair | Maintaining the defects and faults of the product to restore its function. | Repair was involved in 45 articles |
| 8 | Refuse | Discarding unwanted products and their functions. | Refuse was involved in 9 articles |
| 9 | Rethink | Evaluating and optimize products for more intensive use. | Rethink was involved in 12 articles |
| 10 | Refurbish | Restoring and renewing old products. | Refurbish was involved in 33 articles |
| 11 | Repurpose | Applying some parts of waste products to new products with different functions. | Repurpose was involved in 10 articles |
| 12 | Regenerate(renewable energy) | Transition to renewable energy and materials. | Regenerate was involved in 33 articles |
| 13 | Share | The sharing of goods or assets between individuals or institutions. | Share was involved in 32 articles |
| 14 | Optimize | Applying digital technology to reduce waste and improve production system | Optimize was involved in 59 articles |

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|  |  | performance. |  |
| 15 | Loop | Recycling and remanufacturing from waste to maintain a closed cycle of components and materials. | Loop was involved in 52 articles |
| 16 | Virtualize | A strategy that substitutes virtual or immaterial products for physical products. | Virtualize was involved in 20 articles |
| 17 | Exchange | Replacing old and non renewable products with advanced and renewable products. | Exchange was involved in 20 articles |
| 18 | Maintenance | A method of extending the service life of a product through recovery. | Maintenance was involved in 44 articles |
| 19 | Zero Waste Manufacturing | The concept of maximizing the elimination of wastes across the whole waste value chain by means of reuse and recycling. | Zero Waste Manufacturing was involved in 2 articles |
| 20 | Waste Management | Integration of activities from waste generation to final disposal. | Waste Management was involved in 42 articles |
| 21 | Reverse Logistics | Planning, implementation and control of raw materials, inventory, products and relevant information. | Reverse Logistics was involved in 28 articles |

## Appendix 3: Identified impacts of I4.0 technologies on CE practices from 62 publications

| Year | NO. | Relationships | Explanation and Findings | Sources |
|---|---|---|---|---|
| 2017 | 1 | Reuse, Recycle←Dig | At the product design stage, high quality recycling and better reuse of components or products can be promoted by digitalization | Jensen et al. (2017) |
| 20018 | 1 | Regenerate←IoT<br>Share←CM, IoT | The IoT could benefit to the regenerate business model in terms of sensors and apps; | De Sousa Jabbour et al. (2018) |

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| | | Optimise←CPS, IoT<br>Loop←IoT, CPS, CM<br>Virtualise←CM, IoT, AM<br>Exchange←AM, IoT | CM and the IoT could expand the potential of the share business model;<br>CPS and the IoT can uphold the optimize business model;<br>Loop approach can be supported by the IoT, CPS and CM;<br>CM, IoT and AM could promote the Virtualise business model;<br>AM and the IoT help the Exchange business model obtain benefits. | |
| 20018 | 2 | Reduce←IoT<br>Maintenance←BD(A) | Material waste could be reduced through the information of products which is collected by the IoT;<br>Preventive and predictive maintenance demands BD(A). | Bressanelli et al.(2018a) |
| 20018 | 3 | Refurbish, Remanufacture, Recycle, Loop ←IoT, BD(A) | Refurbish, Remanufacture, Recycle and Loop can be strengthened by IoT and BD(A). | Bressanelli et al. (2018b) |
| 20018 | 4 | Recover←WSNs | Sensors can recover components by tracking products after production | Okorie et al. (2018) |
| 2019 | 1 | Waste Management, Reduce (waste)←AM | Waste in product manufacturing can be reduced by AM's more accurate design specifications. | Kerdlap et al.(2019) |
| 2019 | 2 | Regenerate, Share, Optimise, Loop, Virtualise, Exchange←Block | In each enterprise case, blockchain applications are linked to regeneration, sharing, optimization, cycling, virtualization and exchange | Kouhizadeh et al.(2019) |
| 2019 | 3 | Remanufacture←IoT, BD(A), AM, Rob, VAR, RFID<br>Repair←AM | In remanufacturing, IoT, VR and AR are applicable;<br>Using the product service business model, the after-sales service of the company's Repair / Remanufacturing activities can be provided by AM;<br>The real-time production scheduling of engine remanufacturing can be upheld by giving resource availability information through RFID and IoT.<br>Robot remanufacturing processes can use cloud services to offer "robot control as a service" for real-time adaptive control; | Kerin and Pham (2019) |

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| | | | In the remanufacturing, operations management can be supported by BD(A) methods to track product changes. | |
| 2019 | 4 | Reduce(cost), Repair←AM, VAR<br>Maintenance←ClC | The cost reduction of remanufacturing operations and the improvement of product repair quality can be achieved through AM and AR tools;<br>Early detection of problems for predictive maintenance can be enabled by ClC. | Yang et al. (2019) |
| 2019 | 5 | Reduce, Recover←IoT | The improvement of Process-oriented performance and the reduction of energy consumption can be achieved through IoT.<br>Information management in EoL product recovery operations can be promoted by the IoT. | Garrido-Hidalgo et al. (2019) |
| 2019 | 6 | Loop, Reverse Logistics, Maintenance, Reduce, Reuse, Waste Management, Share ←AI<br>Share ←IoT | AI can make more accurate decisions about material reuse;<br>The reduction of resource consumption relies on artificial intelligence to provide accurate resource data and help circular product design;<br>The connection of sharing demand and supply information can be quickened through AI and the IoT;<br>The function of AI to gather process and operational data can identify and prevent failures that may cause waste;<br>AI contributes to close the loop through improvement of reverse logistics operations in the logistics chain;<br>The improvement of predictive maintenance can be made through AI to advocate intelligent inventory management activities | Ghoreishi et al. (2019) |
| 2019 | 7 | Waste Management←ClC | Real-time management of all data on waste types, waste quantities and | Mattos Nascimento |

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| | | Recover←BD(A) | collection sites can be facilitated by ClC;<br>Material recovery can be improved through better simulation calibration and dynamic model optimization with big data. | et al. (2019) |
| 2019 | 8 | Share←IoT | The application of IoT to search real-time information will perfect data collection, sharing of resource consumption and material waste. | Rajput et al. (2019) |
| 2019 | 9 | Recycle←AM<br>Reuse←BD(A)<br>Waste Management←IoT | The reuse of data and services can be facilitated by BD(A) developing open source tools, programs, and openness;<br>Implementing new Waste Management strategies in smart cities through the use of Internet of Things;<br>Developing CBMs centered on recycled materials is a primary goal for AM. | Rosa et al. (2019) |
| 2019 | 10 | Sharing Economy←IoT, ClC | In Industry 4.0, the sharing economy in the circular economy can be promoted through the IoT and ClC. | Trang Thi et al. (2019) |
| 2019 | 11 | Reduce←AI | The agile operation, intelligent food supply chains of AI provides the ability to reduce waste. | Tseng et al. (2019) |
| 2019 | 12 | Maintenance←AR, DT<br>Reuse←RFID, WSNs<br>Recycle←IoT | Advanced technologies such as AR and digital twins can be used for monitoring, maintenance and diagnosis;<br>The value of reuse can be increased through the use of RFID and sensor technology;<br>The IoT technologies makes the process of product recycling more efficient and effective. | Zheng et al. (2019) |
| 2020 | 1 | Optimize←Auto | I4.0 automation instead of manual processes can realize the optimization of CE procurement process. | Bag et al. (2020a) |

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| 2020 | 2 | Reduce←Rob, BD(A), VAR<br>Optimize←IoT, CPS, AM | Intelligent robots contribute to reduction of waste by improving production efficiency, manufacturing quality and resource efficiency;<br>The IoT makes information transparent through intelligent programming to optimize material consumption;<br>Facility design for efficient energy supply can be optimized by using CPS to achieve flexible design configuration of energy supply components;<br>Waste reduction can be achieved by big data analytics that track, record and analyze the source and cause of waste;<br>Optimized designs to reduce waste generation can be achieved by applying AM in the production process to reduce the use of material and energy;<br>Reductions in material and energy consumption can be realized by VR through cost-effective simulation, control and prediction to minimize errors of design. | Chen et al. (2020) |
| 2020 | 3 | Reverse Logistics←IoT, CPS, BD(A), ClC | Using the IoT, CPS, BD(A) and ClC can improve information processing to achieve seamless vertical and horizontal flow of information in forward and reverse logistics chains. | Bag et al. (2020b) |
| 2020 | 4 | Reuse, Recycle ←IoT, BD(A) | Reuse and recycling methods are more closely linked to the growing role of the IoT and BD(A). | Ćwiklicki et al. (2020) |
| 2020 | 5 | Share←IoT<br>Optimize←CPS, IoT<br>Loop←IoT, CPS<br>Virtualize←CM, IoT, AM | Make sustainable production decisions based on the via IoT data received, enabling regeneration to be consistent with I4.0;<br>The application of cloud-based resources and the IoT can realize sharing alignment with Industry 4.0; | Dev et al. (2020) |

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|  |  | Exchange←AM, IoT | I4.0 upheld by CPS and IoT is consistent with optimization;<br>I4.0 supported by IoT, CPS and cloud services is coherent with loop;<br>CM, IoT, and AM technologies in I4.0 are aligned with virtualization;<br>By applying AM and IoT, exchange can integrate with I4.0. |  |
| 2020 | 6 | Reduce, Recover←Block | To better design, manufacture, sell, use, and recover products, blockchain can be leveraged to enable manufacturers to monitor products and collect essential data throughout their life cycle;<br>Blockchain's ability can extend product life, maximize the application of resources, and reduce emissions to promote circular economy. | Esmaeilian et al. (2020) |
| 2020 | 7 | Waste Management←IoT<br>Waste Management←Dig | By applying the IoT as an integrator, municipal waste can be separated, waste characteristics identified, and sustainable waste disposal technologies confirmed;<br>Realizing the sustainability of Waste Management becomes more possible, reliable, transparent, efficient and optimized through the IoT, digitization and ICT. | Fatimah et al. (2020) |
| 2020 | 8 | Refurbish, Remanufacture, Recycle←AM | From improvements in refurbishment and remanufacturing processes to influence on production systems such as energy consumption and the application of recycled raw materials, AM has brought tremendous advances to sustainability research. | Hernandez Korner et al. (2020) |
| 2020 | 9 | Reduce←Auto | The reduction of waste can be realized by improving the innovation level through the concept of Auto. | Ivascu et al. (2020) |
| 2020 | 10 | Remanufacture← BD(A), AI, VAR | Remanufacturing technologies are often associated with BD(A) and AI | Kerin et al.(2020) |

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| | | | solutions, which includes data bearer equipment and identification tags;<br>Drivers of remanufacturing of information aggregation and visualization in CE include VR and AR. | |
| 2020 | 11 | Sharing, Optimize←IoT, AM | The promotion of product sharing, optimization of product traceability, recycling of materials, components, and products can all be achieved through the IoT and AM. | Jabbour et al. (2020) |
| 2020 | 12 | Maintenance, Optimize ←BD(A) | Prediction of product health and wear, reduction of production downtime, planned maintenance, spare parts ordering and optimization of energy consumption can be realized by applying data analysis as a tool. | Kristoffersen et al. (2020) |
| 2020 | 13 | Reuse, Reduce←IoT<br>Share←ClC<br>Optimize←BD(A) | IoT can reduce manufacturing costs and also provide access to product lifecycle information to facilitate reuse;<br>Easy sharing of significant data can be made possible by ClC;<br>BD(A) can be used to optimize the application of machine and human resources. | Kumar et al., (2020) |
| 2020 | 14 | Repair←AM | Repairs of industrial products could rely on AM to make it more efficient. | Kunovjanek et al. (2020) |
| 2020 | 15 | Reuse←Dig | The use and reuse of novel business strategies for resources can be expounded by leveraging advanced digital manufacturing technologies to facilitate circularity. | Lugnet et al. (2020) |
| 2020 | 16 | Reduce←BD(A)<br>Recycle, Reduce←RFID, IoT<br>Waste Management←Rob, BD(A) | The reduction of energy consumption is due to the application of BD(A) to map more sustainable and effective processes, and form a better distribution of production processes; | Massaro et al. (2020) |

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| | | | All monitoring of generated, reused and recycled material fillings can be achieved through the high value of RFID technology and IoT sensors. Such as smart trash cans, smart trucks, robots, mobile applications, optimization software and extensive data analysis among different stakeholders are new methods of Waste Management based on digital solutions. | |
| 2020 | 17 | Optimize←Dig | As an integral part of sustainable decision-making, the ability of digital technology to optimize resource utilization can reduce the harmful effect on the environment. | Morella et al. (2020) |
| 2020 | 18 | Recover←IoT | IoT facilities can be used for product tracking and recovering. | Ozkan-Ozen et al. (2020) |
| 2020 | 19 | Loop←CPS, ClC | CPS, ClC help form a low-power, low-cost closed-loop supply chain. | Rajput et al. (2020) |
| 2020 | 20 | Recycle, Redesign, Maintenance, Remanufacture, Optimize, Waste Management, Loop←IoT<br>Recycle←ClC<br>Recycle, Maintenance, Optimize←CPS<br>Recycle, Remanufacture, Optimize ←DT<br>Remanufacture←Rob, BD(A) | CPSs enables lifecycle management of products and services through maintenance or optimization of remanufacturing practices.<br>IoT, ClC and CPSs achieve the reintroduction of the product value chain by informing users of dismantling and recycling procedures. The IoT can radically improve resource efficiency, extend product life, and close loop.<br>IoT can collect and analyze data related to products, making them easier to redesign, maintain, upgrade, disassemble or recycle.<br>IoT provides relevant data for processes by optimizing remanufacturing and recycling practices<br>Adopting IoT in CE practices can shape new Waste Management strategies. | Rocca et al. (2020) |

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| | | | DT can be used for virtual optimization during disassembly or for recycling and remanufacturing processes.<br>Using Rob, BD(A), and the IoT, the remanufacturing performance of the aerospace industry can be got better. | |
| 2020 | 21 | Recycle, Waste Management←Rob, WSNs<br>Waste Management←Dig | The introduction of sensors and robots holds the promise of completely changing waste sorting and recycling.<br>Digitizing waste and incorporating embedded information can improve the ability of Waste Management and thus the efficient use of resources. | Rossi, J., et al. (2020) |
| 2020 | 22 | Maintenance←IIoT<br>Reduce, Maintenance←SIM<br>Reduce, Loop←SI<br>Maintenance, Repair←VT<br>Reduce←AM | IIoT can assist augment the safety of equipment and operators by maintaining solutions and providing real-time hazard warnings.<br>Virtual simulation of new programs or maintenance activities can support reduce energy consumption and improve processes.<br>The combining of horizontal and vertical systems helps to integrate information in all areas of the organization and reduce manufacturing waste and energy consumption.<br>Closed-loop production processes can be achieved through system integration.<br>Virtualization brings cost and environmental benefits through remote maintenance/repair and training.<br>AM promotes a circular economy by reducing the amount of materials used, the manufacture of waste, and the inventory required for products. | Sartal et al. (2020) |

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| 2020 | 23 | Reduce, Recycle←3D | The operation of 3Dp can be achieved by recycling 3D printed waste and products.<br>3DP technology can recycle waste as a raw material for printing.<br>Recycling systems in the 3DP market can be effective in saving energy and reducing carbon emissions. | Sun et al. (2020) |
| 2020 | 24 | Waste Management←IoT | The Internet of Things has the potential for waste collection. | Turner et al. (2020) |
| 2020 | 25 | Optimize, Recycle, Remanufacture←AM<br>Optimize←CM | Additive manufacturing plays a role in improving and optimizing the material design process and can recycle and remanufacturing products throughout their life cycle.<br>Optimized maintenance costs can be achieved through AM technologies such as cloud manufacturing. | Sharma et al. (2020) |
| 2021 | 1 | Share, Optimize, Virtualize, Exchange←Block | Blockchain platform can well meet the elements of sharing, optimization, virtualization, and exchange. | Upadhyay et al. (2021) |
| 2021 | 2 | Reuse, Remanufacturing, Recycle, Reduce←AM<br>Reduce, Remanufacture, Recycle, Reuse ←BD(A)<br>Remanufacture←IoT<br>Recycle, Reduce←VAR<br>Reduce←AV<br>Recycle←Rob, CS | BD(A)A and AM technologies are well placed to help the dismantling or reuse of materials.<br>AM can help with product or component remanufacturing.<br>AM is being positively impacted on recycling.<br>AM reduces pollution by reducing the need for transportation.<br>BD(A)A provides strategies for reducing the cost of assessment through remanufacturing, and IoT can facilitate innovation in the development of remanufactured products.<br>Recycling issues during product design can be addressed by BD(A)A. | Laskurain-Iturbe et al. (2021) |

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| | | | VAR can help work out a group of metrics in terms of recycling performance.<br>AM reduces pollution by reducing the need for transportation.<br>By reducing the failure rate/quantity of the product, AV and VAR can reduce the generation of waste.<br>AM and Rob have moderate positive effects on recycling variables, and BD(A)A and CS have less positive effects on recycling variables. | |
| 2021 | 3 | Reduce←CPS | The use of CPSs in CE can significantly improve efficiency and reduce waste. | Ahmed et al. (2021) |
| 2021 | 4 | Reverse Logistics, Waste Management←BD(A)<br>Reuse, Recycle, Loop ←IoT | Reverse logistics systems and Waste Management can be facilitated by BD(A) through different cycles during the reutilization/recycling phase.<br>Reuse can be achieved by relying on the IoT by monitoring and tracking the usage and condition of products.<br>IoT enables loops in the recycling process by leveraging its advantages in monitoring and tracking. | Cagno, E., et al. (2021) |
| 2021 | 5 | Maintenance, Reuse, Remanufacture, Recycle←IoT | IoT provides chances for the maintenance, reuse, remanufacturing and recycling of CE in an intelligent way. | Cui, Y., et al. (2021) |
| 2021 | 6 | Reduce, Repair←VAR<br>Reduce←IIoT, AM | VR/AR can improve the ability to proactively maintain equipment through monitoring, evaluation, and repair, and can reduce downtime and increase productivity.<br>The shortening of time to market and the reduction of cost can be achieved through IIoT and AM functions. | Enyoghasi C et al. (2021) |

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| 2021 | 7 | Repair, Refurbish, Remanufacture, Recycle←AI, IoT, BD(A)<br>Repair, Refurbish, Maintenance, Remanufacture←AM | Additive manufacturing can be used in the process of repair, refurbishment, maintenance, manufacturing, and remanufacturing.<br>Repair, refurbishment, remanufacturing or recycling of products withdrawn from the supply chain can be achieved through advanced technologies such as AI, IOT, BD(A), and machine vision. | Fofou R F et al. (2021) |
| 2021 | 8 | Zero Waste Manufacturing←AM | The introduction of intelligent manufacturing processes such as AM has promoted zero waste of raw materials. | GUPTA, H., et al. (2021) |
| 2021 | 9 | Remanufacture←IoT, CPS<br>Recycle←AM | Additive manufacturing facilitates the recycling of products and materials.<br>The combining of IoT and CPS can help intelligent remanufacturing. | Kazancoglu Y et al. (2021) |
| 2021 | 10 | Waste Management←IoT | In the development of smart and green cities, the IoT plays a positive role in the Waste Management system. | Khan I S et al. (2021a) |
| 2021 | 11 | Recycle, Reuse, Waste Management←IoT, RFID<br>Reduce←Block | The application of I4. 0 technologies, such as the IoT, GPS or RFID, promotes product reuse or recycling design and improves Waste Management.<br>The use of blockchain technology reduces transaction costs, waste and carbon footprint, thus contributing to the company's circular economy. | Khan S et al. (2021b) |
| 2021 | 12 | Remanufacture←IoT<br>Recover, Recycle←Dig | The product life cycle and cycle level of remanufacturing process can be observed by the IoT.<br>Postconsumer product recovery and recycling process can be supported by the digitization of CE. | Sahu, A., et al. (2021) |
| 2021 | 13 | Repair←AI | Authors emphasized the use and employment of AI technology in AM-based repair of remanufacturing system | Yusoh, S. S. M., et al. (2021) |

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| 2021 | 14 | Waste Management←AI, ML, DT | New research efforts to promote construction project design and Waste Management are inseparable from advanced industrial 4.0 technologies, such as AI, ML and DT. | Mesa et al. (2021) |
| 2021 | 15 | Reuse, Recycle←Block | the improvement of the visibility, automation of the blockchain will strengthen the reusability, upgrading, recycling and circular performance management of the supply chain. | MUKHERJEE, A. A., et al. (2021) |
| 2021 | 16 | Reduce(cost)←IoT, CPS, Rob, WSNs | The application of IoT, CPS, robotics and sensor technologies helps reduce costs. | Nara E et al. (2021) |
| 2021 | 17 | Waste Management←IoT, AI, Rob, BD(A) | The rapid revolution of Waste Management department can be realized through the use of different technologies (Robot, BD(A), AI, IoT). | ORTEGA-GRAS et al. (2021) |
| 2021 | 18 | Reduce←AM, Rob | Material cost and production time can be reduced through data analysis, AM and robotics. | PALADINI, S., et al. (2021) |
| 2021 | 19 | Reduce←3D, AM | The reduction of logistics cost and delivery time can be realized by AM. By reducing the product to the minimum required for mechanical function, 3D printing can control its filling density. | PONIS, S., et al. (2021) |
| 2021 | 20 | Reduce, Recycle, Reuse←BD(A) | Reuse, waste reduction and product recycling can be promoted through BD(A) and the data provided. | Pinheiro M et al. (2021) |