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Assessing relations between Circular Economy and Industry 4.0: a systematic literature review

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Industry 4.0 (I4.0) and Circular Economy (CE) are undoubtedly two of the most debated topics of the last decades. Progressively, they gained the interest of policymakers, practitioners and scholars all over the world. Even if they have been usually described as two independent research fields, there are some examples presenting overlaps between these topics, represented by hybrid categories like Circular I4.0 and Digital CE. Starting from these two perspectives, an innovative framework both highlighting the links between I4.0 and CE and unveiling future research fields has been developed. Basing on one of the two perspectives, results show as it is possible to enhance a set of different relations. Depending on a dedicated area of either CE or I4.0 it is possible to see the prevalence of some I4.0 technology than others. However, the influence of I4.0 technologies on CE is always verified.

Keywords: Circular Economy; Circular Industry 4.0; digital circular economy; Industry 4.0; systematic literature review

1. Introduction

Circular Economy (CE) and Industry 4.0 (I4.0) represent the two most important industrial paradigms driving academia and industry in recent years (Suárez-Eiroa et al. 2019; Rüßmann et al. 2015). CE is a commonly agreed term (Winans, Kendall, and Deng 2017). The CE is an industrial system that is restorative or regenerative by intention and design. This concept replaces the ‘end-of-life’ concept with restoration, shifts to the use of renewable energy, eliminates the use of toxic chemicals (which impair reuse), and aims for the elimination of waste through the superior design of materials, products, systems, and within this, business models (The Ellen MacArthur Foundation 2013; Bocken et al. 2016; Okorie et al. 2018). The CE allows the decoupling of economic growth from finite resource constraints, by providing opportunities for business regarding new ways of creating value, generating revenue, reducing costs, being resilient, and creating legitimacy (Manninen et al. 2018). Instead, I4.0 is a paradigm referring to a wide range of concepts, whose clear classification – as well as their precise distinction – is not possible (Lasi et al. 2014). Most definitions of I4.0 consider advanced digital technologies the main driver. In particular, the Boston Consulting Group identified nine technologies as building blocks of I4.0: big data and analytics, autonomous robots and vehicles, additive manufacturing, simulation, augmented and virtual reality, horizontal/vertical system integration, the Internet of Things (IoT), cloud, fog, and edge technologies, and blockchain and cyber-security (Rüßmann et al. 2015). The integration of these technologies within an industrial context can enable a set of important improvements in competitiveness:

- Production technologies (Zhou, Zhou, and Liu 2015),
- Financial performance (Schuh et al. 2014),
- Market expansion (Sanders, Elangeswaran, and Wulfsberg 2016),
- Supply chain management (Porter and Heppelmann 2014),
- Product lifecycle management (Porter and Heppelmann 2014),
- Workforce empowerment (Oesterreich and Teuteberg 2016), and
- Business models (Lee, Kao, and Yang 2014).

Given the importance these two paradigms have acquired over time, much literature discusses CE and I4.0 from several perspectives (Liao et al. 2017; Smart et al. 2017; Govindan and Hasanagic 2018). However, there is still a great distance between theory and practice (Gorissen, Vrancken, and Manshoven 2016). Regarding the CE perspective, authors and scholars described challenges, opportunities, frameworks, models, and best-in-class multinationals (Angioletti et al.

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2016; Antikainen, Uusitalo, and Kivikytö-Reponen 2018; Askoxylakis 2018; Ge and Jackson 2014). However, very limited contributions about what kind of technologies can support the implementation of CE, especially in Small and Medium Enterprises (SMEs), are available (Y. Wang, Zhang, and Zuo 2016; X. V. Wang and Wang 2018; Soroka et al. 2017). Regarding the I4.0 perspective, many contributions assessed the potential support offered by key enabling technologies to companies (Ge and Jackson 2014; Isaksson, Hallstedt, and Öhrwall Rönnbäck 2018; He, Xu, and Xu 2010; Gorissen, Vrancken, and Manshoven 2016). However, only in a very few cases was the environmental benefit (the circularity level) reachable through the adoption of I4.0-based technologies assessed (Angioletti, Despeisse, and Rocca 2017; Lahrour and Brissaud 2018; van Schaik and Reuter 2016). Starting from these premises, this paper has several aims: (i) to investigate how I4.0 technologies influence the CE and (ii) to classify these relations through an innovative framework. The paper is organised as follows. In Section 2, the topic is conceptualised, with a description of the CE and I4.0. In Section 3, the research methodology is described. In Section 4, the results of the literature review are discussed. In Section 5, open issues are discussed. In Section 6, concluding remarks and future research avenues are offered.

2. Topic conceptualisation

The work is based on two main concepts, the CE and I4.0. In this section, these concepts are presented, along with definitions.

2.1. Circular economy

Commonly agreed definitions of the CE are those proposed by the Ellen MacArthur Foundation (2015) and Su et al. (2013). First, the CE is defined as a global economic model to minimise the consumption of finite resources, by focusing on intelligent design of materials, products, and systems. Second, the CE aims at overcoming the dominant linear (e.g. take, make, and dispose) economy model (i.e. a traditional open-ended economy model developed with no built-in tendency to recycle; Stahel and Reday-Mulvey 1981; Pearce and Turner 1991). However, only in the last few years has the relevance of the CE been amplified worldwide (Reuter et al. 2013). Before the CE was introduced, a traditional (linear) lifecycle was the only process followed during the conceptualisation, design, development, use, and disposal of products (Su et al. 2013). Progressively, closed-loop patterns – completely focused on balancing economic, environmental, and societal impacts – have substituted old industrial practices.

2.2. Industry 4.0

As described in Section 1, there is no consensus among experts about which technologies can be classified under the I4.0 umbrella. Thus, we decided to follow an alternative strategy during the implementation of this work. Initially, they adopted the nine pillars described by Rüßmann et al. (2015) as keywords to exploit during the literature assessment. Basing on the resulting literature gathered from the web, only five of the nine pillars were further assessed. This way, cyber-physical systems (CPSs), the IoT, big data and analytics (BDA), additive manufacturing (AM), and simulation were identified as the main I4.0-based technologies related to the CE. For clarification, brief descriptions of these four technologies are provided. First, CPSs are an integration of computation and physical processes. Embedded computers and networks monitor and control the physical process, usually with feedback loops, where physical processes affect computations, and vice versa (Lee, Bagheri, and Kao 2015). Second, the IoT are technologies that allow interaction and cooperation among people, devices, things, or objects through the use of modern wireless telecommunications, such as radio frequency identification (RFID), sensors, tags, actuators, and mobile phones (Nasiri, Tura, and Ojanen 2017). Third, BDA is the application of advanced data analysis techniques for managing big datasets (Soroka et al. 2017). Fourth, AM describes a suite of technologies that allow the production of a growing spectrum of goods via the layering or 3D printing of materials (Dutta et al. 2001). Finally, simulations consider a wide range of mathematical programming techniques to achieve purposes related to CE and I4.0 paradigms. What is rarely assessed by the literature is the relation between I4.0 and the CE, and their reciprocal effect on the overall performance of a company.

3. Research methodology

To better identify the relation between I4.0 and the CE, a systematic literature review was implemented according to Denyer and Tranfield (2009) guidelines. As previously defined in Section 1, this paper has several aims. First, the existing relations between I4.0 and the CE were investigated. Second, they were classified based on an innovative framework of analysis. In this section, how the data were collected and analysed, and are reported is described. First, the search criteria for selecting the papers were identified. Second, other information sources were consulted, to increase the initial number of documents. Third, papers and other documents were classified, to consider their appropriateness for the scope of analysis. Finally, the selected documents were analysed in detail, by considering the year of publication, methodology, geographic provenience of the authors, and macro- and micro-focuses. The research progress of this paper is described in the following sub-section.

3.1. Search criteria

To follow a transparent approach and secure the validity of the data, specific databases were selected. The search criteria are summarised in Figure 1.

The review process considered only formal and informal literature (including books and scientific and industrial reports), by focusing on titles, abstracts, and keywords. The reference databases used were Scopus and Web of Science, because they are internationally renowned. Initially, a structured keyword search was conducted in Scopus. Subsequently, Web of Science was consulted for reliability reasons. Only papers written in English and published between 2000 and 2018 were evaluated.

3.2. Article search

By exploiting the ‘advanced search’ section of Scopus and Web of Science, 20 different search strings were used to gather documents that examined, at the same time, the CE and I4.0 (or some of their sub-topics). Table 1 reports the search strings and the resulting number of documents.

The final set of 20 strings generated 690 and 518 documents from Scopus and Web of Science, respectively. After the inclusion and exclusion criteria were applied (see Figure 1), 158 documents were considered. The documents included 110 journal articles, 41 conference proceedings, 5 book chapters, and 2 scientific reports.

3.3. Article content analysis

The output of the search process in terms of the number of works published by year is shown in Figure 2.

The total number of documents (158) and their concentration (96% within the last five years) revealed the high attention devoted to these topics by the authors.

Regarding scientific journals with impact factors, Figure 3 shows some have dedicated major attention to this topic. About 12% of these documents were published in the form of conference proceedings in Procedia CIRP.

Figure 4 shows the countries where the institutions with which the first authors were affiliated are located. The distribution was concentrated in the United Kingdom (UK), Germany, the United States (US), China, and Italy. These five countries accounted for about 38% of the total number of works published.

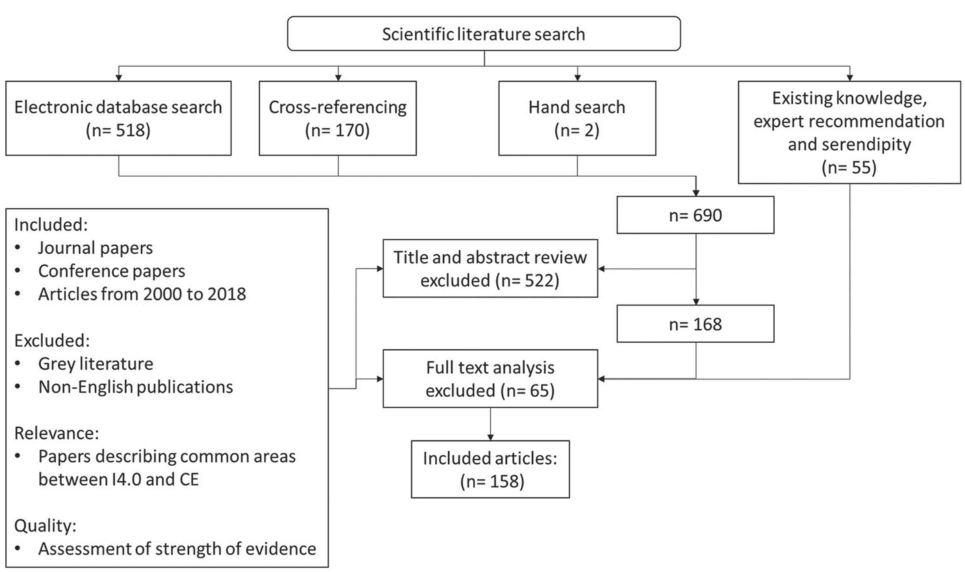

Figure 1. Search strategy.

Table 1. Search strings and resulting documents.

ID	Query	Scopus™ documents	Web of Science™ documents
#1	TITLE-ABS-KEY (circular AND economy AND industry 4.0) AND (LIMIT-TO (LANGUAGE, "English)")	18	10
#2	TITLE-ABS-KEY (circular AND economy AND additive AND manufacturing) AND (LIMIT-TO (LANGUAGE, "English)")	20	17
#3	TITLE-ABS-KEY (circular AND economy AND big AND data) AND (LIMIT-TO (LANGUAGE, "English)")	33	25
#4	TITLE-ABS-KEY (circular AND economy AND cloud AND manufacturing) AND (LIMIT-TO (LANGUAGE, "English)")	7	2
#5	TITLE-ABS-KEY (circular AND economy AND internet AND of AND things) AND (LIMIT-TO (LANGUAGE, "English)")	28	16
#6	TITLE-ABS-KEY (circular AND economy AND cyber-physical AND system) AND (LIMIT-TO (LANGUAGE, "English)")	4	3
#7	TITLE-ABS-KEY (circular AND economy AND augmented AND reality) AND (LIMIT-TO (LANGUAGE, "English)")	1	1
#8	TITLE-ABS-KEY (circular AND economy AND 3d AND printing) AND (LIMIT-TO (LANGUAGE, "English)")	16	9
#9	TITLE-ABS-KEY (circular AND economy AND fourth AND industrial AND revolution) AND (LIMIT-TO (LANGUAGE, "English)")	3	1
#10	TITLE-ABS-KEY (circular AND economy AND simulation) AND (LIMIT-TO (LANGUAGE, "English)")	123	80
#11	TITLE-ABS-KEY (circular AND economy AND smart AND production) AND (LIMIT-TO (LANGUAGE, "English)")	29	14
#12	TITLE-ABS-KEY (circular AND economy AND smart AND manufacturing) AND (LIMIT-TO (LANGUAGE, "English)")	16	10
#13	TITLE-ABS-KEY (circular AND economy AND data AND mining) AND (LIMIT-TO (LANGUAGE, "English)")	46	27
#14	TITLE-ABS-KEY (circular AND economy AND digital) AND (LIMIT-TO (LANGUAGE, "English)")	70	28
#15	TITLE-ABS-KEY (circular AND economy AND smart) AND (LIMIT-TO (LANGUAGE, "English)")	76	48
#16	TITLE-ABS-KEY (circular AND economy AND intelligent) AND (LIMIT-TO (LANGUAGE, "English)")	60	28
#17	TITLE-ABS-KEY (reuse AND industry 4.0) AND (LIMIT-TO (LANGUAGE, "English)")	48	63
#18	TITLE-ABS-KEY (recycle AND industry 4.0) AND (LIMIT-TO (LANGUAGE, "English)")	14	65
#19	TITLE-ABS-KEY (recycling AND industry 4.0) AND (LIMIT-TO (LANGUAGE, "English)")	66	65
#20	TITLE-ABS-KEY (remanufacturing AND industry 4.0) AND (LIMIT-TO (LANGUAGE, "English)")	12	6
	Total	690	518

Macro-topics were also addressed by published papers (see Figure 5), which assessed the influence and application of I4.0 technologies on CE performance and contexts.

The analysis highlighted the multidisciplinary aspect of the research. The methodology was broadly based on the theoretical approach (with 72 works). Less frequently used were analytical studies, case studies, and surveys (62, 18, and 6 works, respectively). Therefore, it is now possible to analyse the macro-topics and then, define the main characteristics of existing works.

4. Results

Results gathered from the literature review can be categorised into two groups, either how I4.0 technologies can influence the CE, or vice versa, how CE-related areas are covered by I4.0 technologies. For each view, a dedicated subset of micro-topics was identified, and papers were classified based on these topics (see Table 2). The classes listed in the first column refer to CE-related topics. The classes listed in the second column refer to I4.0 pillars.

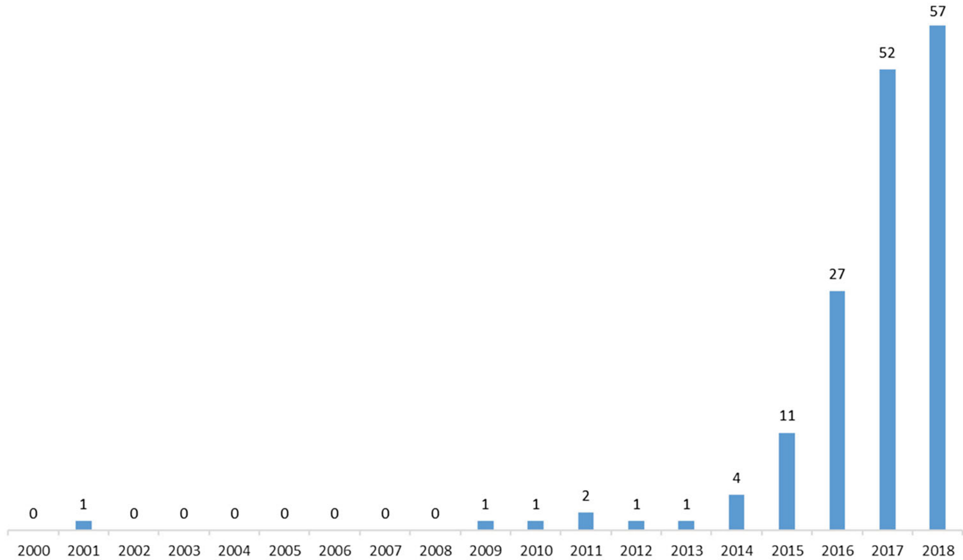

Figure 2. Historical series of published papers.

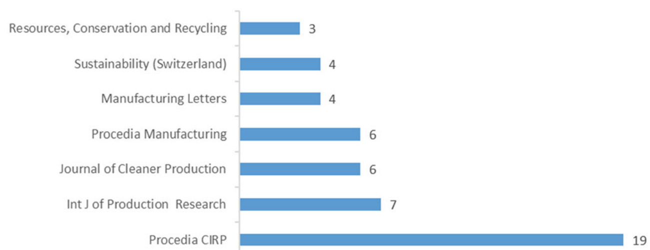

Figure 3. Top five journals.

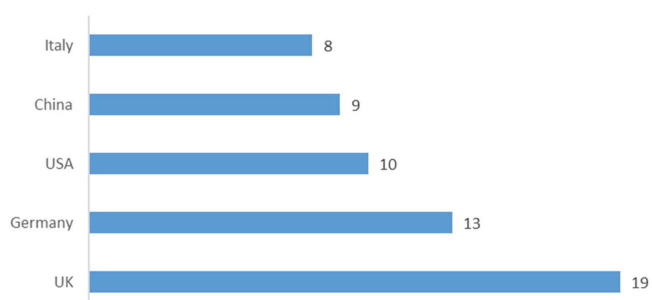

Figure 4. Top five publishing nations.

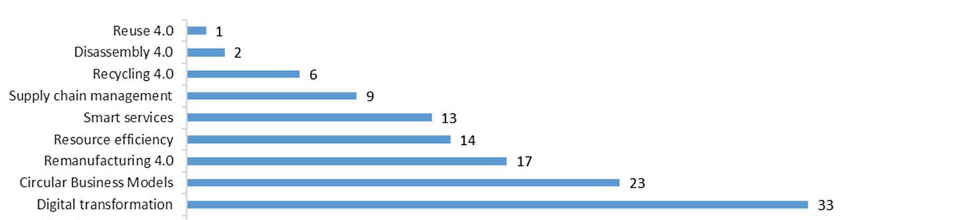

Figure 5. Macro topics of published papers.

Table 2. List of classification items.

CE-related classification items		I4.0-related classification items	
CBMOD	Circular Business Models	AM	Additive Manufacturing
DIGIT	Digital Transformation	BDA	Big Data and Analytics
DISAS	Disassembly	CPS	Cyber-Physical Systems
LIFEC	Lifecycle Management	IOT	Internet of Things
RECYC	Recycling	SIM	Simulation
REMAN	Remanufacturing	Generic	Any I4.0 technology
RESOU	Resource Efficiency		
REUSE	Reuse		
SMSER	Smart Services		
SUPCM	Supply Chain Management		

4.1. Enabling the CE through I4.0 technologies

The first aim is to understand how I4.0 technologies can influence the CE. Starting from a list of the most general papers describing this aspect, the focus shifts to assessing each specific I4.0 technology. The final aim is to discover hidden correlations.

4.1.1. General overview

An initial overview of the literature can be done by considering the papers on the relation between the CE and I4.0 from a generic perspective. One general assertation shared among experts is that I4.0 can act as an enabler of the CE. A company willing to become circular cannot avoid considering I4.0 technologies within its value chain. In the literature, several works focused on this direction, especially in the form of reviews (Cattelan Nobre and Tavares 2017; Kuo and Smith 2018; Liao et al. 2017; Okorie et al. 2018). The most common way to describe the relation between I4.0 and the CE was digitalisation of the CE. Through this term, the experts considered I4.0 technologies as a galaxy of opportunities supporting companies in improving their circular performance through the adoption of digital technologies (see Table 3). Another common perspective was related to the role that I4.0 technologies could have in enabling circular business models (CBMs). In this perspective, I4.0 technologies acquire a strategic role involving customers, co-providers (and stakeholders in general) within the value chain, to reach a CE. In a few cases, the discussion considered other CE-related aspects, such as resource efficiency, remanufacturing, lifecycle management, and smart services (SSs). In these cases, I4.0 technologies are enablers of innovative ways for monitoring the exploitation of natural resources or product lifecycle stages and integration with existing technologies. Finally, in rare cases, disassembly and supply chain management (SCM) were discussed, with I4.0 technologies considered the main element for developing and managing supplier–customer relationships.

4.1.2. Additive manufacturing

AM is one of the most game-changing technologies in today's society (Angioletti et al. 2016). This importance is enhanced by the number of papers describing the relations between the CE and I4.0 that considered AM as a reference element (see Table 4). Commonly, these relations were described in terms of how AM could support the lifecycle management of products and processes. Only in some cases did experts identify other connections. Some scholars discussed the exploitation of AM for upgrading current recycling processes – through either new sustainable (Clemon and Zohdi 2018; Mandil et al. 2016; Sauerwein and Doubrovski 2018; Woern et al. 2018; Zhong and Pearce 2018) or networks (Santander et al. 2018) – and digitalising the manufacturing process, for example, through a new kind of process (Dutta et al. 2001) or managerial strategies (Unruh 2018). Others presented the idea of using AM to support the remanufacturing of products or components (Lahrour and Brissaud 2018; Leino, Pekkarinen, and Soukka 2016), the development of CBMs focused on recycled materials (Mattos Nascimento et al. 2018); (Millard et al. 2018), the exploitation of biomaterials (van Wijk and van Wijk 2015; Voet et al. 2018), or the reuse of products/materials (Bloomfield and Borstrock 2018).

4.1.3. Big data and analytics

BDA, in contrast to the discussions of AM, has been considered less frequently by experts and no perspective on exploiting BDA for improving CE practices was prevalent. Even if BDA is generally known as one of the easiest ways to digitise the CE (Cattelan Nobre and Tavares 2017), other perspectives have been discussed, like exploiting it: (i) to develop automated

Table 3. How I4.0 can support the CE.

Reference	DIGIT	CBMOD	RESOU	REMAN	LIFEC	SMSER	DISAS	SUPCM
(Antikainen, Uusitalo, and Kivikytö-Reponen 2018)		x						
(Baines 2015)						x		
(Bianchini et al. 2018)		x						
(Bressanelli et al. 2018b)		x						
(Bressanelli et al. 2018a)		x						
(Butzer et al. 2016)				x				
(Chang, Ong, and Nee 2017)							x	
(de Man and Strandhagen 2017)		x						
(Eden 2017)			x					
(Fisher et al. 2018)	x							
(Gorissen, Vrancken, and Manshoven 2016)		x						
(Hughes 2017)			x					
(Isaksson, Hallstedt, and Öhrwall Rönnbäck 2018)					x			
(Jensen and Remmen 2017)					x			
(Jin et al. 2014)		x						
(Kölsch et al. 2017)		x						
(Kowalkowski et al. 2017)						x		
(Kuo and Smith 2018)			x					
(A. Q. Li and Found 2017)		x						
(Liao et al. 2017)	x							
(Lopes de Sousa Jabbour et al. 2018a)	x							
(Lopes de Sousa Jabbour et al. 2018b)	x							
(Mařík et al. 2016)			x					
(Moreno and Charnley 2016)	x							
(Neligan 2018)			x					
(Okorie et al. 2018)	x							
(Pagoropoulos, Pigosso, and McAloone 2017)	x							
(Planing 2017)	x							
(Prendeville et al. 2016)		x						
(Rajala et al. 2018)	x							
(Ruggeri et al. 2017)				x				
(Sarkis and Zhu 2018)								x
(Shanshan Yang et al. 2018)				x				
(Sinclair et al. 2018)					x			
(Smart et al. 2017)			x					
(Srai et al. 2016)	x							
(Stark et al. 2014)				x				
(Stock and Seliger 2016)	x							
(Thomas 2018)	x							
(Tolio et al. 2017)				x				
(Townsend and Coroama 2018)			x					
(Ünal, Urbinati, and Chiaroni 2018)		x						
(X. Wang, Ong, and Nee 2018)	x							
(Wilts and Berg 2017)			x					
(B. Xu 2016)				x				
(Yeo, Pepin, and Yang 2017)				x				
Total	13	11	8	7	3	2	1	1

approaches assessing potential value pathways for secondary materials (Davis, Aid, and Zhu 2017; Jose and Ramakrishna 2018) or discovering potential industrial symbioses (Song et al. 2017), (ii) to develop open-source tools, procedures, open data, and services for promoting reuse (Franquesa, Navarro, and Bustamante 2016; Franquesa and Navarro 2018) or cloud service platforms for data collection and analytics (Lindström et al. 2018), (iii) to assess innovative business models through integrative frameworks (Chiappetta Jabbour et al. 2017) or for particular types of companies (Soroka et al. 2017), and (iv) to gather or manage data on the lifecycle of products (J. Li et al. 2015) or implementing smart manufacturing practices (Kusiak 2018) (see Table 5). In rare cases, experts focused on exploitation of BDA for other reasons, such as improving disassembly sequence planning (Marconi et al. 2018), considering recycling issues during product design (Lin 2018), assessing cost

Table 4. How AM can support the CE.

Reference	LIFEC	RECYC	DIGIT	REMAN	CBMOD	RESOU	REUSE
(Angioletti et al. 2016)			x				
(Angioletti, Despeisse, and Rocca 2017)	x						
(Bassi 2017)	x						
(Bloomfield and Borstrock 2018)							x
(Clemon and Zohdi 2018)		x					
(Despeisse et al. 2017)			x				
(Dutta et al. 2001)			x				
(Giurco et al. 2014)			x				
(Lahrour and Brissaud 2018)				x			
(Le, Paris, and Mandil 2017a)				x			
(Le, Paris, and Mandil 2017b)				x			
(Leino, Pekkarinen, and Soukka 2016)				x			
(Ma et al. 2018)	x						
(Mandil et al. 2016)		x					
(Mattos Nascimento et al. 2018)					x		
(Millard et al. 2018)					x		
(Minetola and Eyers 2018)	x						
(Moreno et al. 2017)					x		
(Müller et al. 2018)	x						
(Santander et al. 2018)		x					
(Sauerwein, Bakker, and Balkenende 2017)	x						
(Sauerwein and Doubrovski 2018)		x					
(Schmidt et al. 2017)	x						
(Sheng Yang et al. 2017)	x						
(Syed-Khaja, Perez, and Franke 2016)	x						
(Unruh 2018)			x				
(van Wijk and van Wijk 2015)						x	
(Voet et al. 2018)						x	
(Woern et al. 2018)		x					
(Zhong and Pearce 2018)		x					
Total	9	6	5	4	3	2	1

Table 5. How BDA and Analytics can support the CE.

Reference	DIGIT	RESOU	SMSER	CBMOD	LIFEC	DISAS	RECYC	REMAN	SUPCM
(Cattelan Nobre and Tavares 2017)	x								
(Chiappetta Jabbour et al. 2017)				x					
(Davis, Aid, and Zhu 2017)		x							
(Franquesa, Navarro, and Bustamante 2016)			x						
(Franquesa and Navarro 2018)			x						
(Ge and Jackson 2014)								x	
(Jose and Ramakrishna 2018)		x							
(Kache and Seuring 2017)									x
(Kusiak 2018)					x				
(J. Li et al. 2015)					x				
(Lin 2018)							x		
(Lindström et al. 2018)			x						
(Marconi et al. 2018)						x			
(Salminen, Ruohomaa, and Kantola 2017)	x								
(Seele and Lock 2017)	x								
(Song et al. 2017)		x							
(Soroka et al. 2017)				x					
(Tseng et al. 2018)	x								
Total	4	3	3	2	2	1	1	1	1

reduction strategies through remanufacturing (Ge and Jackson 2014), and assessing challenges and opportunities in SCM practices (Kache and Seuring 2017).

4.1.4. Cyber-physical systems

CPSs, as shown for BDA, were the least discussed I4.0 technology in terms of supporting CE practices. However, differently from AM and BDA, CPSs presented a clear direction in terms of how they could support the CE (see Table 6). Many scholars saw CPSs as a way to enable either better lifecycle management of products or the development of new services, especially for maintenance reasons (Caggiano 2018; Herterich, Uebernickel, and Brenner 2015a). Only in a very few cases was the focus on remanufacturing practices or multi-agent systems for managing the extraction of natural resources (Martín-Gómez, Aguayo-González, and Marcos Bárcena 2018).

4.1.5. Internet of Things

The IoT was considered, together with AM, one of the most important technologies able to support the transition to the CE (see Table 7). Apart from papers focused on a generic description of potential uses of the IoT for extending the product lifecycle, there was a common understanding that the IoT can spread its potential effects on a wide number of CE-related areas. One option is adopting the IoT for enabling new waste management strategies in smart cities (Esmaeilian et al. 2018), creating collaboration (Romero and Molina 2012; Romero and Noran 2017) and improving the circularity level of metallurgical processes (Reuter, Matusewicz, and van Schaik 2015). Another opportunity for exploiting the IoT is the digitalisation of CE practices, for example, by implementing smart industrial environments (Hatzivasilis et al. 2018) or dynamic feedback control loops (Reuter 2016). Again, the IoT is suitable for developing new services and CBMs (Alcayaga and Hansen 2017). In a few cases, the optimisation of SCM performance (J. Xu 2009) and remanufacturing processes (French, Benakis, and Marin-Reyes 2017) were considered by experts.

4.1.6. Simulation

Simulation followed the same trend discussed for AM and the IoT (see Table 8). Numerous papers focused on the effects of simulations on CBMs and product lifecycle management. Others identified specific ways in which simulation can support the CE. One method is the optimisation of SCM performance – for example, through probabilistic neural networks (He, Xu, and Xu 2010) – or the modelling of material flows (Schäfers and Walther 2017). Another option is exploiting simulation to support the remanufacturing of products, for example, in the form of decision-support tools (Kuik, Kaihara, and Fujii 2016; X. V. Wang and Wang 2018). Again, simulation can improve the efficiency in exploiting natural resources – for example, through the calculation of eco-efficiency indexes (Rönnlund et al. 2016) – and enable the development of new services, especially for maintenance reasons (Ashjaei and Bengtsson 2017). Only in one case did experts discuss simulation as a support tool for recycling, but in terms of calculating recycling performance indexes (van Schaik and Reuter 2016).

Table 6. How CPSs can support the CE.

Reference	LIFEC	SMSER	REMAN	RESOU
(Barbosa et al. 2016)	x			
(Caggiano 2018)		x		
(Gürdür and Gradin 2017)	x			
(Hehenberger et al. 2016)	x			
(Herterich et al. 2015)		x		
(Herterich, Uebernickel, and Brenner 2015b)		x		
(Herterich, Uebernickel, and Brenner 2015a)		x		
(Jardim-Goncalves, Romero, and Grilo 2017)		x		
(Lee, Bagheri, and Kao 2015)		x		
(Liu et al. 2016)			x	
(Martín-Gómez, Aguayo-González, and Marcos Bárcena 2018)				x
(Miranda et al. 2017)	x			
(Rødseth, Schjølberg, and Marhaug 2017)	x			
(Sharpe et al. 2018)	x			
(Thoben, Wiesner, and Wuest 2017)	x			
(Yu, Xu, and Lu 2015)		x		
Total	7	7	1	1

Table 7. How the IoT can support the CE.

Reference	LIFEC	RESOU	DIGIT	SMSER	CBMOD	SUPCM	REMAN
(Alcayaga and Hansen 2017)				x			
(Askoxylakis 2018)					x		
(Esmaeilian et al. 2018)		x					
(French, Benakis, and Marin-Reyes 2017)							x
(Hatzivasilis et al. 2018)			x				
(Holligan, Hargaden, and Papakostas 2017)	x						
(Mashhadi and Behdad 2018)	x						
(Menon, Kärkkäinen, and Gupta 2016)	x						
(Menon et al. 2018)	x						
(Nasiri, Tura, and Ojanen 2017)			x				
(Pacis, Subido Jr., and Bugtai 2017)	x						
(Pistol, Bucea-Manea-Tonis, and Bucea-Manea-Tonis 2017)					x		
(Reuter, Matusewicz, and van Schaik 2015)		x					
(Reuter 2016)			x				
(Romero and Molina 2012)		x					
(Romero and Noran 2017)		x					
(Spring and Araujo 2017)				x			
(Tjahjono et al. 2017)						x	
(Verdugo Cedeño et al. 2017)				x			
(Y. Wang, Zhang, and Zuo 2016)	x						
(J. Xu 2009)						x	
(Zallio and Berry 2017)	x						
Total	7	4	3	3	2	2	1

Table 8. How simulation can support the CE.

Reference	CBMOD	LIFEC	SUPCM	REMAN	RESOU	SMSER	RECYC
(Alexandris et al. 2018)	x						
(Ashjaei and Bengtsson 2017)						x	
(Borangiu, Thomas, and Trentesaux 2013)						x	
(Deschamps et al. 2018)		x					
(He, Xu, and Xu 2010)			x				
(Karastoyanov and Karastanev 2018)				x			
(Kuik, Kaihara, and Fujii 2016)				x			
(Lieder, Asif, and Rashid 2017)	x						
(Lieder et al. 2017)	x						
(Moreno et al. 2018)	x						
(Panarotto, Wall, and Larsson 2017)	x						
(Rönnlund et al. 2016)					x		
(Schäfers and Walther 2017)			x				
(Schroeder et al. 2016b)		x					
(Schroeder et al. 2016a)		x					
(Siddiqi et al. 2017)				x			
(Simons 2017)	x						
(Sun and Wang 2011)			x				
(Trentesaux and Giret 2015)		x					
(Tsai 2018)		x					
(Turner et al. 2016)		x					
(van van Schaik and Reuter 2016)							x
(van Schalkwyk et al. 2018)					x		
(X. V. Wang and Wang 2018)				x			
(Zhang et al. 2016)			x				
(Zhao, Dang, and Zhang 2011)			x				
Total	6	6	5	4	2	2	1

4.2. Selecting I4.0 technologies for the CE

Scholars have also focused on how CE-related areas fit with I4.0 technologies. Starting from a list of the most general papers describing this aspect, the focus shifts to assessing which set of I4.0 technologies is suitable for a specific CE-related area. Once again, the aim is to discover hidden correlations.

4.2.1. Digital transformation

In general terms, authors and scholars who examined the digitalisation of the CE did not select a specific I4.0 technology, preferring to maintain the widest number of potential developments in the future (see Table 9). Only in a few cases did experts focus on several technologies. AM was the most discussed topic, followed by BDA and the IoT. First, AM is adopted to develop a new kind of manufacturing processes (Dutta et al. 2001) or managerial strategies (Unruh 2018). Second, BDA supports responsible business management (by analysing the transition to CE; Salminen, Ruohomaa, and Kantola 2017) and industrial symbiosis (Tseng et al. 2018). Third, the IoT allows the development of industrial networks (Hatzivasilis et al. 2018; Reuter 2016). AM seemed to be related more to digitalisation of a company's internal processes. In contrast, BDA and the IoT support the digitalisation of relations between a company and its industrial context.

4.2.2. Lifecycle management

Regarding lifecycle management, the literature considers all five I4.0 technologies discussed in this paper, with a focus on AM (see Table 10). Depending on the authors, AM can be exploited to (i) improve the overall CE performance (Angioletti, Despeisse, and Rocca 2017; Bassi 2017; Sheng Yang et al. 2017), (ii) improve the impacts and energy consumption (Ma et al. 2018; Minetola and Eyers 2018), or (iii) improve product development and design (Müller et al. 2018; Sauerwein, Bakker, and Balkenende 2017) processes (Schmidt et al. 2017; Syed-Khaja, Perez, and Franke 2016). Other I4.0 technologies considered by experts as valuable support for the CE are CPSs, the IoT, and simulation. CPSs can be adopted to (i) assess sustainability levels (Gürdür and Gradin 2017), (ii) develop maintenance management activities (Hehenberger et al. 2016; Rødseth, Schjølberg, and Marhaug 2017), (iii) integrate product, process, and manufacturing systems (Miranda et al. 2017), and (iv) improve the traceability of circular practices (Sharpe et al. 2018). The IoT is considered by experts as a good method for linking product lifecycle management and digital manufacturing, for example, through cloud computing

Table 9. I4.0 technologies enabling digital transformation.

Reference	AM	BDA	IOT	Generic
(Angioletti et al. 2016)	x			
(Cattelan Nobre and Tavares 2017)		x		
(Despeisse et al. 2017)	x			
(Dutta et al. 2001)	x			
(Fisher et al. 2018)				x
(Giurco et al. 2014)	x			
(Hatzivasilis et al. 2018)			x	
(Liao et al. 2017)				x
(Lopes de Sousa Jabbour et al. 2018a)				x
(Lopes de Sousa Jabbour et al. 2018b)				x
(Moreno and Charnley 2016)				x
(Nasiri, Tura, and Ojanen 2017)			x	
(Okorie et al. 2018)				x
(Pagoropoulos, Pigosso, and McAloone 2017)				x
(Planing 2017)				x
(Rajala et al. 2018)				x
(Reuter 2016)			x	
(Salminen, Ruohomaa, and Kantola 2017)		x		
(Seele and Lock 2017)		x		
(Srai et al. 2016)				x
(Stock and Seliger 2016)				x
(Thomas 2018)				x
(Tseng et al. 2018)		x		
(Unruh 2018)	x			
(X. Wang, Ong, and Nee 2018)				x
Total	5	4	3	13

Table 10. I4.0 technologies supporting lifecycle management.

Reference	AM	CPS	IOT	SIM	BDA	Generic
(Angioletti, Despeisse, and Rocca 2017)	x					
(Barbosa et al. 2016)		x				
(Bassi 2017)	x					
(Deschamps et al. 2018)				x		
(Gürdür and Gradin 2017)		x				
(Hehenberger et al. 2016)		x				
(Holligan, Hargaden, and Papakostas 2017)			x			
(Isaksson, Hallstedt, and Öhrwall Rönnbäck 2018)						x
(Jensen and Remmen 2017)						x
(Kusiak 2018)					x	
(J. Li et al. 2015)					x	
(Ma et al. 2018)	x					
(Mashhadi and Behdad 2018)			x			
(Menon, Kärkkäinen, and Gupta 2016)			x			
(Menon et al. 2018)			x			
(Minetola and Eyers 2018)	x					
(Miranda et al. 2017)		x				
(Müller et al. 2018)	x					
(Pacis, Subido Jr., and Bugtai 2017)			x			
(Rødseth, Schjølberg, and Marhaug 2017)		x				
(Sauerwein, Bakker, and Balkenende 2017)	x					
(Schmidt et al. 2017)	x					
(Schroeder et al. 2016a)				x		
(Schroeder et al. 2016b)				x		
(Sinclair et al. 2018)						x
(Sharpe et al. 2018)		x				
(Sheng Yang et al. 2017)	x					
(Syed-Khaja, Perez, and Franke 2016)	x					
(Thoben, Wiesner, and Wuest 2017)		x				
(Trentesaux and Giret 2015)				x		
(Tsai 2018)				x		
(Turner et al. 2016)				x		
(Y. Wang, Zhang, and Zuo 2016)			x			
(Zallio and Berry 2017)			x			
Total	9	7	7	6	2	3

(Holligan, Hargaden, and Papakostas 2017). The IoT can be also useful for developing new assessment methods that quantify environmental impacts related to smart infrastructures (Mashhadi and Behdad 2018), new energy management tools (Y. Wang, Zhang, and Zuo 2016), or new Internet platforms that manage product lifecycle knowledge and information (Menon, Kärkkäinen, and Gupta 2016; Menon et al. 2018). Third, simulation can be generally adopted for assessing lifecycle performance, for example, environmental impacts (Deschamps et al. 2018) and economic impacts (Tsai 2018). Among several forms of simulation, Digital Twin (DT) is the most common method for supporting data modelling and exchange (Schroeder et al. 2016a, 2016b) or holons development (Trentesaux and Giret 2015; Turner et al. 2016). Less commonly, the discussion focused on BDA or maintained a generic perspective.

4.2.3. Disassembly 4.0 and Reuse 4.0

Given the scarcity of documents focusing on either disassembly or reuse, the present work cannot offer a good estimation of trends (see Table 11). The only papers found in the literature saw BDA or I4.0 technologies in general as good support for disassembly. In this case, BDA was exploited for disassembly sequence planning.

Table 11. I4.0 technologies supporting disassembly.

Reference	BDA	Generic
(Chang, Ong, and Nee 2017)		x
(Marconi et al. 2018)	x	
Total	1	1

Table 12. I4.0 technologies supporting reuse.

Reference	AM
(Bloomfield and Borstrock 2018)	x
Total	1

The only paper focused on reuse strategies considered AM the main solution (see Table 12). In this case, reuse was intended in terms of facilitating the disassembly and reassembly of textiles.

4.2.4. Resource efficiency

Several authors investigated the contribution offered by I4.0 technologies in improving the efficient exploitation of natural resources (see Table 13). Most experts saw the IoT as a valuable method for managing natural resources, followed by BDA, AM, simulation techniques, and CPSs. Regarding the IoT, the intent is to adopt it to enable new waste management strategies in smart cities (Esmaeilian et al. 2018), creating collaborative networks (Romero and Molina 2012; Romero and Noran 2017) or improving the circularity level of metallurgical processes (Reuter, Matusewicz, and van Schaik 2015). BDA, instead, was seen as a good solution for either developing automated approaches assessing potential value pathways for secondary materials (Davis, Aid, and Zhu 2017; Jose and Ramakrishna 2018) or discovering potential industrial symbioses (Song et al. 2017). AM can be useful in terms of exploitation of biomaterials (van Wijk and van Wijk 2015; Voet et al. 2018). Furthermore, simulation techniques can be exploited for calculating a set of eco-efficiency indexes (Rönnlund et al. 2016). Finally, CPSs can be adopted for managing the extraction of natural resources through multi-agent systems (Martín-Gómez, Aguayo-González, and Marcos Bárcena 2018). In addition, some generic papers did not consider a specific I4.0 technology.

4.2.5. Recycling 4.0

In contrast, the clear prevalence of digitalisation of recycling as an I4.0 technology was observed, as AM (see Table 14). Depending on the works, AM was considered either in terms of new sustainable process (Clemon and Zohdi 2018; Mandil et al. 2016; Sauerwein and Doubrovski 2018), equipment (Woern et al. 2018; Zhong and Pearce 2018), and networks (Santander et al. 2018). Only in a few cases did experts also consider BDA and simulation. BDA has been adopted for considering recycling issues during product design (Lin 2018), and simulation can be exploited as a support tool for recycling, for example, for calculating a set of recycling performance indexes (van Schaik and Reuter 2016).

Table 13. I4.0 technologies supporting resource efficiency.

Reference	IOT	BDA	AM	SIM	CPS	Generic
(Davis, Aid, and Zhu 2017)		x				
(Eden 2017)						x
(Esmaeilian et al. 2018)	x					
(Hughes 2017)						x
(Jose and Ramakrishna 2018)		x				
(Kuo and Smith 2018)						x
(Mařík et al. 2016)						x
(Martín-Gómez, Aguayo-González, and Marcos Bárcena 2018)					x	
(Neligan 2018)						x
(Reuter, Matusewicz, and van Schaik 2015)	x					
(Romero and Molina 2012)	x					
(Romero and Noran 2017)	x					
(Rönnlund et al. 2016)				x		
(Smart et al. 2017)						x
(Song et al. 2017)		x				
(Townsend and Coroama 2018)						x
(van Schalkwyk et al. 2018)				x		
(van Wijk and van Wijk 2015)			x			
(Voet et al. 2018)			x			
(Wilts and Berg 2017)						x
Total	4	3	2	2	1	8

Table 14. I4.0 technologies supporting recycling.

Reference	AM	BDA	SIM
(Clemon and Zohdi 2018)	x		
(Lin 2018)		x	
(Mandil et al. 2016)	x		
(Santander et al. 2018)	x		
(Sauerwein and Doubrovski 2018)	x		
(van Schaik and Reuter 2016)			x
(Woern et al. 2018)	x		
(Zhong and Pearce 2018)	x		
Total	6	1	1

4.2.6. *Remanufacturing 4.0*

When discussing the digitalisation of remanufacturing, the greatest number of experts identified simulation and AM as the most promising I4.0 technologies (see Table 15). First, simulation can be adopted for developing dedicated decision-support tools (Kuik, Kaihara, and Fujii 2016; X. V. Wang and Wang 2018). AM, instead, can be useful for supporting the remanufacturing of products or components (Lahrour and Brissaud 2018; Leino, Pekkarinen, and Soukka 2016). Few works focused on BDA, CPSs, and the IoT. BDA has been exploited for assessing cost reduction strategies through remanufacturing (Ge and Jackson 2014), CPSs for improving current remanufacturing performance (Liu et al. 2016), and the IoT for developing innovative ones (French, Benakis, and Marin-Reyes 2017). However, several papers did not consider a specific I4.0 technology.

4.2.7. *Circular business models and smart services*

There is no doubt that the exploitation of I4.0 technologies supports the adoption of the CE, and consequently, CBMs. Several works described this topic from a general perspective (see Table 16). Only in a few cases was this hypothesis supported with a clear explanation of how to implement CBMs in a real context. Simulation was the prevalent technique, followed by AM, BDA, and the IoT. From one perspective, simulation (in the form of blockchain) was exploited for (i) auditing cooperative CE networks (Alexandris et al. 2018), (ii) assessing the impact of business model changes (Simons 2017), for example, through agent-based (Lieder, Asif, and Rashid 2017) or multi-method approaches (Lieder et al. 2017), and (iii) assessing redistributed manufacturing (Moreno et al. 2018) or service-based design (Panarotto, Wall, and Larsson 2017) potential. Regarding AM, the main goal has been developing CBMs focused on recycled materials (Mattos Nascimento et al. 2018;

Table 15. I4.0 technologies supporting remanufacturing.

Reference	SIM	AM	BDA	CPS	IOT	Generic
(Butzer et al. 2016)						x
(French, Benakis, and Marin-Reyes 2017)					x	
(Ge and Jackson 2014)			x			
(Karastoyanov and Karastanev 2018)	x					
(Kuik, Kaihara, and Fujii 2016)	x					
(Lahrour and Brissaud 2018)		x				
(Le, Paris, and Mandil 2017a)		x				
(Le, Paris, and Mandil 2017b)		x				
(Leino, Pekkarinen, and Soukka 2016)		x				
(Liu et al. 2016)				x		
(Ruggeri et al. 2017)						x
(Shanshan Yang et al. 2018)						x
(Siddiqi et al. 2017)	x					
(Stark et al. 2014)						x
(Tolio et al. 2017)						x
(X. V. Wang and Wang 2018)	x					
(B. Xu 2016)						x
(Yeo, Pepin, and Yang 2017)						x
Total	4	4	1	1	1	7

Table 16. I4.0 technologies enabling circular business models.

Reference	SIM	AM	BDA	IOT	Generic
(Alexandris et al. 2018)	x				
(Antikainen, Uusitalo, and Kivikytö-Reponen 2018)					x
(Askoxylakis 2018)				x	
(Bianchini et al. 2018)					x
(Bressanelli et al. 2018b)					x
(Bressanelli et al. 2018a)					x
(Chiappetta Jabbour et al. 2017)			x		
(de Man and Strandhagen 2017)					x
(Gorissen, Vrancken, and Manshoven 2016)					x
(Jin et al. 2014)					x
(Kölsch et al. 2017)					x
(A. Q. Li and Found 2017)					x
(Lieder, Asif, and Rashid 2017)	x				
(Lieder et al. 2017)	x				
(Mattos Nascimento et al. 2018)		x			
(Millard et al. 2018)		x			
(Moreno et al. 2018)	x				
(Moreno et al. 2017)		x			
(Panarotto, Wall, and Larsson 2017)	x				
(Pistol, Bucea-Manea-Tonis, and Bucea-Manea-Tonis 2017)				x	
(Prendeville et al. 2016)					x
(Simons 2017)	x				
(Soroka et al. 2017)			x		
(Ünal, Urbinati, and Chiaroni 2018)					x
Total	6	3	2	2	11

Table 17. I4.0 technologies enabling smart services.

Reference	CPS	BDA	IOT	SIM	Generic
(Alcayaga and Hansen 2017)			x		
(Ashjaei and Bengtsson 2017)				x	
(Baines 2015)					x
(Borangiu, Thomas, and Trentesaux 2013)				x	
(Caggiano 2018)	x				
(Franquesa and Navarro 2018)		x			
(Franquesa, Navarro, and Bustamante 2016)		x			
(Herterich, Uebernickel, and Brenner 2015a)	x				
(Herterich, Uebernickel, and Brenner 2015b)	x				
(Herterich et al. 2015)	x				
(Jardim-Goncalves, Romero, and Grilo 2017)	x				
(Kowalkowski et al. 2017)					x
(Lee, Bagheri, and Kao 2015)	x				
(Lindström et al. 2018)		x			
(Spring and Araujo 2017)			x		
(Verdugo Cedeño et al. 2017)			x		
(Yu, Xu, and Lu 2015)	x				
Total	7	3	3	2	2

Millard et al. 2018). BDA can be useful for assessing innovative business models through integrative frameworks (Chiappetta Jabbour et al. 2017) or for particular types of companies (Soroka et al. 2017). Finally, the IoT has been described as a good way to link the CE and I4.0 (Askoxylakis 2018). These contributions showed that more efficient exploitation of field data could improve the overall circularity of a system.

Linked to CBMs, authors and scholars' works about SSs follow the same logic (see Table 17). However, CPSs were considered by experts the most common method for gathering data from the field. They can be exploited for developing several types of smart services (Herterich, Uebernickel, and Brenner 2015a; Jardim-Goncalves, Romero, and Grilo 2017; Yu, Xu, and Lu 2015), for example, cloud-based smart diagnostic services for manufacturing processes (Caggiano 2018) or health management and prognostics (Lee, Bagheri, and Kao 2015). Only in a few cases were BDA, the IoT, and simulation

Table 18. I4.0 technologies supporting supply chain management.

Reference	SIM	IOT	BDA	Generic
(He, Xu, and Xu 2010)	x			
(Kache and Seuring 2017)			x	
(Sarkis and Zhu 2018)				x
(Schäfers and Walther 2017)	x			
(Sun and Wang 2011)	x			
(Tjahjono et al. 2017)		x		
(J. Xu 2009)		x		
(Zhang et al. 2016)	x			
(Zhao, Dang, and Zhang 2011)	x			
Total	5	2	1	1

considered as alternatives. BDA was used to develop algorithms that estimate the use value of devices (Franquesa, Navarro, and Bustamante 2016; Franquesa and Navarro 2018) or support cloud-based service platforms (Lindström et al. 2018). Again, the IoT was mainly adopted for developing service-based business models (Alcayaga and Hansen 2017; Spring and Araujo 2017; Verdugo Cedeño et al. 2017). Finally, simulation was exploited for developing smart maintenance management services, for example, through fog computing (Ashjaei and Bengtsson 2017). Other works did not focus on a specific I4.0 technology. The most frequently discussed type of SSs was innovative maintenance management practices enabled by I4.0 technologies.

4.2.8. Supply chain management

Another area of focus for scholars in which I4.0 technologies could support the adoption of CE was related to SCM, particularly in the definition of closed-loop chains (see Table 18). Given the general complexity of issues related to SCM, simulation was seen by experts as the most valuable way to try to adopt more circular practices. For this aim, He, Xu, and Xu (2010) and Sun and Wang (2011) described probabilistic neural networks for green supply chain performance evaluations, Schäfers and Walther (2017) exploited it to model material flows and Zhao, Dang, and Zhang (2011) and Zhang et al. (2016) analysed industrial networks. The IoT and BDA were also described by experts. These technologies were mainly described as new ways for improving information transparency within the supply chain (Tjahjono et al. 2017; Kache and Seuring 2017) or evaluating supply chain performance (J. Xu 2009). However, these technologies can generally function like data gathering and data management instruments supporting simulation processes.

5. Discussion

To summarise the findings presented in the previous section, the most common way scholars described the connection between the CE and I4.0 was either the influence of I4.0 on the development of new kinds of CBMs or the potential benefits resulting from the digitalisation of processes, mainly in terms of innovative lifecycle management strategies. No single I4.0 technology was prevalent. Most experts considered all of them together. Some additional information could be gathered only by selecting a dedicated area of either the CE or I4.0.

From the CE perspective, the focus was on I4.0 technologies. Information in the previous tables confirmed that the I4.0 technologies described in this paper could have a positive effect on the lifecycle management of products. Only in the case of BDA was this hypothesis not verified. Then, depending on each I4.0 technology, other topics were prevalent. AM was clearly related to recycling of products and materials, allowing an innovative way to reintroduce them in the market. CPSs strongly support the development of innovative services, especially for maintenance applications. Simulation is logically related to either better management of complex supply chains (e.g. closed-loop chains) or the remanufacturing of complex products. Finally, BDA and the IoT, contrarily, do not offer a similar clearness, and they can affect the CE in several ways, such as digitalisation of CE practices, lifecycle management, exploitation of natural resources, development of CBMs, SSs, and SCM (Cattelan Nobre and Tavares 2017; Holligan, Hargaden, and Papakostas 2017; Jose and Ramakrishna 2018; Askoxylakis 2018; Alcayaga and Hansen 2017; Tjahjono et al. 2017).

From the I4.0 perspective, the focus is on CE-related topics. It is easier to identify what I4.0 technology better fits with a specific CE-related area. AM, BDA, and the IoT were the most frequently described I4.0 pillars in terms of digital enablers of CE. Again, CPSs were the most described in terms of I4.0 technologies supporting innovative lifecycle management strategies, followed by AM, the IoT, and simulation. New forms of disassembly are supported by BDA, and AM is suitable for new types of reuse and recycling processes. The IoT and BDA, together, can improve efficient exploitation of natural

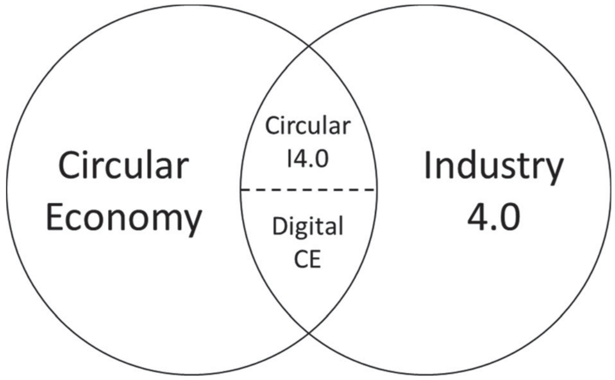

Figure 6. The hybrid categories of Circular I4.0 and Digital CE.

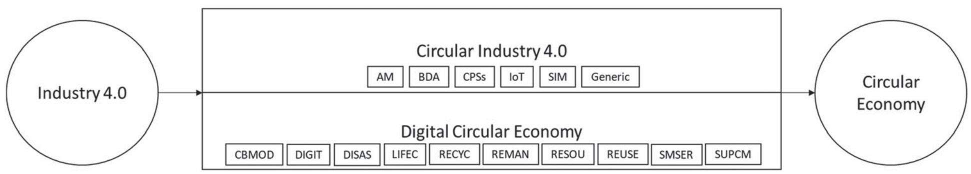

Figure 7. I4.0 like an enabler of CE.

resources. Simulation and AM fit better with new forms of remanufacturing processes. Simulation, BDA and the IoT support the development of CBMs, and together with CPSs, the development of new services. Finally, simulation and the IoT better fit with the management of complex processes and supply chains.

The two perspectives are shown in Figure 6. The framework of analysis considered the two concepts of the CE and I4.0. However, as shown previously, depending on the perspective of the analysis (I4.0-based versus CE-based), the integration of the CE with I4.0 can be described in a different way. First, the focus was on I4.0 technologies, and the intersection was constituted by papers that discussed the 'digital CE.' Second, the focus is on CE-related areas, and the intersection was constituted by papers that discussed 'circular I4.0.'

What is clearly shown by the international literature is the type of relation driving the CE and I4.0. In general terms, I4.0 is known as an enabler of the CE, and not vice versa. In addition, there is an evident gap in the literature about the type of contribution that I4.0 can offer to the CE. This way, the previous picture can be reframed as in Figure 7. There is also a clearer view of the sub-elements of Digital CE and Circular I4.0 described by the scientific literature.

The systematic literature review described in this paper showed that the greatest number of documents followed a theoretical perspective. Many benefits and strategies potentially exploitable and achievable from the integration of the CE and I4.0 have been discussed in the literature. Analytical works focused on best practices presenting some issues about the opportunity to replicate their performance. Generally, these works focused on a specific company or process, and could hardly be generalised to an entire industrial sector. The selected companies were either too big or too specialised to be considered generic SMEs. Thus, their use as a reference point for newcomers is limited. From this perspective, there is a critical need for new works explaining in practice to newcomers how to implement the CE and I4.0 principles in different markets.

6. Conclusions

The paper assessed the relation between I4.0 and CE principles through a systematic literature analysis. To identify overlap, the current state of knowledge was assessed in detail. Documents were classified in two hybrid categories, named Circular I4.0 and Digital CE. Subsequently, an innovative framework mapping the new integrated perspective was developed. Results demonstrated that, depending on the view, it is possible to show a specific set of relations. Considering how I4.0 technologies influence the CE, it is possible to confirm that I4.0 technologies can have a positive effect on the lifecycle management of products. Only in the case of BDA was this hypothesis not verified. Then, depending on each I4.0 technology, other topics were prevalent. AM is related to recycling of products and materials. CPSs support the development of innovative services, especially for maintenance applications. Simulation is related to either better management of complex supply chains or the remanufacturing of complex products. Finally, BDA and the IoT do not offer a similar clearness, and they can affect the

CE in several ways. Considering, instead, CE-related topics, it is easier to identify what I4.0 technology better fits with a specific CE-related area. AM, BDA, and the IoT were the most frequently described digital enablers of the CE. CPSs are considered good supporting elements for developing innovative lifecycle management strategies. BDA supports new forms of disassembly, and AM is suitable for new types of reuse and recycling processes. The IoT and BDA, together, can improve efficient exploitation of natural resources. Simulation and AM better fit with new forms of remanufacturing processes. Simulation, BDA and the IoT support the development of CBMs, and together with CPSs, the development of new services. Finally, simulation and the IoT better fit with the management of complex supply chains.

6.1. Managerial insights

The proposed perspectives offer the possibility for managers, executives, and practitioners operating in CE and I4.0 fields to consider two possible alternatives when implementing the CE in practice, by exploiting the potential offered by I4.0 technologies. First, by adopting the circular I4.0 perspective, managers can choose their CE targets, and according to them, identify the set of I4.0 technologies that best support the managers' strategy. Second, by adopting the digital CE perspective, managers can define the set of I4.0 technologies that support their transition to the CE and verify over time their influence on CE performance.

6.2. Research perspectives

Although several relations were identified in this paper, there are many unsolved research areas that require additional research in the CE and I4.0 fields. First, there is still a lack of empirical evidence on how CE and I4.0 principles are applied in practice by companies. This issue calls for a better understanding of how I4.0 technologies can properly support stakeholders (e.g. customers and suppliers) involved in CBMs, by enabling and supporting the active involvement of external users during all the phases of a circular lifecycle. Second, when adopting I4.0 technologies, CBMs involving a large and complex system of actors might present additional challenges than those related to the embedded inertia of the system itself. Third, further investigation is needed to understand the potential impact of I4.0 technologies in designing CBMs. Finally, the practical implementation of Circular I4.0 and Digital CE requires continuous monitoring and control of the entire lifecycle, becoming circular and integrated, enabled by I4.0 technologies. We hope that this work, although preliminary, has provided a reference framework for further investigations.

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