Review

The Role of Digital Technologies in Operationalizing the Circular Economy Transition: A Systematic Literature Review

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Abstract: The enabling role of Digital Technologies towards the Circular Economy transition has been recognized. Nonetheless, to support the transition, the operationalization of the discourse is still needed. The present study performs a systematic literature review, deepening the knowledge on the role of Digital Technologies in operationalizing the Circular Economy transition. The analysis is shaped according to the ReSOLVE framework, as it has been recognized as able to operationally guide industrial firms towards the Circular Economy transition. Despite the broad focus on the topic by the extant literature, the results of the analysis show limited Circular Economy aspects addressed and specific technologies considered, making it difficult to have a complete overview on the implementation of Digital Technologies in the Circular Economy transition, operatively addressing it. Shortcomings are identified regarding the lack of an integrated and holistic analysis of the relationships, the need for investigating the decision-making process and specific Circular Economy practices, all from an empirical perspective. The paper eventually suggests streams for further research while offering theoretical and practical implications.

Keywords: circular economy; ReSOLVE; Industry 4.0; Digital Technologies; systematic literature review

1. Introduction

Deep and rapid economic, environmental and social changes are taking place, shaping the political, managerial and academic discourses [1,2]. The industry is not exempt from these current macro-trends and opportunities arise for two specific paradigms, namely Circular Economy (CE) and Industry 4.0 (I4.0) [3,4].

CE focuses on closing the material loop, shifting from a linear economy to a circular one, decreasing material extraction, waste disposal and, consequently, environmental pressure [5,6]. CE can be applied at different levels, namely micro (single firm, from a single product to the advertisement), meso (industrial systems and networks) and macro (society or country) [6]. Although focusing more on an environmental perspective, it is impossible to separate CE from the economy and society, which links CE to the concept of strong sustainability [7,8]. On the other hand, I4.0 enables intelligent factories and products, providing opportunities for enhanced performance in terms of production activities, organizational strategies, business models and skills [9,10]. A central role in I4.0 is played by Digital Technologies (DTs) [11].

The two concepts have been largely addressed in a separate manner; nonetheless, in the last years, they started being integrated [12]. From a general perspective, it is widely accepted that DTs can enable the CE transition [13]. DTs indeed allow more efficient and

flexible processes [14], while also providing transparent access to product data and resource consumption [13]. Despite the growing interest in the role of DTs as an enabler for CE transition, some points remain still not properly addressed. Particularly, focusing on the CE micro level, the need for making the overall discourse more operational, addressing the different phases of the CE transition [15], has been underlined [16]. The Regenerate, Share, Optimize, Loop, Virtualize, Exchange (ReSOLVE) framework has been identified as an important tool to operationally guide industrial firms [17]; despite its relevance, only a few studies so far have focused on the enabling role of DTs in the context of the ReSOLVE framework. The majority of the contributions, indeed, still focus only on specific CE aspects, such as recycling or resource efficiency. On the other hand, contributions focusing on the ReSOLVE consider the role of very few and specific DTs. Both situations underlined the lack of an overall, comprehensive and integrated approach towards the investigation of the role of DTs as an enabler for CE.

Based on the considerations above, the present work aims at conducting a systematic literature review, so to better understand the possible role of DTs within the context of the ReSOLVE framework. To the best of the authors' knowledge, such an analysis is still missing, and a detailed identification of the relationships among all the available DTs and the action areas of the ReSOLVE framework needs to be investigated.

The remainder of the paper is structured as follows. We provided a background on the frameworks for the analysis of CE and DTs (Section 2). Following, we described the systematic literature review methodology, clearly outlining the steps (Section 3). After a descriptive evaluation of the results (Section 4), we analyzed the literature in terms of emerging themes, addressing the possible role of DTs in the context of the ReSOLVE framework (Section 5). We then discussed some specific issues for which additional research is necessary (Section 6). Finally (Section 7), we outlined pivotal implications of our study and paved the way for further research.

2. Materials

The section introduces the frameworks used in the present work for the analysis of the literature, in terms of content for both CE and DTs. As anticipated in the previous section, to understand if and how DTs can enable the CE transition, we focused on the relationship between DTs and the ReSOLVE framework. Particularly, as a limited set of contributions addresses directly the ReSOLVE framework and its different action areas, we decided to further link specific CE aspects to the ReSOLVE areas.

2.1. Circular Economy

Despite the soaring relevance of CE in the current debate, a common definition and agreement on pivotal concepts is not easy to find [6,18]. Nonetheless, to allow the CE transition in the industrial sector, the concept must be disclosed from a concrete viewpoint; this would support industrial firms to fully exploit resources while maintaining their value and minimizing environmental impact [19].

Among the different frameworks conceptualizing the CE, the discourse has been largely focused on the 3Rs (Reduce, Reuse, Recycle) model [20]. The model soon evolved into the 6Rs model (Redesign, Reduce, Reuse, Remanufacture, Recycle, Recover) and then into the 9(10)Rs model (Refuse, Redesign, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) [6,21]. The Rs or waste hierarchy models have been included in the butterfly diagram [22] proposed by the Ellen MacArthur Foundation [23]. Following a cradle-to-cradle approach, the diagram highlights the difference between the loop for biological and technical nutrients. As for the technical loop, activities such as reuse, refurbishment and remanufacturing are strongly recommended [24]. Focusing on the need for industrial firms to move from linear to circular modes of production, and particularly on the opportunities deriving by the technical loop [25], the Ellen MacArthur Foundation [26] developed the ReSOLVE framework. The framework entails major circular

business opportunities [27]. It proposes six areas of actions for implementing the CE transition, namely: Regenerate, Share, Optimize, Loop, Virtualize and Exchange (Figure 1).
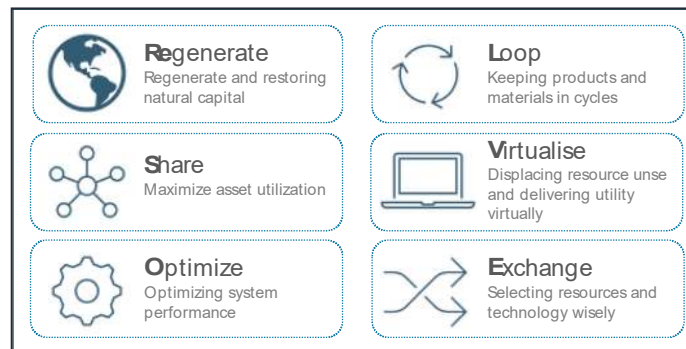

Figure 1. The Regenerate, Share, Optimize, Loop, Virtualize, Exchange (ReSOLVE) framework. Adapted from [26,28].

Several strategies can be related to the six areas [27,29], allowing the definition of operational actions for the CE transition [30]. A comprehensive and largely shared overview of possible CE operational actions for the CE transition is offered by Rosa et al. [31], who identified 10 aspects: Circular Business Model (CBM), i.e., the overarching concept; Digital Transformation (DIGIT); Disassembly (DISAS); Lifecycle Management (LIFEC); Recycling (RECYC); Remanufacturing (REMAN); Resource Efficiency (RESOU); Reuse (REUSE); Smart Services (SMSER) and Supply Chain Management (SCM). Leveraging on the indications provided by Kalmykova et al. [29] and Lewandowski [27], we linked the 10 CE aspects to the ReSOLVE areas (Table 1). This operation would allow a clear classification of the literature according to the ReSOLVE areas.

Table 1. Linkage of CE aspects with ReSOLVE's actions.

Circular Business Models	
ReSOLVE Action Areas	**CE Aspects**
Regenerate	Lifecycle management
Share	Reuse
Optimize	Resource efficiency Supply chain management
Loop	Disassembly Remanufacturing Recycling
Virtualize	Smart services
Exchange	Digital transformation

2.2. Digital Technologies

The largest shared classification for DTs, see for example [32,33], is the one proposed by Rußmann et al. [14]. According to this classification, nine DTs can be identified (Figure 2):

- Internet of Things (IoT): technologies allowing the interaction, cooperation, collection and exchange of data among people, devices, things or objects through the use of modern wireless telecommunications [34];
- Big data analytics (BDA): information assets characterized by high volume, velocity and variety, requiring specific technology and analytical methods for being transformed into value [35];

- Cloud/fog/edge technologies (CLOUD): architectural models enabling pervasive, convenient and on-demand network access to shared resources such as networks or servers [36];
- Cybersecurity and blockchain (CYB): technologies, tools, guidelines and policies guaranteeing the protection of the cyber environment, allowing confidentiality, integrity and availability of data [37];
- Horizontal/Vertical system integration (HVSYS): universal data integration network, enabling an automated value chain within or among firms by means of linking products, plants, manufacturers, customers and suppliers [38];
- Simulation (SIM): a real-time reflection of the physical world (products, machines, human beings) in virtual models; it can allow testing and optimizing systems before implementing the physical change [31];
- Augmented reality (AR): technologies providing an interactive computer simulation, immersing the user in a programmed environment, simulating a sense of reality whether in the sight, in the hearing or the tactile sense [39];
- Autonomous robots (ROBs): robots able to operate completely autonomously, to interact with each other and to cooperate with human beings; sensors and control units facilitate the autonomous decision-making process and symbiotic work with humans [40];
- Additive manufacturing (AM): production of items directly from CAD models, with fabrication performed layering the material; AM offers the valuable ability to build parts with geometrical and material complexity, not feasible with traditional manufacturing processes [41].
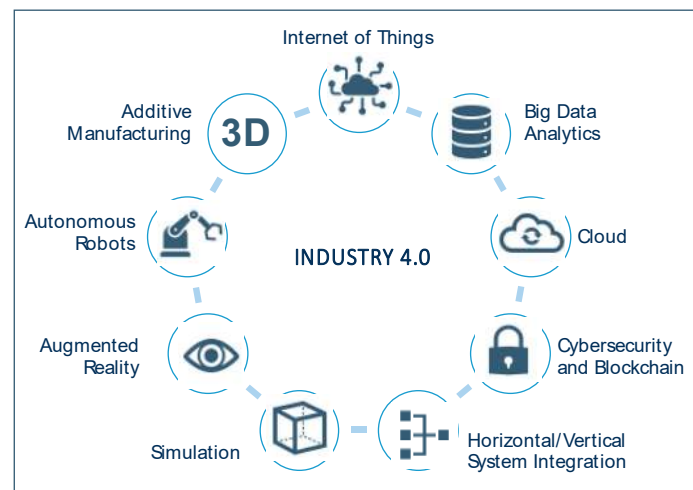
Figure 2. The nine Digital Technologies supporting Industry 4.0. Adapted from [14].

3. Methods

The present study employs a systematic literature review to identify, select and critically appraise relevant research. To guarantee a scientific and replicable approach, we referred to the steps proposed by Tranfield and Denyer [42], proceeding through (i) questions formulation, (ii) source identification, (iii) study selection and evaluation, (iv) analysis and synthesis and (v) reporting and using results. Additionally, to increase clarity and transparency, we used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)statement as the backbone of our analysis [43].

3.1. Question Formulation

We formulated the question according to the CIMO logic [42], combining a problematic context (C), for which the design proposition suggests a certain intervention (I), to produce, through specified generative mechanisms (M), the intended outcome (O) [44].

RQ: *How (M) and in which condition (C) DTs (I) can enable the CE transition (O)?*

3.2. Source Identification

For source identification, we investigated the Scopus database [4,45,46]. We performed a keyword-based search, interconnecting keywords deriving from the two paradigms, using terms related to CE (circular economy, circularity) and terms related to DTs (digital*, Industry 4.0, IoT, Internet of Things, Artificial Intelligence, AI) For the latter group of keywords, we selected the most frequent terms used in similar works [47,48]; additionally, we based our choice on the insights provided by Munirathinam [49] and Lee et al. [50], according to whom Internet of Things and Artificial Intelligence could be possibly used as synonymous of Industry 4.0. As for exclusion criteria, we limited the analysis to contributions published in English from the year 2000 onwards. We thus performed the following query: (TITLE-ABS-KEY ("circular economy") OR TITLE-ABS-KEY ("circularity")) AND (TITLE-ABS-KEY ("digital*") OR TITLE-ABS-KEY ("industry 4.0") OR TITLE-ABS-KEY ("iot") OR TITLE-ABS-KEY ("internet of things") OR TITLE-ABS-KEY ("artificial intelligence") OR TITLE-ABS-KEY ("ai")) AND PUBYEAR > 1999 AND LIMIT-TO (LANGUAGE, "English"). The query led to 836 contributions (the search was first performed on December 4th, 2020 and then updated on February 11th, 2021). Figure 3 describes the steps followed in the selection/exclusion of contributions in the identification phase.

3.3. Source Selection

We proceeded with the selection of contributions according to the phases of the PRISMA methodology [51], namely screening, eligibility and inclusion (Figure 3). Concerning the screening, we aimed at discharging contributions (i) out of scope, addressing for example agriculture, construction, geometrical measurement or water; (ii) focusing only on CE; (iii) focusing only on DTs. Figure 3 describes the steps followed for the selection/exclusion of contributions in the screening, eligibility and inclusion phases. To avoid bias, all the phases were conducted autonomously by four reviewers; different results were confronted and discussed, reaching a common agreement. Based on [52,53], we then applied the snowball method, identifying three additional contributions; the contributions were not previously identified as (i) not available on Scopus on the date the last update was performed (n = 1) [54]; (ii) employing specific keywords not included in our query (n = 2) [4,55].
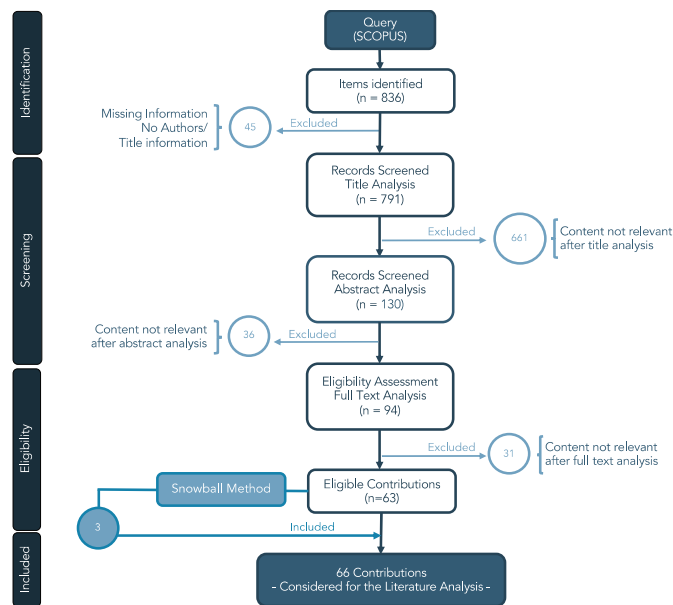
Figure 3. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. The figure reports the different phases of the PRISMA methodology.

The retrieved contributions were classified according to critical dimensions of analysis (Table 2): general information (author; year of publication; journal; document type); bibliometric information (global citations score (GCS) - as by February 11th, 2021; GCS divided by the number of years since publication); content (CE aspects; DTs; type of study; empirical methodology); context (geographical area; sector; size)—see also [56–58]. Based on the discussion provided in Section 2.1, the CE aspects considered were general, ReSOLVE, CBM, DIGIT, DISAS, LIFEC, RECYC, REMAN, RESOU, REUSE, SMSER and SCM. Based on the discussion provided in Section 2.2, the DTs considered were general, IOT, BDA, CLOUD, CYB, HVSYS, SIM, AR, ROB and AM.

3.4. Data Analysis, Reporting and Using of Results

A critical analysis of the retrieved contributions paves the road to a discussion of the data, identifying key messages and areas for which further additional research is necessary [56]. The appraisal was conducted through a descriptive analysis of the results (Section 4) and an evaluation of emerging themes (Section 5). The results deriving from the two analyses are integrated into an overall discussion (Section 6).

Table 2. Source evaluation. For the contributions considered for the review analysis, the table reports the following: general information: author, year of publication, journal, document type (JP: journal paper; CP: conference paper; BC: book chapter); bibliometric information: GCS, GCS/number of years since publication; content: CE aspects; DTs; type of study (R: review; C: conceptual; E: empirical); empirical methodology; context: geographical area, sector, size.

	General Information				Bibliometric Information			Content				Context		
Ref.	Authors	Year	Journal	Doc. Type	GCS	GCS/ Years Since Publ.	CE aspects	DTs	Type of Study	Empirical Methodology	Geogr. Area	Sector	Size
[48]	Awan et al.	2021	Bus. Strateg. Environ.	JP	1	1	General	IOT	R				
[9]	Massaro et al.	2021	Bus. Strateg. Environ.	JP	0	0	General	General	R				
[59]	Okorie et al.	2021	Bus. Strateg. Environ.	JP	0	0	CBM	General	E	Case Study (n = 5)		Manufacturing	
[60]	Ranta et al.	2021	Resour. Conserv. Recycl.	JP	1	1	CBM	General	E	Case Study (n = 5)	North Europe	Multiple	LEs
[61]	Rehman Khan et al.	2021	Int. J. Logist. Res. Appl.	JP	0	0	SCM	CYB	C/E	Survey (n = 290)		Manufacturing	
[54]	Upadhyay et al.	2021	J. Clean. Prod.	JP	0	0	SCM	CYB	R				
[62]	Bag et al.	2020	Resour. Conserv. Recycl.	JP	34	17	SCM	General	E	Survey (n = 112)	South Africa		
[63]	Bag et al.	2020	Resour. Policy	JP	6	3	SCM	General	E	Survey (n = 150)	South Africa		
[64]	Bag & Pretorius	2020	Int. J. Organ. Anal	JP	12	6	DIGIT	BDA	C				
[4]	Cioffi et al.	2020	Appl. Sci.	JP	1	0,5	CBM	General	R				
[65]	Cwiklicki & Wojnarowska	2020	Eng. Econ.	JP	0	0	General	General	R				
[66]	De Marchi & Di Maria	2020	*Book Chapter*	BC	0	0	RESOU, RECYC	General	E	Survey (n = 1229)	Italy	Manufacturing	SMEs
[67]	Demestichas & Daskalakis	2020	Sustain.	JP	2	1	DIGIT	General	R				
[68]	Dev et al.	2020	Resour. Conserv. Recycl.	JP	37	18,5	SCM, REMAN	HVSYS, AM	C				
[69]	Esmaeilian et al.	2020	Resour. Conserv. Recycl.	JP	8	4	RESOU, SCM	IOT, CYB	R				
[70]	Favi et al.	2020	Procedia CIRP	CP	1	0,5	DISAS, REMAN	BDA	C			Nuts disassembly	
[71]	Getor et al.	2020	Resour. Conserv. Recycl.	JP	0	0	RECYC	BDA	C			Plastic waste	
[72]	Ghoreishi & Happonen	2020	*Conference Proceedings*	CP	2	1	CBM	BDA	C/E	Case Study (n = 3)	Finland	Manufacturing	LEs

[15]	Ghoreishi & Happonen	2020	*Conference Proceedings*	CP	3	1,5	ReSOLVE	IOT, BDA, CLOUD, AM	R				
[73]	Ingemarsdotter et al.	2020	Resour. Conserv. Recycl.	JP	5	2,5	CBM	IOT	E	Case Study (n = 1)	Europe	LED lighting	LEs
[74]	Kintscher et al.	2020	J. Commun.	JP	0	0	RECYC	General	C/E	Example from Lit.		Electric vehicle	
[75]	Kouhizadeh et al.	2020	Prod. Plan. Control	JP	21	10,5	ReSOLVE	CYB	C	Example from Lit.			
[76]	Kravchenko et al.	2020	*Conference Proceedings*	CP	0	0	DIGIT	AM	C				
[77]	Kristoffersen et al.	2020	J. Bus. Res.	JP	4	2	DIGIT	IOT, BDA	C			Manufacturing	
[78]	Mboli et al.	2020	*Conference Proceedings*	CP	2	1	SCM	IOT	C/E	Case Study (n = 1)		Coffee machine manufacturing	LEs
[79]	Moller	2020	*Conference Proceedings*	CP	0	0	DIGIT	General	C				
[80]	Nobre & Tavares	2020	Johnson Matthey Technol. Rev.	JP	3	1,5	ReSOLVE	IOT, BDA	R				
[81]	Nobre & Tavares	2020	Johnson Matthey Technol. Rev.	JP	2	1	ReSOLVE	IOT, BDA	R				
[82]	Piscitelli et al.	2020	Procedia Manuf.	CP	2	1	CBM	General	R				
[83]	Poschmann et al.	2020	Chemie Ing. Tech	JP	3	1,5	DISAS	ROB	R				
[84]	Rajput & Singh	2020	J. Clean. Prod.	JP	2	1	DIGIT	General	C				
[85]	Rocca et al.	2020	Sustain.	JP	8	4	DISAS	SIM, AR, ROB	E	Modelling		WEEE	
[31]	Rosa et al.	2020	Int. J. Prod. Res.	JP	41	20,5	General	General	R				
[86]	Rossi et al.	2020	Sustain.	JP	3	1,5	CBM	General	C/E	Example from Lit.	Europe	Manufacturing	LEs
[87]	Uçar et al.	2020	Procedia CIRP	CP	2	1	CBM	IOT, BDA, CLOUD	E	Case Study (n = 3)	Europe	Multiple	
[88]	Yadav et al.	2020	J. Clean. Prod.	JP	40	20	SCM	General	C/E	Experts		Automotive	
[89]	Alcayaga et al.	2019	J. Clean. Prod.	JP	30	10	LIFEC, REUSE, REMAN, RECYC, SMSER	IOT, BDA	R				
[90]	Cezarino et al.	2019	Manag. Decis.	JP	15	5	DIGIT	General	C		Emerging economies		
[55]	Chiappetta Jabbour et al.	2019	Technol. Forecast. Soc. Change	JP	72	24	ReSOLVE	BDA	C				
[91]	Charnley et al.	2019	Sustain.	JP	11	3,67	REMAN	SIM	E		UK	Automotive	LEs

Ref	Author	Year	Journal	Type	Cit	Cit/yr	Strategy	Technology	C/E/R	Method	Country	Sector	Size
[12]	Chauhan et al.	2019	Benchmarking An Int. J.	JP	15	5	RESOU, DIGIT	General	C				
[92]	Garcia-Muiña et al.	2019	Soc. Sci.	JP	24	8	RESOU	IOT	E	Case Study (n = 10)	Italy	Ceramic	
[93]	Garrido-Hidalgo et al.	2019	Comp. Ind.	JP	14	4,67	SCM	IOT, CLOUD	E	Case Study (n = 1)		WEEE	
[94]	Gligoric et al.	2019	Sensors	JP	11	3,67	LIFEC	IOT	C/E	Modelling	Austria	Manufacturing	
[95]	Ingemarsdotter et al.	2019	Sustain.	JP	8	2,67	CBM, LIFEC, RE-USE, RESOU, RE-MAN	IOT	C	Example from Lit.			
[96]	Kerin & Pham	2019	J. Clean. Prod.	JP	41	13,67	DISAS, REMAN	AM, IOT, AR	R				
[97]	Moreno et al.	2019	Smart Innov. Syst. Technol.	JP	9	3	SCM	General	E	Case Study (n = 3)	UK	Manufacturing	LEs
[98]	Nascimento et al.	2019	J. Manuf. Technol. Manag.	JP	99	33	CBM	IOT, AM	C				
[99]	Pham et al.	2019	Sustain.	JP	17	5,67	SMSER	IOT, CLOUD	E	Case Study (n = 1)	Taiwan	Electric vehicle	
[100]	Rajput & Singh	2019	Benchmarking An Int. J.	JP	59	19,67	DIGIT	General	C				
[101]	Rajput & Singh	2019	Int. J. Inf. Manage.	JP	22	7,33	SCM	General	E	Survey (n = 161)			
[102]	Riesener et al.	2019	*Conference Proceedings*	CP	0	0	LIFEC	General	C				
[103]	Sarc et al.	2019	Waste Manag.	JP	28	9,33	RECYC	IOT, ROB	R			Waste management	
[104]	Väisänen et al.	2019	*Conference Proceedings*	CP	0	0	DIGIT	General	C				
[13]	Antikainen et al.	2018	Procedia CIRP	CP	44	11	CBM	General	E	Experts			
[105]	Bianchini et al.	2018	*Conference Proceedings*	CP	6	1,5	LIFEC, RESOU, SMSER, DIGIT	General	C/E	Example from Lit.		Manufacturing	
[106]	Bressanelli et al.	2018	Sustain.	JP	94	23,5	CBM	IOT, BDA	E	Case Study (n = 1)	Italy	Household appliances	SMEs
[107]	Bressanelli et al.	2018	Procedia CIRP	CP	28	7	CBM	IOT, BDA	E	Case Study (n = 1)	Italy	Household appliances	SMEs
[17]	Lopes de Sousa Jabbour et al.	2018	Ann. Oper. Res.	JP	183	45,75	ReSOLVE	IOT, CLOUD, AM	C				
[108]	Makarova et al.	2018	*Conference Proceedings*	CP	0	0	SCM	BDA, HVSYS	C			Automotive	LEs

[109]	Neligan	2018	Intereconomics	JP	10	2,5	RESOU	General	E	Survey (n = 600)	Germany	Manufacturing	SME; LEs
[21]	Okorie et al.	2018	Energies	JP	27	6,75	General	General	R				
[16]	Nobre & Tavares	2017	Scientometrics	JP	99	19,8	DIGIT	IOT, BDA	R				
[110]	Pagoropoulos et al.	2017	Procedia CIRP	CP	73	14,6	DIGIT	General	R				
[111]	Moreno & Charnley	2016	*Conference Proceedings*	CP	27	4,5	DIGIT	General	C/E	Example from Lit.		Manufacturing	
[112]	Reuter	2016	Metall. Mater. Trans. B	JP	37	6,17	RESOU, DIGIT	IOT, BDA	C		Germany	Metallurgy	

4. Digital Technologies Enabling the CE Transition: Descriptive Analysis of Results

4.1. Analysis of General Information

The temporal distribution of the contributions shows a more than linear growth, with 85% of them (n = 53) published from 2019 on, highlighting an increasing interest (Figure 4).
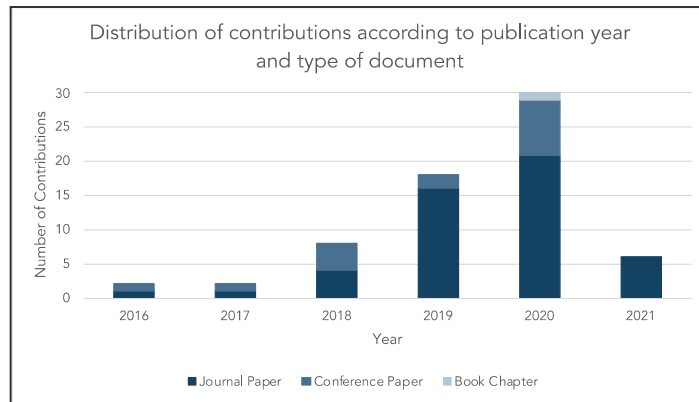
Figure 4. Distribution of the reviewed contributions according to publication year and type of document.

Considering the journal papers, the most recurrent Journals are *Sustainability* (Switzerland) (n = 7) and *Resources, Conservations and Recycling* (n = 6). The distribution shows how the topic has been mainly addressed by sources at the intersection of management- and environment-related areas (Figure 5).
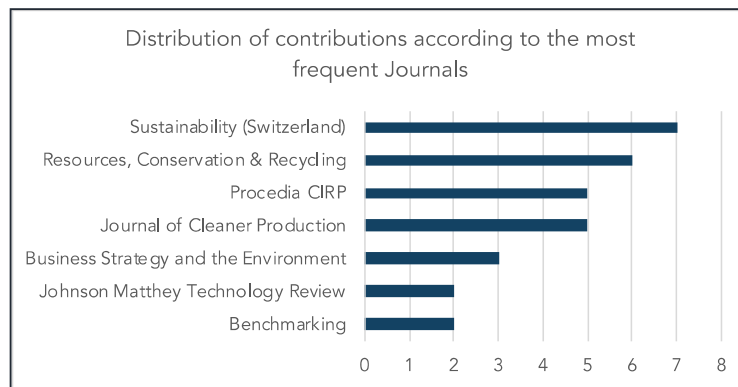
Figure 5. Distribution of the reviewed contributions according to the most frequent journals.

In terms of authorship, 188 different authors were identified; 82% of the authors (n = 154) participated in the discourse with 1 contribution, and 16% (n = 30) with 2 contributions. Nine authors contributed with 3 (Bag S.; Nobre G.C.; Okorie O.; Rajput S.; Singh S.P.; Tavares E.; Tiwari A.) or 5 contributions (Charnley F. Moreno M.) (Figure 6). The affiliations were in the United Kingdom (Charnley F., Moreno M. and Okorie O, Cranfield University until 2019, then University of Exeter; Okorie O. University of Sheffield until 2019, then University of Exeter), South Africa (Bag. S., University of Johannesburg), India (Rajput S. and Singh S.P., Indian Institute of Technology) and Brazil (Nobre G.C.; Tavares E., Federal University of Rio De Janeiro).
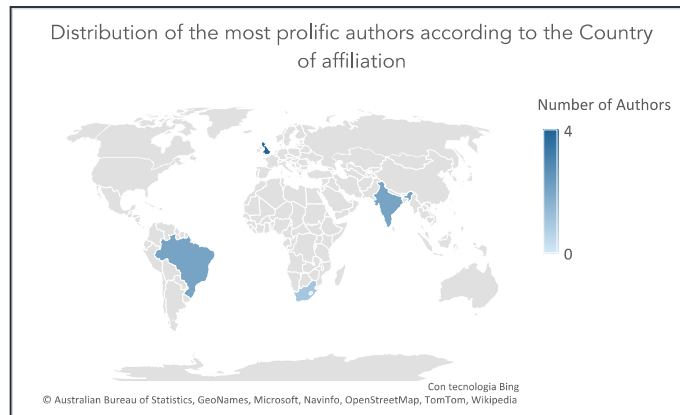
Figure 6. Distribution of the most prolific authors according to the country of affiliation.

4.2. Analysis of Bibliographic Information

As for the impact of the contributions, the highest GCS were 183 [17], 99 [16,98] and 94 [106]. The average GCS was about 21, and 89% of contributions received so far less than 50 citations. The GCS was divided by the number of years since publication to better appreciate the breakthrough literature. The highest scores were 146 [17], 33 [98] and 24 citations/year [55]. The average score was almost 7, and 79% of contributions received so far less than 10 citations/year. As the first ten contributions according to both the analyses were almost overlapping, the second analysis pinpoints the breakthrough potential of specific conceptual works [55,98] and particularly of the empirical ones by Yadav et al. [113] and Bag et al. [62] (Figure 7). However, numerous contributions from 2020 to 2021 received so far 0 citations, so the list of breakthrough contributions might change in a short time.
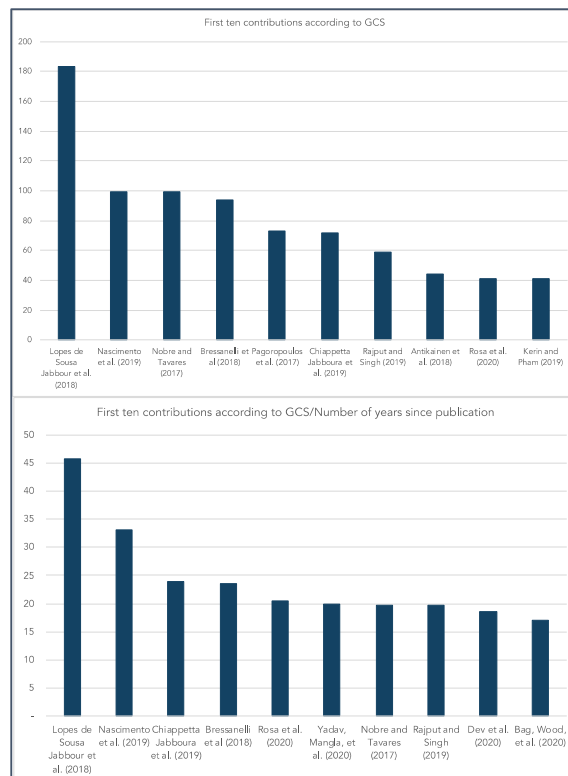

Figure 7. First ten contributions according to GCS and GCS/number of years after publication.

4.3. Analysis of Content

The most discussed CE aspects were related to CBM, SCM and DIGIT, while among the least discussed, REUSE and SMSER can be identified (Figure 8). Referring to the ReSOLVE areas, the main addressed ones were exchange and optimize, while among the least discussed, virtualize and share can be identified (Figure 8). As for DTs, the discourse was led by a general perspective on DTs. The most considered single DTs were IoT and DBA; nonetheless, the two of them were strongly interrelated, as IoT can be fully exploited only if the data collected are then processed with BDA [114] (Figure 9).
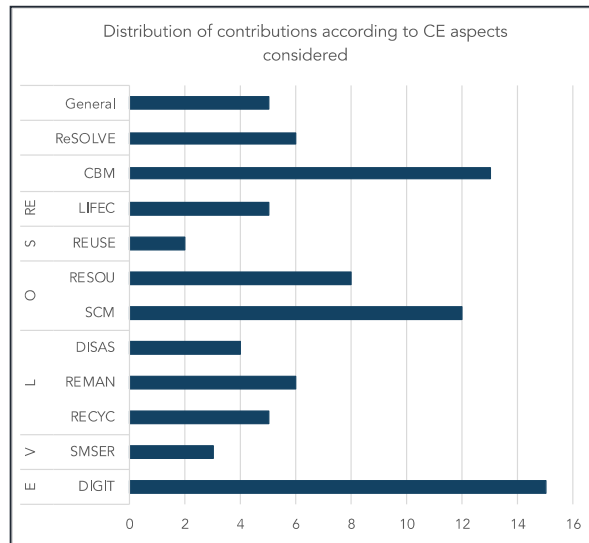

Figure 8. Distribution of the reviewed contributions according to CE aspects considered.
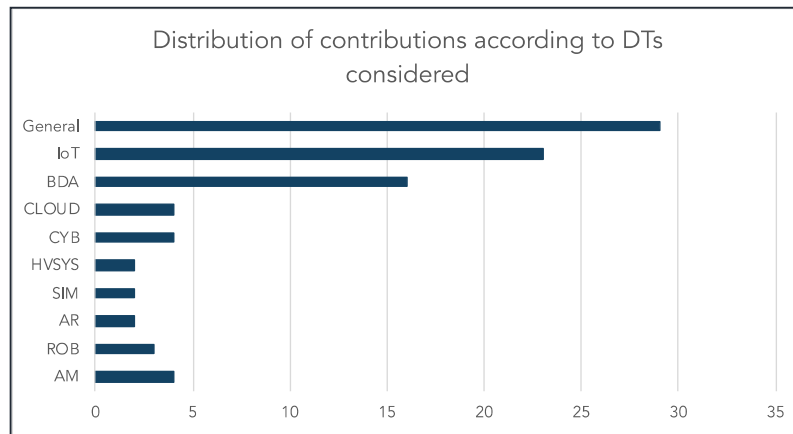

Figure 9. Distribution of the reviewed contributions according to DTs considered.

The integrated analysis of the two paradigms, considering how CE aspects and DTs have been integrated, offers sparks for further discussions (Figure 10): SCM was linked to the highest number of DTs and CYB particularly; DISAS and REMAN were linked with SIM and AR; DIGIT has been addressed from a general perspective in terms of DTs. Additionally, the literature has so far considered the impact of more DTs for the optimize and loop areas, compared to the other areas. Details on the specific relationship will be discussed in 5.1.

			Digital Tecnologies									
			General	IoT	BDA	CLOUD	CYB	HVSYS	SIM	AR	ROB	AM
Circular Economy		General	1	1								
		CBM	6	6	5	1						1
		ReSOLVE		4	3	2	1					2
	Re S	LIFEC	2	3	1							
		REUSE		2	1							
	O	RESOU	4	4	1		1					
		SCM	5	3	1	1	3	2				1
		DISAS		1	1				1	2	2	1
	L	REMAN		3	2			1	1	1		2
		RECYC	2	2	2						1	
	V	SMSER	1	2	1	1						
	E	DIGIT	10	3	4							1

Figure 10. Heatmap of the distribution of the reviewed contributions according to CE aspects and DTs considered.

In terms of the type of study, 58% of contributions were theoretical, both review (n = 19) or conceptual papers (n = 20); the remaining share was either empirical (n = 18) or theoretical with a following empirical application (n = 9) (Figure 11).
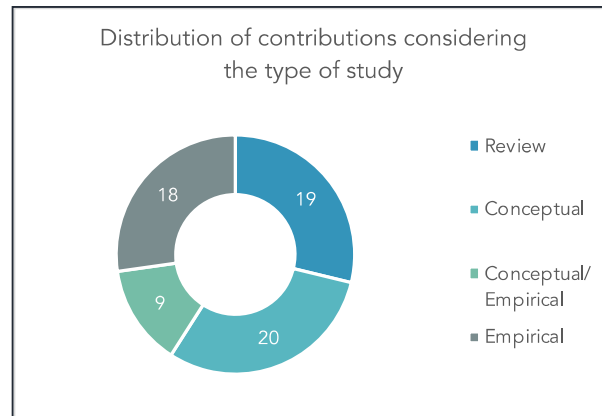

Figure 11. Distribution of the reviewed contributions according to the type of study.

Focusing on the methodology for empirical application (Figure 12), 43% of the contributions (n = 12) employed the case study methodology, followed by surveys or expert opinions. Interestingly, none of the contributions conducted more than 10 case studies, as the majority conducted 1 (n = 6) or 3 (n = 3) case studies.
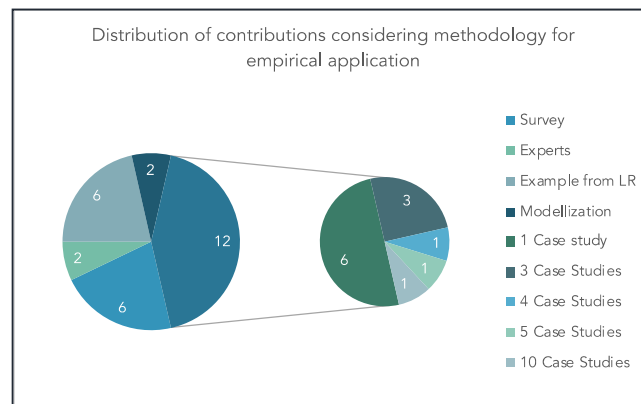

Figure 12. Distribution of the reviewed contributions according to the methodology employed for the empirical application.

4.4. Analysis of Context

Few contributions considered a specific context. In terms of geographical area, only 28% of contributions considered a specific one (n = 18), with a predominance of European countries (n = 14). As for the sector, 55% of contributions addressed a specific sector (n = 29), and most of them focused on the manufacturing sector in general. As for the size of firms, very few contributions considered a specific one, with 82% of contributions not providing any information. Some contributions nonetheless addressed specifically small and medium enterprises (SMEs) (n = 8), large enterprises (LEs) (n = 3) or both (n = 1).

5. Digital Technologies Enabling the CE Transition: Emerging Themes

This section discusses the qualitative findings deriving from the literature review, according to the guidelines provided in Table 1 and addressing the role of DTs in enabling the ReSOLVE framework. Although the relationship between DTs and the CE has been largely investigated, and specific connections have emerged, a general complete overview of the relations between the two topics has not been reached yet (Figure 10) [13,17]. Nonetheless, interesting points have emerged, starting from a consensus that DTs can act as an enabler for CE.

An in-depth analysis of the insights deriving from the reviewed contributions is offered in Table 3. Each contribution is analyzed according to context and motivation, main contribution, main findings, main limitations and main future research. The analysis provides an overview of the different application areas and outcomes of the extant literature; it is followed by an integrated presentation of the results according to the DTs' potentials in operationalizing the CE transition.

Table 3. In-depth analysis of the content**.** For the contributions considered for the review analysis, the table reports the following: context and motivation, main contribution, main findings, main limitations and main future research. Limitations in italic refer to limitations related to the specific aim of the present study according to the authors' perspective.

Ref.	Authors	Context and Motivation	Main Contribution	Main Findings	Main Limitations	Main Future Research
[48]	Awan et al.	I4.0 and CE pose risks and opportunities to various stakeholders, whose interests and expectations should be understood.	Literature review to identify stakeholders' interests and expectations on how I4.0 can be part of CE transition.	The stakeholders' interests and expectations are a reference point to start a discussion toward I4.0 and CE integration and to shape an organization's strategy for stakeholder orientations.	Systematic protocol limitations (timespan). *No focus on specific aspects of the DTs and CE relationship; no focus on operationalization.*	Need for empirical research on I4.0-CE relationships. Need to research on CE practices and their sustainability impacts.
[9]	Massaro et al.	Need for better understanding the union between I4.0 and CE.	Investigation of the link between I4.0 and CE, understanding how I4.0 can foster the impact of CE. Thematic and content analysis on grey and scientific literature, to get the perspective of both academia and practitioners.	The current discussion concerns mainly the use of smart services in waste management, resource efficiency and collaboration. There is the need for a better operationalization, also through the conduction of case studies rather than quantitative analysis.	The combination of grey and scientific literature limited the in-depth analysis. More insights from business cases are needed. *No focus on specific DTs- CE relationships.*	Future research deriving from the limitations discussed. Need to address and bridge the academic and practitioners' perspectives ('third mission' of universities is encouraged).
[59]	Okorie et al.	The CE transition requires firms to evaluate resource flows, supply chains, business models. The evaluation is critical for high-value manufacturing (HVM).	Investigation of the role of value, cost, and other factors of influence, as DTs, in the selection of a CBM for HVM.	DTs are critical enablers for CBMs, helping value creation and capture. The value reached range over sustainability areas and nonconventional forms of value as educational/research value, organizational value, customer value, and information value.	Focus on a specific context. *No focus on specific aspects of the DTs and CE relationship.*	Need for further investigation of the magnitude of the value generated, also through the identification of appropriate metrics.
[60]	Ranta et al.	DTs enable CBMs, but there is a lack of understanding of	Conduction of multiple case studies in four Northern Europe-based	Provision of empirical evidence of improved resource flows and of	Generalizability of the study limited by sample selection, as	Need for more empirical research to test the

		how the process takes place.	forerunner firms with CBMs enabled by DTs.	value creation and capture in firms across diverse industries. CMB's innovation is necessary for radical improvement toward CE. The improvements are enabled more by data integration and analysis than by data collection.	for awareness and competences and specific contextual factors. *No investigation of specific DTs.*	findings of the qualitative case studies. Further research should consider the B2C sector, particularly in the context of sharing economy.
[61]	Rehman Khan et al.	Blockchain technology promises potential improvements for the adoption of CE in SCM.	Investigation of blockchain technology's role for CE to enhance organizational performance in the context of China–Pakistan-Economic-Corridor (CPEC). Survey of manufacturing firms.	Blockchain technology is pivotal in the CE transition and linked to visibility, transparency, smart contracting; these features are required by contexts involving several stakeholders as supply chains and the CPEC. Benefits from the adoption of blockchain address the overall sustainability in the long term.	*Generalizability of the study limited by sample selection. Focus only on blockchain technology.*	n.a.
[54]	Upadhyay et al.	Blockchain research is developing rapidly, urging the investigation over its implications in terms of CE and sustainability.	Critical narrative review of the blockchain technology's contribution to CE through the lens of sustainability and social responsibility.	Potential alignment of blockchain with CE (through reduction of transaction costs, enhancement of supply chain performance and communication, etc.). Possible challenges to blockchain adoption in terms of trust, illegal activities, upfront costs.	Narrative review approach. *Focus only on blockchain technology.*	Future reviews should entail a systematic approach. Need to focus on CE's social impacts and the role of contextual factors on the adoption of blockchain technologies.
[62]	Bag et al.	Relevant impact of DTs on the procurement process.	Investigation over the relationships between Procurement 4.0 and DTs, within the CE context. Survey of South African manufacturers.	Identification of benefits from I4.0 applications in the procurement function within CE. Firms with a strong procurement strategy and effective Procurement 4.0 processes optimized better their procurement processes and attain enhanced CE performance.	Generalizability of the study limited by sample selection. *Focus only on the procurement process. No investigation of specific DTs.*	Need for further research to test all the hypothesis. Need for further research on possible moderators of the effects.
[63]	Bag et al.	The overall trend toward a smart logistics system should be better investigated, defining how I4.0 influences smart logistics.	Survey of South African executives in firms operating in mines, quarries, and processing plants.	I4.0 supports the optimization of operations in the logistics chains. I4.0 helps to build dynamic capabilities to face logistics' uncertainty and impacts more on intelligent logistics than on interconnected and instrumented logistics.	Generalizability of the study limited by sample selection. *Focus only on logistics. No investigation of specific DTs.*	Need for enlarging the sample. Future research could compare the results deriving from different contexts.
[64]	Bag & Pretorius	DTs entails challenges and opportunities for manufacturing firms in terms of sustainability and CE.	Systematic literature review on I4.0, sustainability and CE. Identification of barriers and drivers. Proposal of a research framework integrating I4.0, sustainable manufacturing and CE.	I4.0 can positively influence sustainable manufacturing and CE capabilities. Industrial decision-makers should focus more on sustainable manufacturing as an enabler of CE capabilities.	Systematic protocol limitations as a single academic source and timespan considered. *Focus only on BDA.*	Future research should involve a statistical validation of the proposed research framework.
[4]	Cioffi et al.	Digital innovations support the CE transition, promoting solutions as digital platforms, smart devices, AI.	Systematic literature review on what enabling technologies can promote CBMs.	Innovative technologies enable CE, but a conscious innovation path is needed; despite the benefits, investments return times are long. CE adoption needs managerial and legislative changes and can be eased by digital innovations.	Systematic protocol limitations. *Keywords used not totally aligned with aim of the present research. Focus on Smart Manufacturing and Applied Industrial Technologies.*	Future research should consider the evolution of the academic interest on the topic.
[65]	Cwiklicki & Wojnarowska	I4.0 and CE are pivotal topics in the current debate but need to be better linked.	Identification of the relationships between the CE and I4.0.	CE can be implemented using I4.0: industrial decision-makers can focus on specific CE goals and identify the DTs best supporting them. I4.0's main contribution toward CE relates to recycle/reuse strategies.	Limitations resulting from the blurred concepts of I4.0 and CE. *No investigation of specific DTs nor specific CE aspects.*	Future research should move from the micro-level to the supply chain level.

Ref	Author					
				The most impacting DTs are IoT and BDA.		
[66]	De Marchi & Di Maria	Promising positive scenarios for circular-oriented firms to control the use of resources and monitor internal and external processes from DTs' adoption.	Empirical investigation of the connections between I4.0 and CE strategies. Survey of North Italy manufacturing firms.	Positive relationship between I4.0 and CE adopters, with DTs acting as both enablers and amplifiers of CE. Differences emerge in terms of specific technologies adopted and their implications on the value chain's activities	Generalizability of the study limited by sample selection. *No investigation of specific DTs; focus on limited CE aspects.*	Further research should investigate the topic more extensively, understanding the specific role played by each DT.
[67]	Demestichas & Daskalakis	CE and Information and communication technology (ICT) are pivotal topics in the current debate. These technologies can enable CE.	Extensive academic literature review on prominent ICT solutions paving the way to CE.	The most popular ICT are those allowing data collection analysis, like IoT, blockchain, AI. As for CE, the focus is mainly on the reduce component. Barriers to the adoption of ICT for CE are related to consumer, costs, lack of education on CE and familiarization with technologies.	Systematic protocol limitations. *No investigation of specific DTs nor specific CE aspects.*	Need for efforts to increase CE awareness among industrial decision-makers. Need for metrics to prioritize CE efforts.
[68]	Dev et al.	Firms are looking for a high level of operational excellence through the developments of I4.0 technologies.	Proposal for a roadmap for sustainable reverse supply chain/logistics operations excellence by jointly implementing I4.0 and CE. Focus on an RFID-enabled system and reverse logistics simulation.	Insights for full circularity adoption for sustainable operations management viá inventory and production planning, AM set-up, family-based dispatching rules, and transportation system of the reverse logistics.	The results obtained are context specific. *Focus on limited DTs and limited CE aspects.*	Future research should extend the generalizability of results. Future research could deal with multiple suppliers.
[69]	Esmaeilian et al.	I4.0 creates opportunities for supply chain networks; more details are needed on how I4.0 addresses sustainability and CE challenges.	Review on blockchain technology and I4.0 for advancing supply chains towards sustainability.	Identification of I4.0 capabilities for sustainability and of their main impacts on CE.	Systematic protocol limitations. *Focus only on blockchain technology and IoT.*	Need for empirical research, particularly on the blockchain. Future research should consider the complexity of multi-tiers supply chains and the needs of multiple stakeholders.
[70]	Favi et al.	Design for disassembly is pivotal for the development of new business models based on the I4.0 and CE paradigms.	Proposal of a method to sort and cluster big data related to disassembly time and operations from different industrial sources. Preliminary evaluation through a case study.	Development of a systematic procedure entailing the most relevant statistical algorithms based on data collected according to I4.0 paradigm, to deepen the knowledge on disassembly.	Limited empirical test of the proposed method. *Focus only on disassembly.*	Future research should provide more empirical applications. Future research should focus on a full digitalization of the data collection process.
[71]	Getor et al.	Urge to shift from the linear model of tackling the plastic waste issue to a CE one.	Proposal for a framework integrating AI/database interface for the analysis of historical and real-time data, allowing simultaneous quality control checks and thermal stability tests on different virgin-recycled resin mixing ratios.	The information on the thermal and mechanical properties and structure of resin available through the system will be a reference point for production engineers. AI allows production engineers to carry out analysis on the data captured by the system.	No practical application. The real-life application could face challenges and require several trial-and-error rounds. *Focus only on limited DTs and on a very specific context.*	Further research should focus on the conduction of case studies.
[72]	Ghoreishi & Happonen	Designing products for circularity is rising in relevance. Parallelly, the adoption of AI in CE solutions increases productivity.	Investigation on how AI can integrate with CE as for the product design phase.	AI helps the optimization of resources for product design, the collection of data on products' lifecycle, the remote monitoring, reuse and remanufacturing of products.	Generalizability of the study limited by sample selection. *Focus on limited DTs.*	Future research should focus on the identification of barriers and drivers to the adoption of AI for CE, addressing also AI and CE integration in industrial systems as supply chains.
[15]	Ghoreishi & Happonen	I4.0 helps to overcome the challenges	Review of the role of AI as an accelerator in circular product design.	AI enhancements in business models that support CE are pivotal for	Review limitations.	Need for better detail the AI's impact on different CE aspects, while

		towards CE transition. The application of CE strategies at a product planning stage brings environmental benefits.		the growth and competitiveness of the industries.		also understanding the barriers to the adoption of I4.0 and the benefits deriving from it.
[73]	Ingemars-dotter et al.	The enabling capabilities of IoT over CE are recognized, but it is not clear how to leverage on IoT in the implementations of CE strategies.	Investigation over the mismatch between the 'theoretical opportunities' of IoT for CE and the actual implementation in practice. Case study within a LED company, with previous experience and knowledge on IoT and CE.	IoT supports: servitized business models; tracking of products; conditions monitoring and predictive maintenance; estimations of remaining lifetime; design decisions to improve durability. Implementation challenges lay in the lack of structured data management processes and the difficulty of designing IoT-enabled products.	Generalizability of the study limited by sample selection. *Focus on limited IoTs.*	Future research should consider the conduction of additional case studies. Future research should focus on data management in the context of IoT for CE.
[74]	Kintscher et al.	I4.0 can help in meeting a more efficient recycling process.	Proposal for an approach to integrate I4.0 in recycling processes. Electric vehicles and their batteries are used as an example.	The information share in supply chains is pivotal for enabling an efficient recycling process. Information can be collected and shared on a marketplace.	Generalizability of the study limited by sample selection. *Focus on the recycling process.*	Need to enlarge the sample.
[75]	Kouhiza-deh et al.	Blockchain technology and CE are emergent concepts; the breadth of the blockchain concept and its applications require investigation.	Grounded theory building based on multiple case studies, linking the blockchain applications to the ReSOLVE framework.	Blockchain allows transparent, decentralized, secure transaction processes and, positively impacts on the overall sustainability. Blockchain adoption suffers from infrastructure challenges. Variations across industries and firms' size in blockchain technology adoption for various CE practices are observed.	Generalizability of the study limited by sample selection. *Focus only on blockchain technology.*	Need for more empirical evidence, particularly on the long-term impacts of the blockchain technology on CE. Future research should also focus on the adoption of blockchain in supply chains.
[76]	Kravchenko et al.	AM is an enabler of CE.	Exploration of how AM can enable CE strategies. Identification of the key sustainability aspects to consider in the design of AM-enabled CE strategies.	AM supports several CE strategies and CBMs. Sustainability aspects must be considered at a planning and design stage and used to point out improvement opportunities.	Sustainability aspects are identified but not linked to any specific CE strategy. *Focus only on AM.*	Need for a case-by-case analysis for the identification of tailored AM-enabled technology sustainability wise.
[77]	Kristof-fersen et al.	More guidance is needed on how DTs (as IoT and BDA) can enable CE for improved efficiency and productivity.	Proposal of a theoretically grounded framework and a database of examples of the Smart CE to achieve SDG 12.	DTs hold several potentials for improved efficiency and productivity. The framework can represent an assessment tool to evaluate the DTs capabilities in firms.	First step in detailing mechanisms and strategies of a Smart CE, limited to theoretical grounding. *Focus only on IoT and BDA.*	Future research should provide empirical evidence on the Smart CE, also validating the proposed framework.
[78]	Mboli et al.	As firms are transitioning to CE, technologies allowing the predicting, tracking and monitoring of product's residual value must be identified.	Proposal for an IoT-enabled decision support system for CBMs. Experimental study with a real-world case in the electronic consumer sector.	Products can be tracked and monitored in real-time, through IoT, allowing business analytics. The adoption on the proposed system may support firms in creating more value compared to a linear economy.	Generalizability of the study limited by sample selection. *Focus only on IoT.*	Future research is aimed at focusing on the logistics optimization and price and cost prediction.
[79]	Moller	CE is important within I4.0, and a future ecological and economical model.	Analysis of the digital transformation as an enabler of intelligent manufacturing and its opportunities to CE.	Discussion over the needs for the development of an integrated approach and description of the background for the development.	*No investigation of specific DTs nor specific CE aspects.*	Need for more inter- and transdisciplinary research to achieve an intelligent CE.
[80]; [81]	Nobre & Tavares	Information technology (IT) professionals should incorporate	Development of a framework for the identification of the IT capabilities	Extension of the existing ReSOLVE framework to allow IT professionals to assess their current CE gaps,	The proposed framework could become obsolete due to the	Need for an empirical validation of the framework.

		projects focusing on the organizations' CE transition.	necessary for organizations to be considered technologically circular.	with the aim of fill these gaps and foster the CE transition. Identification of I4.0's role in the CE transition.	rapid evolution of technologies, and it lacks practical confirmation through case studies. *Focus only on IoT and BDA.*	Future research should focus on the development of metrics to self-assess and benchmark the capabilities.
[82]	Piscitelli et al.	The full adoption of CE principles within organizations and supply chains encounters obstacles related to the lack of advanced technologies.	Systematic review of literature related to CE from an I4.0 perspective, understanding how I4.0 technologies can unlock the circularity of resources.	CE and I4.0 are closely linked. Technologies support CE in the ability to have more knowledge and in the monitoring of processes and products. CE shows great applications potential in many contexts.	Systematic protocol limitations. *No investigation of specific DTs.*	n.a.
[83]	Poschmann et al.	Robotics can support the disassembly process, which is essential for implementing CE.	Systematic literature review on robotics in disassembly.	Predefined processes and flexible automation are main research streams. Ample possibilities for integrating the disassembly processes into a superordinate CE information system.	Systematic protocol limitations (search string). *Focus only on disassembly and ROB.*	Future research will focus on the information processes and system concepts towards an autonomous disassembly system.
[84]	Rajput & Singh	The adoption of I4.0 can impact positively on CE and cleaner production.	Proposal for a model for I4.0 set-up to achieve CE and cleaner production, through the optimization of products-machine allocation.	The proposed model optimizes trade-offs between energy consumption and machine processing cost, achieving CE and cleaner production.	The model is developed according to specific hypotheses. *No investigation of specific DTs nor specific CE aspects.*	Future research deriving from the limitations discussed.
[85]	Rocca et al.	Companies are urged to re-think their business strategies in view of both the CE and I4.0 paradigms.	Presentation of a laboratory application case, testing an electrical and electronic equipment disassembly plant configuration through a set of simulation tools.	Practical demonstration through a laboratory experiment of DTs enabling CE. DTs allow better use of resources, increased production sustainability and benefits along the product lifecycle.	Generalizability of the study limited by the specific context investigated. *Focus only on disassembly and ROB, SIM, AM.*	n.a.
[31]	Rosa et al.	I4.0 and CE are pivotal current topics. They can be described as independent, but overlaps are identified.	Systematic literature review on the relations between I4.0 and CE. A useful double perspective is offered.	I4.0 can generally positively impact the lifecycle management of products and specific insights are dependent on the DTs considered.	Systematic protocol limitations. *No focus on operationalization.*	Need for empirical evidence on how CE and I4.0 are applied in practice.
[86]	Rossi et al.	CE is recognized as a source of value creation, but its application is still lagging. I4.0 can support CE implementation.	Evaluation of how and how much CBMs are enhanced by I4.0. Analysis based on literature case studies, and on the application of an assessment tool with secondary data.	Proposal of a systematized framework considering CBMs enhanced by intelligent assets, allowing the gathering of timely and consistent data for reliable decision making.	Framework validity assessed only through secondary data.	Need for a systematic literature review on the topic. Need for empirical application of the framework.
[87]	Uçar et al.	DTs as IoT, BDA and AI are main supporters for CE, but DTs specific effects on CE are not explored.	Identification of the roles of DTs supporting CE through literature review and case studies.	DTs can act as enablers or triggers, with the former being the dominant ones.	Findings based only on secondary data. *Focus only on IoT, BDA and CLOUD.*	Need for empirical research to further validate the study findings and consider different contexts of application.
[88]	Yadav et al.	The discourse on the adoption of Sustainable Supply Chain Management (SSCM) need to be updated accordingly to changing business environments.	Development of a framework to overcome SSCM challenges through I4.0 and CE solutions. Test of the framework through hybrid Best Worst Method in the Indian automotive sector.	Identification of 28 SSCM challenges and 22 solution measures. Managerial, organizational and economic challenges emerge as the most critical.	Generalizability of the study limited by the specific context investigated. *Focus only on SCM.*	Future research should consider large scale application, as well as the validation of the framework in other contexts.

[89]	Alcayaga et al.	The discourse on circular strategies, smart products and product- service systems has been addressed in isolated ways or with partial overlaps, a holistic overview is missing.	Synthesis of the literature from the three domains, describing interrelations among the concepts. Proposal of a conceptual framework of smart-circular systems, extending the technical loops.	Better understanding of smart-circular systems and outlines of a research agenda.	Integrative literature limitations as for the identification of relevant literature. No empirical validation of the framework.	Need for evidence-based knowledge, through insights from empirical studies. Need for cross-sectional and longitudinal studies. Future research should investigate smart-circular strategies.
[90]	Cezarino et al.	I4.0 can potentially unlock sustainability and CE in emerging economies, but further investigation is needed.	Investigation of the relationships between I4.0 and CE and the limitations for their adoption, focusing on Brazil. Proposal of a framework to overcome limitations.	Exploration of the relationships between I4.0 and CE through four perspectives: political, economic, social and technological.	Generalizability of the study limited by the specific context investigated. *No investigation of specific DTs.*	Need for empirical research to collecting primary data. Future research should address other emerging economies.
[55]	Chiappetta Jabbour et al.	CE and big data present several synergistic relationships.	Integration of CE and big data. Proposal of a ReSOLVE based models with the identification of key stakeholders and the management of volume, velocity, variety, and veracity of big data.	Development of an integrative framework, enhancing the comprehension of the CE-big data nexus. Development of a matrix illustrating the complexity of large-scale data and stakeholders' management. Outline of a research agenda.	No empirical validation of the framework and the relational matrix. *Focus only on IoT and BDA.*	Need for an empirical validation of the framework and the relational matrix. Need for empirical research to test the suggested propositions.
[91]	Charnley et al.	Growing interest in the relationships between CE and I4.0, but deeper knowledge is needed.	Investigation on how simulation informed by I4.0 and IoT can accelerate the adoption of circular approaches in UK manufacturing.	The analysis of in-service data from automotive components can influence decisions surrounding remanufacture and can lead to significant cost, material and resource savings.	*Generalizability of the study limited by the specific context investigated. Focus only on remanufacturing and SIM.*	Future research should base on the study to conduct more quantitative and mathematical evaluations.
[12]	Chauhan et al.	I4.0 and CE attracted the attention of academia and practitioners, and the connection between them need further investigation.	Application of the situation, actor, process, learning, action, performance linkages framework to analyze the role of I4.0 in realizing CE.	Top managers are essential actors for integrating I4.0 to achieve sustainability, in light of CE. IoT and CYB are pivotal for supporting CE transition.	Limitations related to the possible biased of experts' judgments.	Need for conducting case studies so to understand the roles of digitization and data-driven technologies in achieving the goals of CE.
[92]	Garcia-Muiña et al.	Eco-design, associated with IoT technologies can help in developing products consistent with CE principles.	Test of eco-design as a tool to define an equilibrium between sustainability and CE in the manufacturing environment of ceramic tile production. Identification of IoT as an enabler for CBMs.	Empirical validation in a manufacturing environment of sustainability paradigms through eco-design tools and DTs, proposing the CBM as an operational tool to promote the competitiveness of enterprises.	*Generalizability of the study limited by the specific context investigated. Focus only on IoT.*	n.a.
[93]	Garrido-Hidalgo et al.	Growing need to manage backward materials and information flows in the supply chain, through approaches based on Information and Communication Technologies (ICT).	Proposal for an end-to-end solution for Reverse Supply Chain Management based on ICT. Application to an industrial case study regarding WEEE recovery towards CE.	Demonstration of the potential of ICT adoption for Reverse Supply Chain Management. IoT facilitates information management, contributing to CE transition. Identification of communication bottlenecks that need to be tackled to enhance the reliability of large-scale IoT networks.	*Generalizability of the study limited by the specific context investigated. Focus only on IoT and CLOUD.*	Future research will assess the economic and environmental viability of the proposed approach.
[94]	Gligoric et al.	Item-level identification can foster disruptive innovation, enabling CBMs.	Proposal of a method to facilitate IoT for building a product passport and support data exchange, enabling CE.	SmartTags can be used in CE for unique item-level identification and detection of environmental parameters.	The solution is evaluated according to specific hypotheses. *Focus only on IoT.*	Need for further research to test all the hypotheses.
[95]	Ingemars-dotter et al.	IoT contributes to CE transition, but little is	Analysis on how companies implement IoT for	IoT entails capabilities as tracking, monitoring, control, optimization.	Exclusion of prototypes and start-up	Future studies should include additional cases

		known on practical implementations.	CE strategies based on secondary data. Confront of the implementations with the opportunities described in the literature.	Current implementations of IoT-enabled CE mainly target efficiency in use and product life extension.	companies from the analysis. Findings based only on secondary data. Literature review limitations, as the exclusion of low cited contributions. *Focus only on IoT.*	in to increase the robustness of the results; in-depth case studies with companies would be relevant.
[96]	Kerin & Pham	Remanufacturing is an important part of a CE, but a specific focus on I4.0 supporting remanufacturing is missing.	Review of the literature on the applicability of IoT, VR and AR in remanufacturing.	Identification of 29 research topics requiring further investigation. Greater automation is required in manufacturing process to apply I4.0.	*Focus only on remanufacturing and on IoT, VR, AR.*	n.a.
[97]	Moreno et al.	The debate on redistributed manufacturing (RDM) examined potential environmental impacts, but there is the need to understand the potential of RDM as an enabler of CE.	Exploration of DTs potential for RDM as an enabler of CE in the consumer goods industry. Investigation through multiple case studies. Evaluation of the Discrete Event Simulation as a tool to assess CE scenarios.	Identification of several opportunities for CE through the implementations of DTs. Overall, the redistribution of industrial systems could benefit from the CE transition.	Findings based only on secondary data and in a specific context of investigation, with precise assumptions. *Focus only on remanufacturing.*	Need for further research releasing the assumptions. Future research should focus on the evaluation of the economic and environmental impacts of the CE opportunities investigated.
[98]	Nascimento et al.	I4.0 can increase the productivity of a recycling factory and optimize the management of workflows in the entire value chain from a CE perspective.	Exploration of how I4.0 technologies can enable CBM focused on the reuse/recycle of material. Proposal of a conceptual framework for evaluating the synergies, validated through a focus group.	Provision of recommendations for CBMs to reuse scrap integrating web technologies, reverse logistics and AM.	Possible bias and subjectivity in the validation. Generalizability of the study limited by the specific sample of experts.	n.a.
[99]	Pham et al.	Potentials to combine I4.0 and CE to enhance the sustainability of manufacturing sectors.	Exploration of the I4.0 factors accelerating the sharing economy. Investigation through a case of electric scooters in Taiwan.	I4.0 is an enabler for sharing economy. I4.0 technologies are helpful to overcome specific barriers to CE adoption.	*Generalizability of the study limited by the specific context investigated.* *Focus only on IoT and CLOUD.*	Need to approach CE with a holistic, policy-oriented approach.
[100]	Rajput & Singh	An integrated I4.0-CE approach can increase efficiency and optimize the entire value chain. Thanks to I4.0, possible technological barriers to the CE transition might be overcome.	Identification of I4.0 barriers to CE. Prioritization of barriers and identification of contextual relationships among them through Interpretive Structural Modelling.	The main barriers are process digitalization, sensor technology and design challenges. An I4.0-CE approach would allow operations management sustainability, optimizing production and consumption, while also providing opportunities for customization.	Possible bias and subjectivity in the identification of contextual relationships. *No investigation of specific DTs.*	Future research should provide more detailed and empirical evidence on barriers.
[101]	Rajput & Singh	I4.0 and CE can boost sustainability within firms as well as in supply chains.	Exploring connections between CE and I4.0 in supply chains, in terms of barriers and enablers. Barriers and drivers are factorized through Principal Component Analysis.	Identification of 26 drivers and 15 barriers. The most significant enablers connecting CE and I4.0 in supply chains are AI, Service and Policy Framework, and CE; the most significant challenges are Interface Designing and Automated Synergy Model.	*Focus only on SCM.*	Future research should provide more detailed and empirical evidence on barriers and adoption of I4.0 technologies.
[102]	Riesener et al.	Digital transformation enables the CE transition, but how DTs can act as enabler needs further investigation.	Proposal for a framework comprising 9 success factors for CE transition, based on digital transformation technologies.	Identification of the linkages between the phases of a product lifecycle and the design levels of business engineering.	*No investigation of specific DTs.*	Future research should better investigate the different success factors.

[103]	Sarc et al.	I4.0 are implemented in the field of waste management to achieve CE.	Identification of systems and methods used in waste management sector and of technologies applied in other sectors that could be relevant as well.	Robotic-based sorting and lifting systems in waste management are pivotal, as they also partially replace humans. Limitations can be identified, material- and technology-wise.	*Focus only on recycling and IoT and ROB.*	Future research should address the sensors needed for a successful application of I4.0 for waste management.
[104]	Väisänen et al.	DTs are enablers of CE, with opportunities on multiple levels.	Identification of the most prolific technologies enabling CE at different levels. Discussion on the requirements and barriers for a successful implementation of identified digital solutions.	Several possibilities for DTs software supporting CE are identified at the micro-level. The need for cooperation, networking and data management at the meso-level is stressed. Blockchain technologies play a pivotal role but concerns on data ownership are unsolved. CE is not easy to achieve at a macro-level.	Results are conceptual and based on available literature.	Need for case-based empirical research on digital solutions and their effects on CE on each level.
[13]	Antikainen et al.	Digitalization can support CE transition, but many challenges still need to be solved.	Understanding of the main opportunities and challenges of digitalization implementing CE transition. Collection of insights through a workshop.	Identification of several opportunities for digitalization supporting CE transition, as virtualization. Networking and collaboration with stakeholders, and digital collaboration platforms are pivotal for enabling CBMs, and can be fostered by blockchain.	*Limitation related to the possible biased of experts' judgments.*	Future research should provide more detailed and empirical evidence.
[105]	Bianchini et al.	Gap between the CE concept and its implementation. Digital transformation can support CE in tackling the specific issue.	Proposal of a model linking the adoption of IoT and big data to CBMs. Discussion over the model through literature cases.	Description of how the application of IoT and big data, could support CBMs during the entire product life cycle. The need to involve the entire supply chain for proper implementation is underlined.	Findings based only on secondary data.	Future research should address the transition to a digital circular supply chain.
[106]	Bressanelli et al.	DTs are key enablers for the introduction of servitized business models and CE, but more investigations are needed.	Development of a conceptual framework, based on the literature and a case study, focusing on the enabling role of IoT and BDA.	Identification of 8 functionalities enabled by IoT and BDA; investigation of their effects on CE. The results highlight that to move towards CE, companies should couple IoT with BDA.	Findings based only on one case study, so the generalizability is limited. Focus only on IoT and BDA.	Need for empirically investigating a larger sample. Future research should focus on other DTs.
[107]	Bressanelli et al.	Product-Service Systems (PSS) promote sustainability and CE. DTs enable PSS, but more details are needed on their relationships.	Exploration of the role of DTs in enabling PSS. Analysis through a case study of a firm leveraging IoT and BDA.	IoT and BDA are relevant and help firms overcoming challenges (as operational risks, technology improvement, return flow uncertainties), through 4 digitally enabled functionalities.	Findings based only on one case study, so the generalizability is limited. Focus only on IoT and BDA.	Need for empirically investigation of a larger sample. Future research should focus on other DTs.
[17]	Lopes de Sousa Jabbour et al.	DTs can unlock the circularity of resources within supply chains, but linkages between CE and I4.0 need to be better explored.	Proposal of a roadmap to enhance the application of CE principles in firms through I4.0.	Discussion over mutual I4.0-CE relationships. Understanding of the potential contributions of technologies to the ReSOLVE framework. Outline of a research agenda for the integration of I4.0 and CE.	Results are conceptual. *Focus only on recycling and IoT, CLOUD, AM.*	Need for empirical research for operationalizing the proposed framework. Further research should consider in-depth case studies.
[108]	Makarova et al.	Reverse logistics is pivotal in the CE transition. The planning of the reverse logistics is difficult, but I4.0 can support it.	Description of industrial development in the CE transition and new trends in the development of logistics.	Proposal for a system allowing the planning and organization of processes, so to minimize raw materials' consumption and reduce negative environmental impacts.	*Focus only on SCM.*	Future research should focus on simulation models for the adoption of the proposed system.
[109]	Neligan	Opportunities and challenges of digitali-	Empirical findings on the importance of digitalization to improve material	Opportunities deriving from DTs are limitedly exploited and ad-	Generalizability of the study limited by the specific context investigated.	Future research should focus on barriers and drivers to the CE transi-

		zation for CE transition need investigation.	efficiency in the German industry.	dressed primarily to improve efficiency in the manufacturing process.	*No investigation of specific DTs.*	tion, while also evaluating the economic benefit from the adoption of DTs and CE.
[21]	Okorie et al.	Opportunities to apply the CE to the rapidly changing paradigm of I4.0 need investigation.	Systematic review of the empirical literature related to DTs, I4.0, and circular approaches.	Proposal for an integrative CE-DT framework based on Technology life cycle (TLC).	Systematic protocol limitations. Specific limitations related to the use of TLC. *No investigation of specific DTs nor specific CE aspects.*	Future research should focus on BDA and a holistic approach to stakeholders. Need to examine the methods employed in CE-I4.0 research.
[16]	Nobre & Tavares	Technologies as IoT and BDA can leverage the adoption of CE. It is fundamental to understand the current debate on the integration of the concepts.	Bibliometric study on the application of big data/IoT within the context of CE.	A disconnection between industry initiatives and scientific research is highlighted. Specific contexts in terms of geographic area, economy and greenhouse gas emissions could have a higher interest in CE than what shown by the analysis of publication.	Systematic protocol limitations (timespan). *Focus only on IoT and BDA.*	Future research should focus on exploratory and practical studies.
[110]	Pagoropoulos et al.	Both CE and DTs are facing rapid proliferation.	Systematic literature review on how DTs can support CBMs.	Identification of 7 DTs. DTs support the CE transition optimizing material flows. A lack of empirical studies is highlighted.	Systematic protocol limitations. *No investigation of specific DTs nor specific CE aspects.*	Future research should provide more detailed and empirical evidence.
[111]	Moreno & Charnley	Redistributed manufacturing and CE can potentially disrupt current models of consumer goods production and consumption.	Exploration of digital intelligence and redistributed manufacturing as enablers of CE. Analysis of literature case studies.	The integration of DTs can enable the distribution of knowledge, customization and CBMs. Circular innovations support more regenerative and resilient systems of production and consumption.	Findings based only on secondary data. *No investigation of specific DTs nor specific CE aspects.*	Need for empirical research to further validate the findings.
[112]	Reuter	Process metallurgy support CE; the digitalizing of the material production could provide additional support.	Evaluation of the different possibilities and application for the metallurgical IoT.	Identification of opportunities, limits, tools, and methods of process metallurgy and recycling within the CE, through the adoption of DTs.	Generalizability of the study limited by the specific context investigated. *Focus only on IoT and BDA.*	Future research should focus, among the others, on the role of the disruptive CBMs.

5.1. Digital Technologies Enabling the ReSOLVE Framework

A narrow group of contributions investigated the relationship between the DTs and the overall ReSOLVE framework (Figure 10). The contributions were mainly review or conceptual papers. They considered one DT or a limited set of them, paving the path for more integrated analyses. From this perspective, Nobre and Tavares [80] linked some aspects related to IoT and BDA to the different areas of action of the framework. BDA and their requirements for appropriate applications in the different areas were also discussed [55]. IoT was also considered together with CLOUD and AM [15,17], and a framework for fostering their adoption was also proposed. Lastly, different examples of CYB applications in the ReSOLVE framework, focusing particularly on the benefits related to traceability and security, have been provided [75]; however, the proposed applications were still at a pilot or planning stage.

The reviewed contributions are nonetheless mostly focused on specific CE aspects associated with the ReSOLVE action areas (Table 1).

5.1.1. DTs enabling the Regenerate area

The Regenerate area has been so far connected to a limited series of DTs (Figure 10). Regenerate area could benefit from DTs thanks to the application of IoT in the form of sensors for the collection of data and BDA for the elaboration of the collected data [17]. A decisive positive impact of IoT on the product lifetime extension is underlined in terms of

monitoring, control and optimization, allowing additional support and value to the customer [95]. As a part of IoT, the use of Smart Tags for building a product passport and enabling data sharing and exchanging is supported [94]. The use of BDA is then necessary for a proper elaboration and use of such data, facilitating the decision-making process [89]. Riesener et al. [102] detailed different phases of the lifecycle, namely manufacturing, usage and reutilization/recycling. As for the manufacturing phase, CBY, IoT and HVSYS can help to solve information asymmetry; concerning the usage phase, CYB and particularly blockchain might support the handover to different customers, also enabling the traceability of the product and the acquisition and verification of related data [115]. Regarding the reutilization/recycling phase, BDA might allow different cycles, fostering a reverse logistics system and waste management [116].

5.1.2. DTs enabling the Share area

The research over the use of DTs in support of the Share area appears rather limited (Figure 10). IoT allows the monitoring and tracking of the use and condition of products, thus enabling reuse [95]. As a large amount of data would be collected, BDA and CYB become again of fundamental importance to manage the complexity [102]. The collection of data on the product condition and the related decisions for reuse would allow better cooperation among the tiers of the value chain [66,89].

5.1.3. DTs enabling the Optimize area

The enabling role of different DTs in terms of Optimize area received rather good attention (Figure 10). Nonetheless, despite evidence that DTs can support resource efficiency [12,66], firms still lag as for DTs adoption and exploitation [109]. A pivotal role is played by IoT for monitoring, control and optimization [95], allowing also the identification of resource waste in real-time [92]. The IoT would then require the support of BDA [102,112]. Nonetheless, the collection and analysis of data could be insufficient, and the use of CYB is suggested to share the product information among the different stakeholders, while also facilitating the paperwork activities and the checking of the status of the products along the supply chain [69].

From a general perspective, the role of DTs is also studied concerning supply chain management [101]. As the management of inbound and outbound logistics is particularly relevant, firms might benefit from DTs applications in procurement and logistics, also helping build the capabilities needed for collecting, processing and sharing information [62,63]. From a practical viewpoint, IoT can allow the real-time evaluation of the product value along the tiers [78], with an exchange of the data stored in a CLOUD inventory [88,93].

DTs could also support reverse logistics, with a particular relevance of BDA, on data collected with an HVSYS perspective [108], possibly fostered by AM production system [68]. The transparency and security of data exchange and any type of digital transactions can be guaranteed by the use of CYB; from a larger perspective, the use of CYB could also support supply chains in making their practices more transparent, secure and correct [54,61]. Possible different configuration scenarios can be then analyzed thanks to SIM [97]. As a last remark, preliminary insights on the combined support from DTs and CE to enhance sustainability started being discussed [61,88].

5.1.4. DTs enabling the Loop area

The Loop area can benefit from the adoption of different DTs (Figure 10). Particularly, a good variety of DTs proves to foster actions related to the disassembly of products. An interesting role is played by AR, which could be useful in planning the disassembly sequence, as it would allow the visualization of all the information and equipment needed in the process, besides helping in training operators [96]. ROBs also have an interesting role in the disassembly process [85], although issues in terms of economic feasibility may pose limitations [83]. As for the determining and optimizing of the disassembly process,

both SIM [85,91] and BDA for mining a repository of disassembly processes [70] are considered as possible options.

The remanufacturing process requires different data related to the product, i.e., its status, maintenance history, disassembly and reassembly [117]. From this perspective, the use of IoT via sensors would be helpful to track the product history, through real-time monitoring that could bring positive effects in different processes [89,118]. However, although few cases can be spotted where IoT is relevant for looping strategies, empirical studies show that IoT is not largely used for product remanufacturing [95]. Additional opportunities have been conceptualized from the integrated use of IoT and AM, but the realization has not been demonstrated [68]. AM nonetheless can contribute to sustainability, presenting lower cost related for example to set-up, and can play an important role in the loop area when the workload is distributed along the different tiers of the supply chain [68,119]. For the latter point, the use of an HVSYS would allow real-time data management throughout the entire chain, thus facilitating the loop strategies [68]. Lastly, SIM can assist remanufacturing processes, as discrete event simulation models are essential to determine the quality of a product [91].

As for the recycling process, IoT would provide benefits in terms of monitoring and tracking [103], enabling looping [71,95]. Two relevant aspects emerged as connected to the adoption of IoT: first, to make proper decisions, data should be collected with an HVSYS perspective [74]; second, as many data would be collected, BDA becomes fundamental to manage the complexity [102]. Lastly, the use of ROB would facilitate the recycling process, while also bringing benefits from a social sustainability perspective [103]. Additional insights are provided highlighting a strong correlation between the adoption of recycling practices and the adoption of BDA, ROB and AM, suggesting also that I4.0 might allow greater integration among the partners of the value chain [66]. Nonetheless, several issues emerge trying to link the concept of CE with the one related to industrial systems; incorporating CE into industrial networks requires a change in the economic paradigm [120] that would be allowed only by a strong willingness of all the involved partners to embark in this transition [121]. The main obstacle and critical resource for the transition is the trust among the partners [122], which becomes even more pivotal if the transition is enabled by DTs [123]. Additionally, moving from a single firm to the value chain and then the industrial system would require the identification of the best set of DTs to use [124].

5.1.5. DTs enabling the Virtualize area

The enabling role of DTs towards the Virtualize areas has been so far investigated from a rather limited perspective (Figure 10). As for SMSER, the discourse has been approached from a general viewpoint, without much detail on specific DTs. Exact points have arisen in terms of the need of being able to collect data to monitor and evaluate the conditions of the product, using for example IoT [89], complemented with CLOUD [99] and DBA for the analysis [105]. Additionally, also AM can be interesting for the customization of products based on interactions among different tiers of the value chain [68]. The action area can be supported by IoT, as they could foster the relationship and communication between organizations, suppliers and customers [68].

5.1.6. DTs enabling the Exchange area

The area has been largely addressed mainly from a general, broad and theoretical perspective (Figure 10), understanding how the presence and adoption of new technologies could foster and support the transition towards new update CE practices. DTs could indeed offer a solution for core data records concerning a sustainable product and material database [79]. Opportunities can be found at different levels, as the optimization of the resources use, the engagement in business models enabled by software development, the share of information on a network level, the creation of infrastructures supporting the tracking and monitoring [104], while also fostering cleaner production [84]. Although so far, the discourse has been mainly theoretical, some first empirical applications can be found for specific CE aspects, as redistributed manufacturing [111].

Concerning specific DTs, the discourse mainly developed around the adoption of IoT and BDA [16,67,77,112], with the latter playing a fundamental role also in terms of predictive analytics [64] with the support of CLOUD [67]. Positive impacts were also observed concerning AM, as it could easily support CE strategies focused on materials [76].

At this stage, contributions also focused on the identification of barriers and challenges to and for DIGIT [67,100,104]. Some of the barriers refer to organizational aspects (lack of competencies, need for coordination, need for technical development), to economic aspects (financial and operational risk), as well as the digitalization process itself. Particularly, the adoption of DTs can be strongly hindered by organizational resistance deriving from both the employees and the management, who can oppose the change within their organization [125] and might lack specific competence and skills [126]; particularly, the role of managers has been considered of fundamental importance to support the integration of DTs in the light of CE [12]. Additional challenges seem to emerge concerning the context of the investigation, with developed countries facing mainly issues related to the low maturity level of the desired technology [127] after national strategies and policy have been formulated [128], and the developing countries still struggling with the setting of proper standards and legislation [127]. Specific barriers in the context of emerging economies were indeed pointed out in terms of the macro environment [90]. Additionally, an important role is played by the availability of the technologies, also from an economic perspective [17]. In this scenario, it is pivotal to identify the best drivers to overcome the barriers [129].

5.2. Digital Technologies Enabling the CE Transition: Further Insights

According to the overview provided in 2.1, the ReSOLVE framework entails major circular business opportunities [27]. The literature has largely addressed the role of DTs as possible enablers of CBMs; however, the important operational role of the ReSOLVE framework has not been considered. For having an overview as complete as possible, we considered also this general viewpoint. From a broad perspective, DTs allow the industry to embrace innovative, productive and sustainable CBMs [86,105]. A central role is played by the exploitation of data [13] and consequently data collection, integration and analysis, using IoT, CLOUD and BDA [60]. DTs would also allow greater involvement of customers in the definition of CBMs [9], leading for example to customized services [97].

Analyzing specific DTs, IoT is undoubtedly among the pivotal ones: on the one hand, it can support the definition of servitized CBMs [73]; on the other hand, it can advance the tracking, monitoring and control of products [73,95], favoring a real-time analysis of the product's residual value [78]. The adoption of IoT implies the need for a good quality of data and appropriate data management [73], so that BDA becomes fundamental [15,107]. Additionally, IoT and BDA together can support specific aspects at each product life cycle stage (as product design; marketing activities; monitoring and tracking of the product; technical support and maintenance; product optimized use, upgrade and renovation) [106]. To effectively adopt IoT and BDA, some aspects are necessary [72] such as (i) the collaboration with stakeholders and particularly customers to obtain the data, (ii) the capability of workers to analyze and manage the data and (iii) the consideration of impacts from a sustainability perspective, thus including economic and social aspects—given the high cost of DTs, and the strong relationship between product and customer satisfaction [130,131]. Lastly, within this framework, CLOUD is fundamental for the storage and share of data [87]. The literature also offers insights into the relationship between CBMs and AM as an enabler of CE. AM emerges as capable to increase productivity and manufacturing freedom on demand, targeting the needs of each customer, while also enhancing sustainability, with economic, environmental and social implications [98].

6. Digital Technologies Enabling the CE Transition: Discussion and Open Issues

The analysis of the literature confirmed the relevant role of DTs in enabling and supporting the CE transition. The trend in terms of year of publication (Figure 4) underlines

how the research on the topic is relatively young, as also noted by previous research [21,82,104]. The geographical distribution of the authors is showing a global interest in the topic by both developing and developed countries (Figure 6), as also previously underlined [4]. The descriptive analysis of the different CE aspects (Figure 8) highlights how the research is still mainly focused on specific aspects of CE, and it is not integrated into a more structured and operative framework, as the ReSOLVE one [16]. In this way, DTs are related to specific CE aspects or processes, and it is difficult to have a complete overview of all the benefits that DTs could bring to the overall CE transition (Figure 10). As also emerged from the descriptive analysis, the discourse is still mainly driven by theoretical contributions, and particularly literature reviews, so that advancement from both a conceptual and (mostly) an empirical perspective is strongly recommended (Figure 11). The urgency is also underlined by the breakthrough potential of the empirical research conducted on the topic (Figure 7). Particularly, considering the insights that emerged from the present review (see also Table 3), the following issues are worthy of note and urge for additional research efforts.

Integrated and holistic perspective on the DT–CE relationship. Shortcomings can be identified in the evaluation of the relationships between DTs and CE from both sides. Regarding DTs, the largest share of contributions focuses on one or a limited set of DTs (Figure 9), while the contributions addressing DTs in general terms mainly provide few examples on specific DTs or applications. Nonetheless, DTs are for their nature interconnected, and it may not be possible to adopt a DT without at least a partial presence of another one [104]. The research on the integration of the different DTs shows indeed a growth potential for better investigating their role in the CE transition [48,110]. As for CE, the literature is still mainly focused on specific CE aspects, not considering a more integrated approach (Figure 8). Although the literature largely recognized the enabling role of DTs, there is an urgency to investigate how they enable the transition from a more operative perspective [107], as the one offered by the ReSOLVE framework [16]. Additionally, as emerged from the review, specific ReSOLVE action areas and aspects of CE are more investigated than others (Figure 8), leaving ample room for additional research. To move towards enhanced CE, firms should adopt CE practices. As DTs enable the CE transitions, it comes directly that DTs could also enable and support the adoption of specific CE practices. The investigation of the relationship should consider the intensity with which a specific DT could impact the CE transition, not only from an overall perspective but also regarding specific action areas and specific practices that a firm could implement—see, for example, [132]. Such analysis would make it easier for the industry to understand if, how and to what extent the adoption of specific DTs could impact the CE transition, possibly allowing them to better organize their resources and concentrate their efforts towards the adoption of those DTs that could be more efficacious.

The decision-making process. The CE practices would have to undergo an adoption process that could be influenced by several factors, as demonstrated for example for industrial sustainability [58,130,133]. The evaluation of these factors would be of fundamental importance to better understand how and to what extent DTs can enhance specific CE practices. In particular, a holistic investigation on the following points is advised, understanding their role in the different phases of the adoption process of CE practices, and how they could change according to the action of different DTs:

- Barriers to CE transition: identification and evaluation of the inhibitors of the adoption process [9,17];
- Drivers for CE transition: identification and evaluation of the fostering factors for the adoption process [17,66];
- Performance measurement: identification and evaluation of the performance reached after the adoption; fundamental for this aspect would be the identification of how the performance could be gauged [17,59]. Another important aspect to consider is the evaluation of performance beyond the ones strictly related to CE. As introduced in the previous section, some authors started investigating the performance related to

the overall sustainability derived from the adoption of CE practices supported by the DTs, see for example [54,98,134]. However, despite the common agreement, additional research seems to be necessary to better determine the relationship between DTs and industrial sustainability [135,136];

- Contextual factors: identification of those contextual factors, as geographical area, sector or firm's size that could influence the adoption process [137] and that so far appear still limitedly investigated (see Section 4.4.); previous research showed a pivotal role of the firm's size, particularly when SMEs and LEs are confronted [138–140];
- Digital maturity level: evaluation of the impact of the digital maturity of the firm on the outcomes, as it might represent a quite important influence [98,141];
- CE management: evaluation of the impact of how CE is managed within the firm, as it might influence the outcomes [137]. For example, the presence of an environmental management system demonstrated to strongly support the CE transition [142]; as a clear predominance for a heterarchical control for DTs has been underlined [143,144], the debate on whether a centralized or decentralized system would be better for environmental-related aspects is still open [145,146].

Empirical research. As abovementioned and shown in the descriptive results (Figures 11 and 12) and highlighted by the in-depth analysis of the content (Table 3), the largest share of the published contributions employs a theoretical approach. This urges for more empirical research, which is also highlighted in previous literature [15,77,87,110]. Although an increase in empirical studies can be appreciated in the latest years (Table 2) [82], there is still ample room for providing practical demonstrations of the impact of DTs on the CE transition. To deepen the understanding of the relationships, the adoption of the case study methodology is suggested, providing more qualitative than quantitative evidence, but allowing a deeper analysis of the context under investigation [101,147] (see also Table 3). As some contributions employed the case study methodology, the investigations present less than five case studies, with the largest share of contributions focusing on one case study (Table 2; Figure 12). To confront an already existing theory toward an empirical application and structuring the theory in light of the observed results, a larger number of case studies is therefore suggested [148,149].

The role of industrial systems and stakeholders. Moving from a micro to a meso-level of analysis, DTs have been proven to facilitate the cooperation and connection of firms, foster industrial symbiosis and help build a collaborative environment to promote the CE [104]. Regardless of the provided insights on the possible influence of DTs on SCM, it is suggested to conduct specific studies investigating industrial systems from the perspective of all the involved firms, not only a focal/single one [131,150] (see also Table 3).

7. Conclusions

The present study critically reviewed the literature on the role of DTs in operationalizing the CE transition, shaping the analysis according to the ReSOLVE framework.

Our analysis indicates a broad focus on the topic, yet there is still the need to tackle it in a more integrated and holistic manner. The discourse is mainly focused on single DTs enabling specific CE aspects; thus, it is tough to have a complete view of all the possible DT implications on the overall CE transition and operatively address the transition itself. From this perspective, the paper suggests interesting directions for further research, aimed at addressing the operationalization of CE through DTs, with an integrated and holistic perspective.

The present study offers contributions from both theoretical and managerial viewpoints. First, we analyzed 66 literature contributions using a comprehensive list of axes for the evaluation: these axes could be useful for scholars and managers alike as a reference guide to continue the exploration of the topic. Second, we provided an analysis of the previous literature according to the axes of evaluation, spurring interest in future research. Third, we suggested the need for additional research on the topic; such research

should provide a more integrated and holistic view on the topic itself, supported by strong empirical evidence. Leveraging on this, further research from academia is fostered, so to support practitioners in understanding the best manner to exploit the enabling potential of DTs.

We conducted our analysis following the principles of ethic, quality and accuracy. Nonetheless, some limitations should be highlighted. First, we conducted our study considering only Scopus as a scientific research database, and different findings may be obtained using other databases. Second, as the role of DTs as an enabler of CE is a current hot topic in the managerial and academic debate, the number of studies on the argument is constantly increasing, and the specific time frame we used could have excluded some relevant recent contributions. Future research should be thus directed to consider the abovementioned limitations, while also investigating the evolution of the research topic.

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