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Review

Driving Circular Economy through Digital Technologies: Current Research Status and Future Directions

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Abstract: The transition from a linear economy (LE) to a circular economy (CE) is not just about mitigating the negative impacts of LE, but also about considering changes in infrastructure, while leveraging the power of technology to reduce resource production and consumption and waste generation, and improve long-term resilience. The existing research suggests that digital technologies (DTs) have great potential to drive the CE. However, despite the exponential growth and increasing interest in studies on DTs and the CE from year 2016 onwards, few systematic studies on the application of DTs to enable the CE have been found. In addition, the current status and development direction of the DT-driven CE is unclear, and the potential of DTs to support CE implementation is under-researched. Therefore, the aim of this paper is to explore the potential of DTs to drive the CE. This paper set out to analyze the current status and development of the DT-driven CE and examine future development trends in the field. Using a systematic literature review approach, this paper is the first attempt to use a mixed method, i.e., to combine macro-quantitative bibliometric methods with a micro-qualitative content analysis method to explore the DT-driven CE. The results, which include the research background, co-occurrence clusters, research hotspots, and development trends of keyword co-occurrence network visualization and keyword burst detection, are presented from a macro perspective using two bibliometric analysis softwares. In addition, the use of 13 specific DTs in the CE is analyzed according to seven disciplinary areas (Environmental Sciences and Ecology, Engineering, Science and Technology and Other Topics, Business Economics, Computer Science, Operations Research and Management Science, and Construction and Building Technology) of greatest interest from a micro-qualitative point of view. Further, future trends and challenges facing DT-driven CE development are explored and feasible directions for solutions are proposed.

Keywords: circular economy; digital technologies; systematic review; bibliometric; Industry 4.0; big data; internet of things (IoT); Building Information Modeling (BIM); artificial intelligent (AI); digital twin

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1. Introduction

Driven by the urgent global need for sustainable development, the world is transitioning from a linear to a circular economy [1]. The linear economic model, in which raw materials are extracted and processed into products that are manufactured, consumed by the user, and then discarded, i.e., converting finite raw materials (natural resources) into waste, is a flawed economic approach that produces a range of negative environmental and economic impacts [2–4]. A circular economy (CE), on the other hand, is a restorative economic system that promotes the cyclical flow of resources that focuses on the full life-cycle management of products from their production and consumption to their reuse, remanufacturing, and recycling [5]. A CE is based on the circularity R-strategies, which evolved from the 3R model (Reduce, Reuse, and Recycle) to multi-R models, such as the 10R model (Refuse, Redesign, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) [6–8] that decouples economic growth from resource depletion on a life cycle basis, and maintains product value at as high a level as possible [9].

Although the CE concept has been advocated globally since the late 1970s, and the importance of circular multi-R models evidenced for environmental and economic sustainability [10], the transition from an LE to a CE is still at an early stage in terms of data. In fact, the Circularity Gap Report (2022) [11] reported that 9.1% of the global economy had been deemed circular in 2018, but this dropped to 8.6% in 2020. Currently, several countries have introduced policies to emphasize the importance of the CE. The core content of the European Union (EU)'s Circular Economy Action Plan (2020) [12] is to extend the concept of the CE through the entire life cycle of products, expanding from the original leading countries to the major economies within the EU, increasing the coverage of the CE, and leading the development of a global CE. In addition, China's 14th Five-Year Plan for the Development of Circular Economy (2021) [13] proposes the development of laws and regulations on CEs, and the improvement of the statistical evaluation system of CEs. Further, private organizations have launched branding strategies, such as IKEA, specializing in second-hand furniture shops that recycle second-hand goods from consumers [14]. Apple's Environmental Progress Report (2023) [15] mentions net-zero carbon emissions to apply to all products manufactured by the year 2030, with the entire product value chain switching to 100% clean electricity.

CE principles cannot be implemented without the support of digital technologies (DTs), and a digital CE is an emerging concept that aims to help to improve resource utilization [16] and become an effective measure to cope with the environmental and economic pressures on businesses [17]. DTs are electronic tools for generating, processing, storing, transmitting, and restoring information, which go hand in hand with electronic computers [4]. In recent years, there has been a growing interest in research related to DTs and CEs, but for the time being, research focusing on CEs and DTs is still in its infancy. A number of studies have made an in-depth study of the use of one or more specific DTs for the CE applied to a particular field [18,19], while others have illustrated how DTs can support CEs through real-life examples from companies [20,21], and focused on innovation in circular business models, particularly the development of product–service systems [19,21]. As a CE driver, digitalization deepens the collection and analysis of data to support the management and optimization of products throughout their lifecycle, making products, services, and supply chains more cyclical through digital means [22].

However, despite the exponential growth of the published research on DTs and CEs from 2016 onwards, few systematic studies on the application of DTs to support CEs have been found. In addition, the current status and development direction of a DT-driven CE is unclear and under-researched. Therefore, the purpose of this paper is to explore the potential of DTs to enable CE adoption and implementation by analyzing the current status and development of a DT-driven CE and examine future development trends in the field.

2. Methods

In this study, a systematic literature review (SLR) approach was used to analyze the state of the art on the topic, which is a comprehensive research method that functions as a knowledge innovator [23]. It is a process of integrating, collating, and evaluating the field literature, where integrating refers to identifying and acquiring the literature, and comprehensively reviewing the literature related to the research topic; collating refers to sorting out the literature; and evaluating refers to analyzing and evaluating [24]. SLR is an integration of quantitative and qualitative analyses via a set of systematic review process provided from national institutes of health [25], which is adapted in this paper, as shown in Figure 1. The adopted methodology comprises the following seven phases: (1) identifying the research questions; (2) searching databases; (3) defining selection criteria; (4) defining quality standards; (5) carrying out a macro-quantitative bibliometric analysis;

(6) conducting a micro-qualitative analysis; and (7) discussing future development trends. Specific tasks for each phase are detailed below.

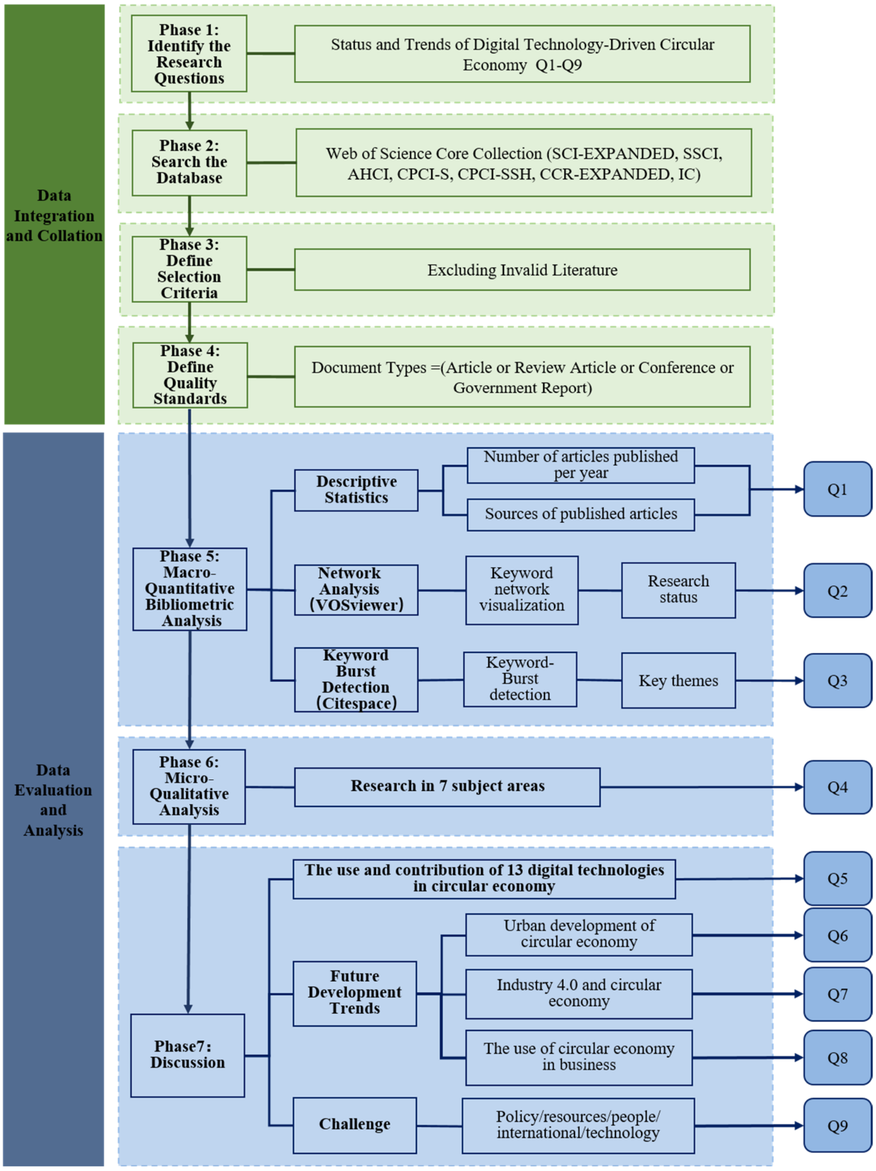


Figure 1. The flow chart of the research methodology (generated by authors).

2.1. Phase 1: Identifying the Research Questions

The aim of this paper is to answer the question, "what are the current status, trends, and contributions of digital technologies to drive a circular economy?". To address the aim of the paper, the following questions are explored, as shown in Figure 1:

Q1: What is the research background of DTs as enablers for the CE?
Q2: What is the current state of research on DTs and the CE?
Q3: What are the key themes/hotspots in DTs and the CE?
Q4: What is the current state of research on DTs and the CE in various subject areas?
Q5: What is the use and contribution of individual DTs in the CE?
Q6: Future trends for urban development via the DT-driven CE.
Q7: Future trends for Industry 4.0. associating DTs with the CE.
Q8: The future use of DTs and the CE in businesses.
Q9: Possible future challenges of the DT-enabled CE.

2.2. Phase 2: Search the Database

This paper collects literature from the web of science core collection (WOSCC) database (1900-present). Web of science (WOS) is one of the most authoritative scientific citation databases in the world that allows users to combine keywords with operators such as AND, NOT, and OR to obtain more relevant search results. The search started with the general keywords “digital technology” and “circular economy”, which were processed as: (TOPIC (digital technology) AND TOPIC (circular economy)). TOPIC included abstracts, titles, and keywords in the search. No time limit was set, and a total of 540 documents were obtained. The entire literature was exported as a tab-delimited file, which was used for subsequent bibliometric data analysis. In order to obtain the most relevant literature for further in-depth analysis, the search was repeated (TITLE (digital technology) AND TITLE (circular economy)) to obtain 35 documents for subsequent micro-analysis. Additional filters were added to refine the search with specific research objectives in mind. That is, a secondary data collection was conducted to add additional keyword searches, as shown in Table 1.

Table 1. Keyword terms and number of searches for data collection (generated by the authors).

Keywords	Number of Documents Searched by TOPIC/TITLE
(digital twin) AND (circular economy)	72/5
(virtual reality) AND (circular economy)	30/2
(augmented reality) AND (circular economy)	24/0
(mixed reality) AND (circular economy)	7/0
(artificial intelligence) AND (circular economy)	209/21
(big data) AND (circular economy)	448/32
(additive manufacturing) AND (circular economy)	221/15
(cyber-physical system) AND (circular economy)	61/1
(3D printing) AND (circular economy)	178/9
(cloud computing) AND (circular economy)	40/0
(BIM) AND (circular economy)	102/11
(blockchain) AND (circular economy)	233/46
(industry 4.0) AND (circular economy)	682/139
(internet of things) AND (circular economy)	293/20
(robotics) AND (circular economy)	60/4

2.3. Phase 3: Define Selection Criteria

During the automated search process, there were results with little relevance, for which criteria needed to be set to reduce bias:

(1) Duplicate literature;
(2) Literature unrelated to how DTs can be applied to the circular economy;
(3) Literature where the subject of the study is not related to circular economy;
(4) Literature that does not refer to the actual use of either type of DT;
(5) Non-English literature.

2.4. Phase 4: Define Quality Standards

In order to ensure the quality of the collected data, the criteria for selecting highly relevant published articles are:

(1) The article is widely cited in its field;
(2) Articles published in peer-reviewed international journals or conferences;
(3) Authoritative development reports issued by the government;
(4) Literature on circular economy using different digital technologies.

2.5. Phase 5: Macro-Quantitative Bibliometric Analysis

This stage focuses on bibliometric macro-analysis. The paper begins with descriptive statistics on the topic in terms of distribution and source, using the analytical tools provided by the WOSCC, which is followed up with the help of bibliometric tools to visually explore the knowledge structure and research trends in the research area in the form of graphs. VOSviewer and Citespace software tools were used for macro quantitative analysis. VOSviewer is a knowledge mapping tool widely used in review literature, which has the advantage of being able to extract key terms from a large amount of literature and generate views to help researchers quickly identifying knowledge structures and research hotspots [26]. Citespace, as a literature analysis software, is highly operational, indicating articles involved in the nodes, clustered content, and keyword highlighting [27]. The above two software tools have been integrated to provide a comprehensive perspective to explore the current status and hotspots of each type of DT and CE. The macro-quantitative analyses are associated with (1) the research background and trend of the scientific research in the field, by obtaining the change in article publication and the source of publication through the visualization of WOSCC analysis; (2) the keyword co-occurrence visualization of VOSviewer to reflect the current status of DTs and CE; (3) the research hotspots through the keyword burst detection by Citespace.

2.6. Phase 6: Micro-Qualitative Analysis

Based on the results of the macro-analysis, further in-depth analysis was undertaken via VOSviewer classified with subjects.

2.7. Phase 7: Discussion

The discussion is structured with the most frequent and important results and findings. The dispersed DTs are presented to illustrate their contribution to the CE. The prominent keywords such as city, Industry 4.0, and enterprise, are discussed in relation to the future development of the CE; and the possible future challenges related to policy, resources, and DTs are presented.

3. Results

3.1. Results of Macro-Quantitative Bibliometric Analysis

3.1.1. Descriptive Statistics

- Number of Publications

The trend of the number of publications can intuitively reflect the trend in the scientific research in a field. As shown in Figure 2, the number of publications on a DT-driven CE has increased year by year. Excluding an article on space infrastructure in year 1998, 540 articles have been published from 2016 to 2023. The number of citations have increased considerably from 2019, with an average of 20 citations per paper and 536 citations recorded for the highly cited paper, reflecting the importance of studies in the field, which has gained increasing recognition and growth in recent years.

- Sources of Publications

A total of 297 publication sources have published articles related to the CE and DTs in the WOSCC database over the last eight years. Table 2 shows the top ten sources, in which *Sustainability* and *Journal of Cleaner Production* have the highest number of publications, about 20% of the total publications. The articles are mainly related to subject areas such as sustainability, environment, technology, construction, economics, and management.

3.1.2. Network Analysis

- Keyword network visualization

The 540 publications on the CE and DTs from 2016 to 2023 were imported into the VOSviewer software tool for the keyword co-occurrence analysis. The visualization results are shown in Figure 3, which indicates the current state of the field studies with "CE" as the core keyword, with more specific DT terms also appearing.

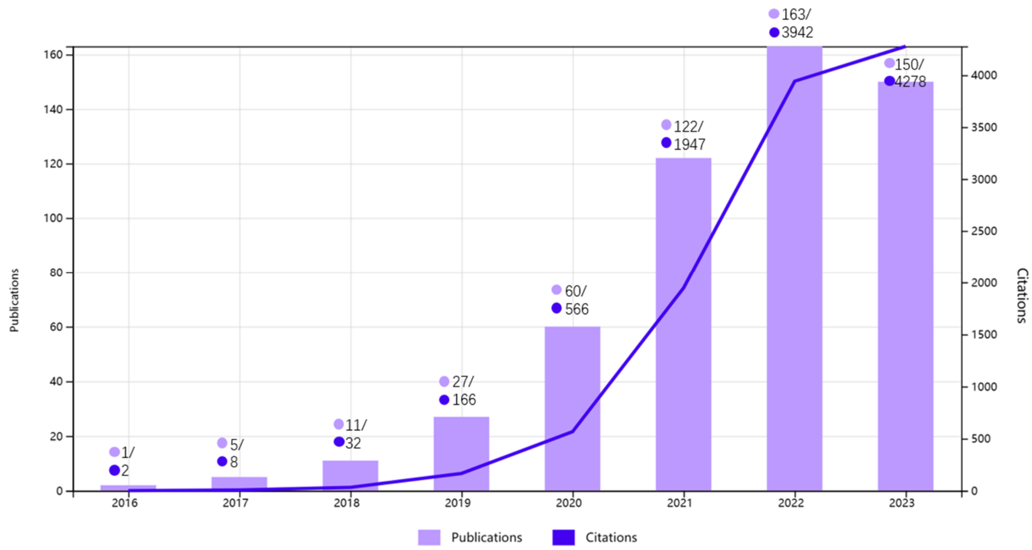


Figure 2. The number of articles and citations on digital technologies (DTs) and circular economy (CE) published annually in the web of science core collection (WOSCC) database from 2016 to 2023.

Table 2. Top 10 most contributory sources of articles on the CE and DTs from 2016 to 2023 (generated by the authors).

Ranking	Publication Titles	Record Count	% of 540
1	*Sustainability*	79	14.630
2	*Journal of Cleaner Production*	31	5.741
3	*Sustainable Production and Consumption*	13	2.407
4	*Business Strategy and the Environment*	12	2.222
5	*Technological Forecasting and Social Change*	11	2.037
6	*Applied Sciences (Basel)*	8	1.481
7	*Buildings*	8	1.481
8	*IFIP Advances in Information and Communication Technology*	7	1.296
9	*International Journal of Production Economics*	7	1.296
10	*Operations Management Research*	7	1.296

In general, DTs include big data [28], the internet of things [29], digital twins [30], blockchains [31], artificial intelligence [32], additive manufacturing [33], 3D printing [34], BIM [35], cyber–physical systems [36], cloud computing [37], virtual reality [38], augmented reality [39], mixed reality [39], and robotics [37]. During the data screening, the DT keywords associated with the CE were used, resulting in studies more related to Industry 4.0 and the CE. Industry 4.0 refers to the integration of DTs into manufacturing and industrial processes and includes a range of technologies such as artificial intelligence, big data, and robotics. Thus, the closely related keywords have been added to the search terms, from which the individual documents obtained using TOPIC, as shown in Table 1, were collated into tab-delimited file format, resulting in a total of 2660 text results. The duplicate text was removed, and synonyms, including singular and plural, and abbreviations were combiend to ensure the quality of the data collected. Using the type of analysis (co-occurrence) and unit of analysis (author keywords), the counting method has been completed with a total of 3859 generated keywords. Due to the large number of keywords, the threshold for displaying keywords is set to "3", which means that keywords present greater than or equal to three times can be displayed on the visualization map of the results, to generate a total of 394 keywords. The closely related 79 keywords were finally generated to form six clusters with different colors, as shown in Figure 4. The results shown in Figures 3 and 4 suggest that adding more literature does not make a significant difference to the study of the current research status and overall development trend of "CE" and "DTs", but more clearly indicates the co-occurrence effect with keywords.

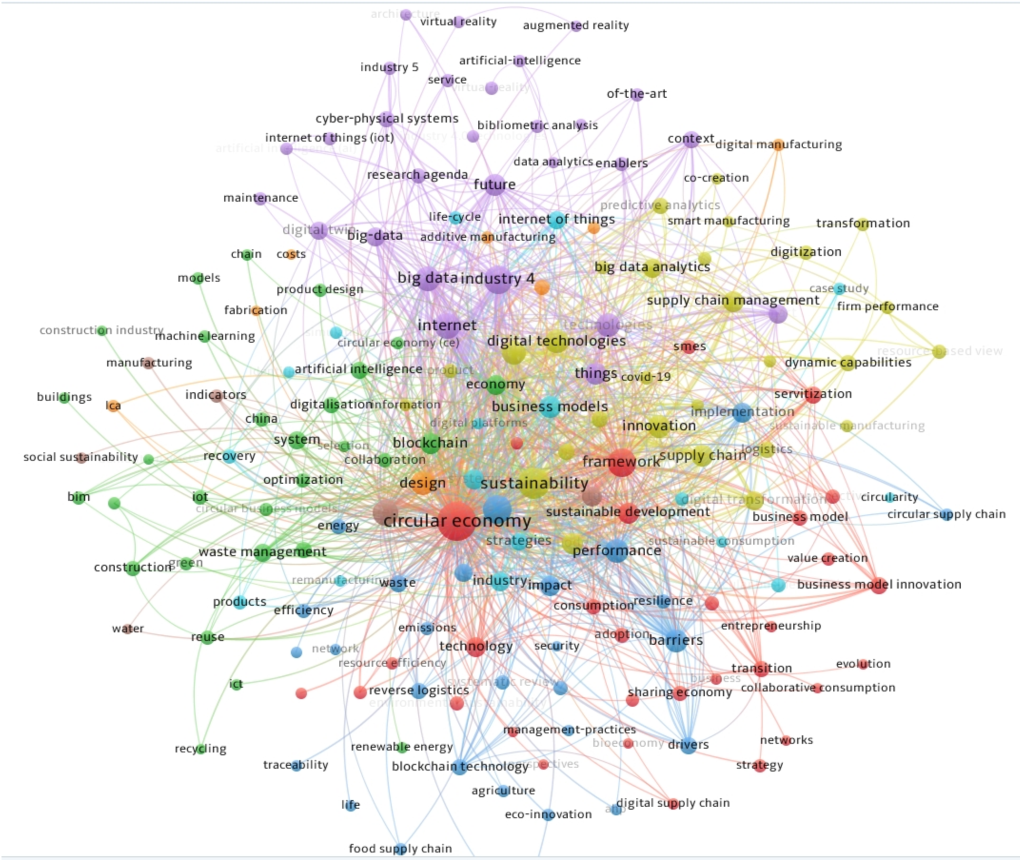


Figure 3. Keyword network visualization on "CE" and "DTs" in the WOSCC database via VOSviewer software tool (generated by the authors).

Figure 4 shows the keyword network visualization, where the size of each circle indicates the weight of the keyword, and the display size of both sides was manually adjusted proportionally in order to balance the display ratio of the keyword and the circle. The distance between the circles indicates the relevance of the two keywords; the higher the relevance, the closer the distance.

As shown in Figure 4, cluster 1 (red) focuses on the core word "circular economy", bordered by 16 keywords such as sustainable, blockchain, and IoT, which indicates sustainable CE implementation relies on the support of DTs in industrial ecology, industrial manufacturing, and technology in engineering research. Cluster 2 (blue) is dedicated to DT-associated computer science, including "big data", "artificial intelligence", "machine learning", "sensors", and "cloud computing", and is also related to the context of "smart city", with more research on waste management. Cluster 3 (yellow) focuses on the use of DTs across the lifecycle of built environment projects, including keywords such as "digital twin", "virtual reality", "augmented reality", "cyber-physical systems", "built environment", "circular design", "BIM", "lifecycle assessment", and "carbon emissions", suggesting the use of DTs in the field of building construction to support CE adoption and implementation. Cluster 4 (green) encompasses methods used in the relevant studies, including "literature review", "bibliometric analyses", and "Citespace", as well as "business models" and "digitalization", which suggests that the current studies on the CE and DTs tend to use bibliometric analysis underpinned by its software tool, i.e., Citespace. Cluster 5 (purple) is the second largest cluster, centered on "industry 4.0" and closely linked to "digital technology" and "sustainability". Cluster 6 (light blue) is associated with "environmental sustainability", "recycling", "3D printing" and "additive manufacturing", which indicates that, in the field of environmental science, there is a focus on recycling using DTs.

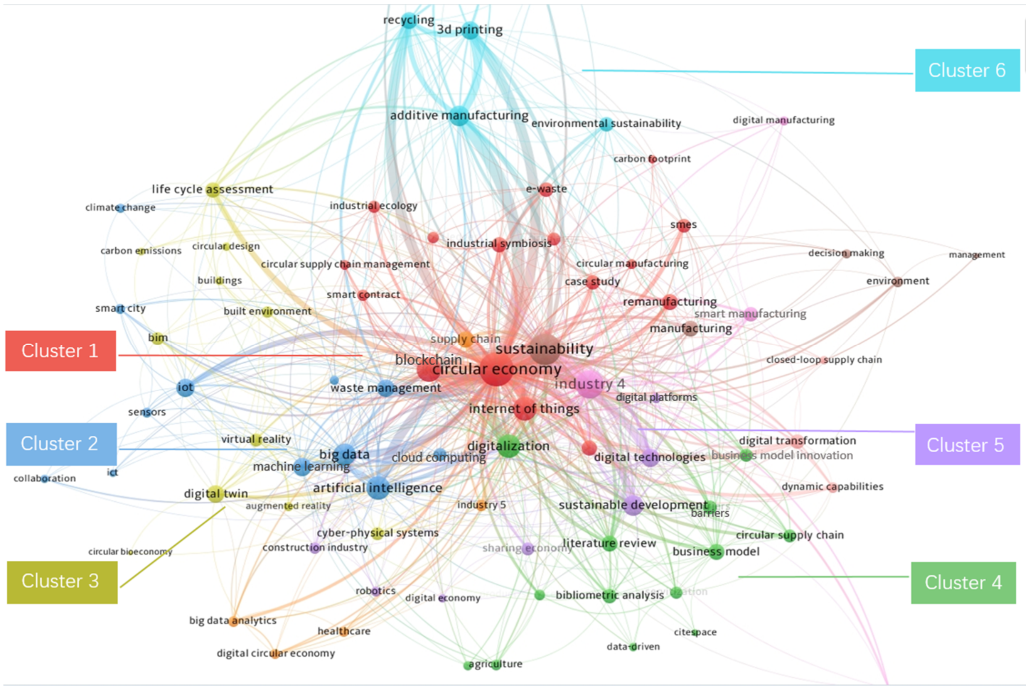


Figure 4. Keyword network visualization on CE and various DTs in the WOSCC database via VOSviewer software tool (generated by the authors).

As shown in Figure 4, the keywords “sustainability”, “circular economy”, and “industry 4.0” form a tight triangle, around which all the clusters are gathered. Industry 4.0 involves not only the application of DTs, but also the promotion of manufacturing. The CE is about sustainable design, the use of recycling products, and the advancement of technology to mitigate environmental problems such as climate change.

3.1.3. Keyword Burst Detection

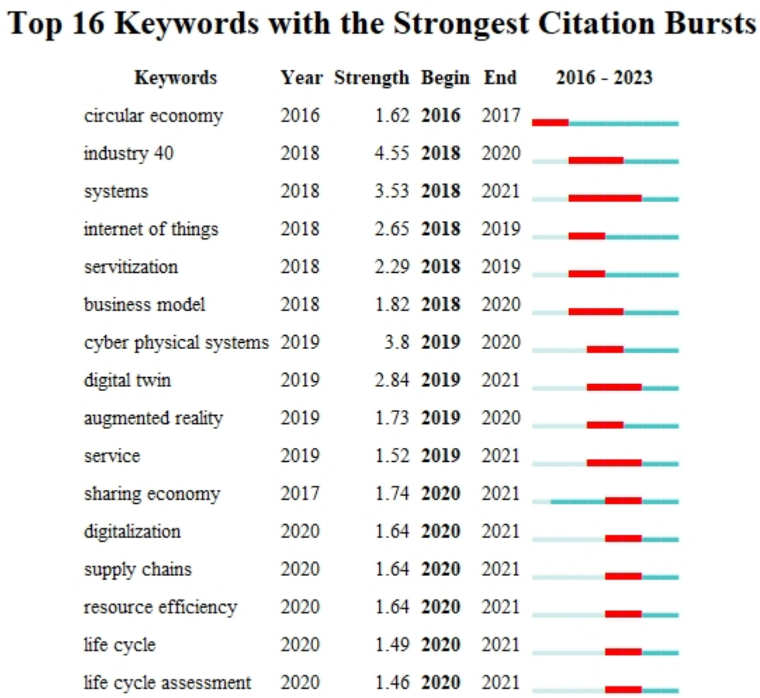
Keyword burst detection in Citespace is used to detect situations where there is a large change in the number of citations in a certain period of time, such as a rise or decline. A red horizontal line is formed from the beginning to the end of the keyword burst, indicating the importance of the keyword in the field and how much attention it has been paid, and the longer the length of the burst, the longer the keyword’s popularity lasts and the more cutting-edge the research is [40] (pp. 2000–2017). Figure 5 depicts the top 16 keywords with the highest burst values from 2016 to 2023.

As shown in Figure 5, the Citespace software tool automatically screens for invalid time and sifts out content before 2016. The keywords presented in Figure 5 are similar to the keywords from the previous visualization of the VOSviewer software tool. The keyword “circular economy” is the strongest citation among the explosive strength keywords. Various DTs centered on “industry 4.0”, such as “IoT”, “cyber-physical systems”, “digital twins”, and “augmented reality”, show highly explosive strength. Through DTs, companies can optimize product lifecycle management, improve efficiency, service, and quality, reduce costs, and make products lean from raw material to final flow, achieving the efficient use of resources.

3.2. Results of the Micro-Qualitative Content Analysis

3.2.1. Classification and Selection of the Research Subject Areas

Figure 6 covers research topics that have received increasing attention since 2016, with a total of 52 subject areas related to the CE and DTs. From 2020, the number of studies has increased rapidly, from 122 articles in 2021 to 163 articles 2022, and there is a continuing trend of growth in 2023, with 150 articles so far. Figure 6 shows the top 10 research areas and their percentages, with Environmental Sciences and Ecology having the highest number of publications, equating to more than 200 articles, followed by Engineering and Science and Technology and Other Topics, with more than 160 articles. Due to the interdisciplinary nature of the research topic, the articles are dispersed in different journals, mainly related to the fields of environment, sustainability, engineering, technology, business, and management. The keywords of each of the 10 research areas were imported into the VOSviewer for a keyword co-occurrence analysis to reveal the current status and research trends of multidisciplinary research, the results of which for the research areas of Materials Science, Chemistry, and Energy Fuels could not be effectively generated due to the small amount of literature, resulting in seven subjects, i.e., Environmental Sciences and Ecology, Engineering, Science and Technology and Other Topics, Business Economics, Computer Science, Operations Research and Management Science, and Construction and Building Technology.


Top 16 Keywords with the Strongest Citation Bursts

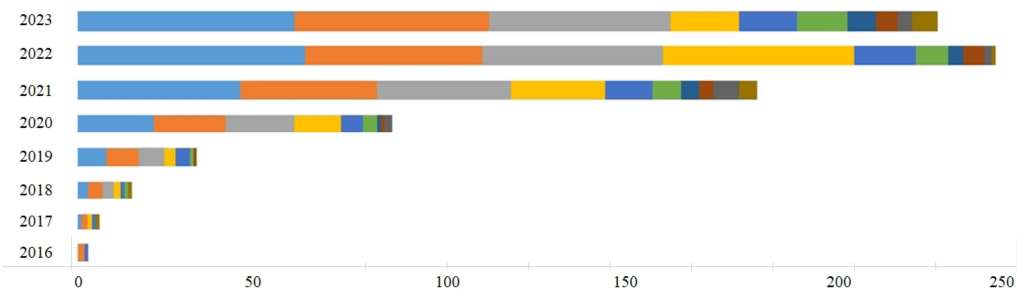
Keywords	Year	Strength	Begin	End	2016 - 2023
circular economy	2016	1.62	**2016**	2017	
industry 40	2018	4.55	**2018**	2020	
systems	2018	3.53	**2018**	2021	
internet of things	2018	2.65	**2018**	2019	
servitization	2018	2.29	**2018**	2019	
business model	2018	1.82	**2018**	2020	
cyber physical systems	2019	3.8	**2019**	2020	
digital twin	2019	2.84	**2019**	2021	
augmented reality	2019	1.73	**2019**	2020	
service	2019	1.52	**2019**	2021	
sharing economy	2017	1.74	**2020**	2021	
digitalization	2020	1.64	**2020**	2021	
supply chains	2020	1.64	**2020**	2021	
resource efficiency	2020	1.64	**2020**	2021	
life cycle	2020	1.49	**2020**	2021	
life cycle assessment	2020	1.46	**2020**	2021	

Figure 5. Top 16 keywords with the strongest citation bursts on CE and DTs from 2016 to 2023 created via Citespace software tool (generated by the authors).

3.2.2. Seven Research Subject Areas

Environmental Sciences Ecology

The collected 201 articles on the CE and DTs in the field of Environmental Sciences and Ecology were imported into the VOSviewer, with a threshold of keyword occurrence as three, to generate a map of the visualized keyword co-occurrence, as shown in Figure 7. "Environmental Science and Ecology" aims to improve people's understanding of the natural environment and provide a scientific basis for environmental protection and sustainable development, and focuses on the conservation of biodiversity, the maintenance of ecosystem functions, the impact of human activities on the environment (e.g., climate change, land destruction, and discusses impacts and countermeasures) and the sustainability of ecosystems. The main thrust of the CE is to maintain the value of products, materials, and resources for as long as possible and to minimize the generation of waste [41]. Therefore, because the goals of the CE are highly correlated with those of Environmental Science and Ecology, there will be a large amount of relevant literature around this subject. From the results presented by the keywords, there are three main clusters: the "red" cluster is centered on "economy", related to "business models", "products", "customers", and "services"; the "green" cluster is focused on "technology", related to "blockchain", "AI", "big data" and "IoT" technologies; and the "blue" cluster is linked to "sustainable development", related to "environmental impacts", "consumption", "sustainable manufacturing", and "climate change".



Color	Research Area	2016	2017	2018	2019	2020	2021	2022	2023
	Environmental Sciences Ecology	0	1	3	8	21	45	63	60
	Engineering	2	2	4	9	20	38	49	54
	Science Technology Other Topics	0	0	3	7	19	37	50	50
	Business Economics	0	1	2	3	13	26	53	19
	Computer Science	1	1	1	4	6	13	17	16
	Operations Research Management Science	0	0	1	1	4	8	9	14
	Construction Building Technology	0	0	0	0	1	5	4	8
	Materials Science	0	0	0	1	1	4	6	6
	Chemistry	0	0	0	0	2	7	2	4
	Energy Fuels	0	1	1	0	0	5	1	7

Figure 6. Number of articles published from 2016 to 2023, categorized into 10 research areas (generated by the authors).

In addition, the main focus of Figure 7 is on how products can be managed through DTs and circular business models for the sustainable life cycle management of the whole process. The environmental impact of a technology is one of the key measures that determine its viability and sustainability [42]. Additive manufacturing can reduce the burden on the environment by reusing end-of-life materials and products in the recycling, reuse, and remanufacturing chain, ensuring that resources continue to be used for as long as possible [33]. However, some studies argue that employing DTs will not further enhance the CE, but rather act as a hindrance [4]. For example, technologies that focus on recycling instead incur significant overheads. Although the implementation of technologies is not mature enough at the moment, DTs have been declared to be the key to the transition to a CE in various industries [43]. Interestingly, DTs have been found to support circular strategies in different sectors, such as the product design sector, operations management sector, supply chain optimization, and post-use recycling sector [17,44].

Engineering

Engineering is a multidisciplinary field that includes mechanical, electrical, civil, and computer engineering. For the engineering research subject area, as shown in Figure 8, each cluster has DTs, of which the "blue" cluster is dominated by DTs related to the construction industry, such as "VR", "AR", "blockchain", "digital twins", and "IoT". The "red" cluster emphasizes "digitalization", which is dominated by "use", "service", "cost", "source", and "life"; and the "green" cluster focuses on how companies could implement CE, taking into account products' "lifecycle", "value chain", "supply chain", and "business model", and improving resource utilization through the adoption of DTs.

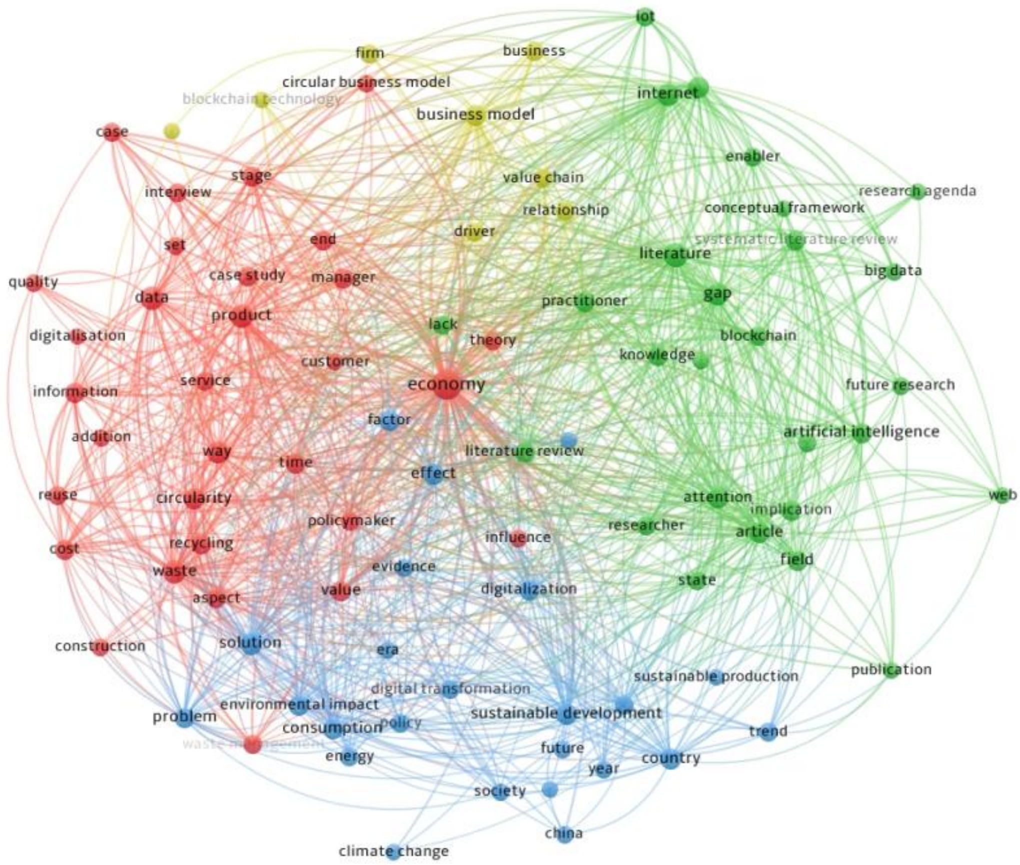


Figure 7. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Environmental Science Ecology between 2016 and 2023 (generated by the authors).

In addition, there are currently a wide range of DT application areas for cyber–physical systems including, but not limited to, communications, energy, healthcare, manufacturing, robotics, the military, household appliances, consumer services, and transport [36]. The utilization of cyber–physical systems in the use phase (maintenance and repair) has received more attention. It can calculate methods for dismantling target components in washing machines and can be integrated with other DTs to monitor products, collect data, and optimize processes to improve productivity and reuse [44,45]. The application of IoT can help to automate production processes and improve efficiency and the quality of life by connecting home devices such as sensors, washing machines, air conditioners, and refrigerators to the digital environment [46]. Additionally, additive manufacturing is a computer-controlled industrial process used in the aerospace and automotive industries to produce parts in various fields [29]. Further, VR and AR provide educational training that simulates real situations, for workers engaged in disassembly or remanufacturing activities to learn manual processes [47], and to avoid hazardous situations [48]. In addition to remote collaboration and simulation training, the use of VR and AR helps designers to view the design results more intuitively and make adjustments [49].

Science and Technology and Other Topics

The “Science and Technology and Other Topics” domain refers to a variety of research areas within the broader scope of science and technology, as shown in Figure 9. The subject area is divided into four clusters: (1) the “green” cluster focuses on “economy” and relates to “service”, “environment”, “recycling”, “waste”, and “energy”; (2) the “blue” cluster concerns “technology” and “business models”; (3) the “red” cluster highlights “stakeholders” in relation to “innovation”, “sustainability”, “digitalization”, and “society”; and (4) the “yellow” cluster mainly illustrates the used methodologies, such as systematic literature reviews, to study and analyze future trends. Additionally, this section mainly highlights the use of technology and the development of sustainability by stakeholders through the optimization of whole processes. For example, the CE in the field of chemistry focuses on the reuse of secondary raw materials and the recycling of resources by converting waste into energy and chemicals, which could be applied to areas such as computer hardware, building materials, and engineering parts.

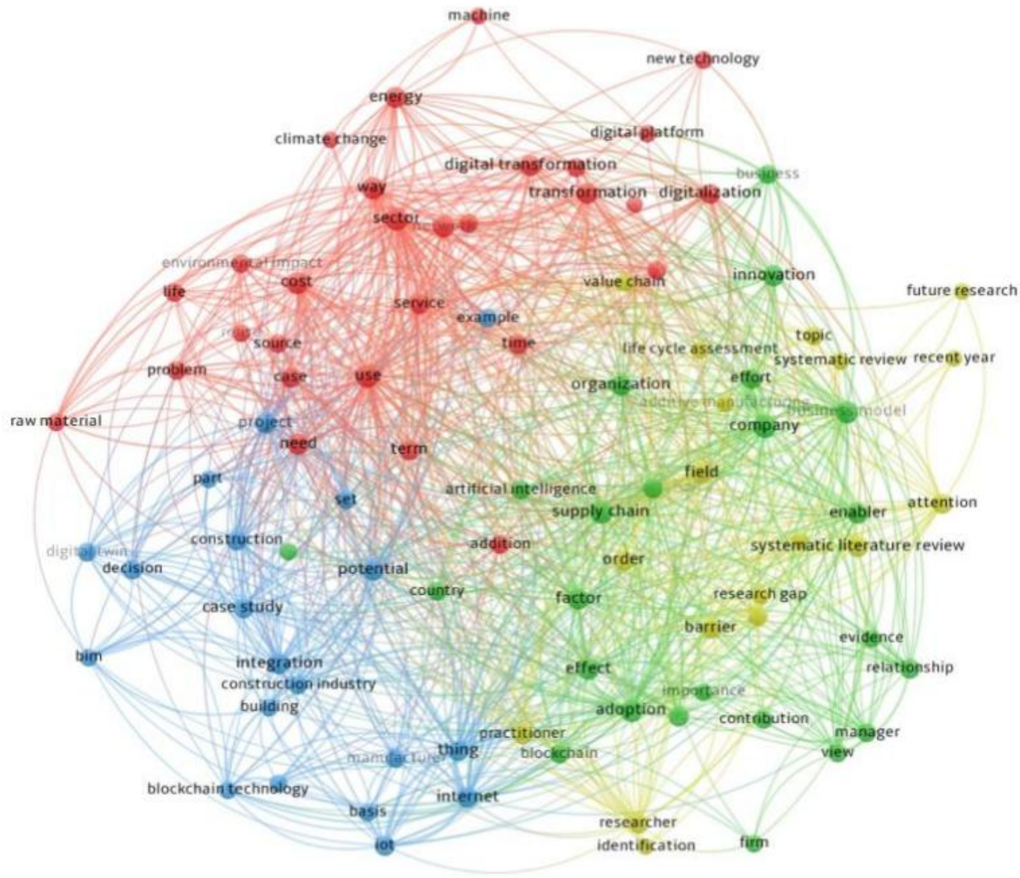


Figure 8. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Engineering between year 2016 and 2023 (generated by the authors).

For the technologies employed in the area of game design, VR with BIM have been integrated with digital twins to advance the CE in built environment research that identifies three key pillars for reducing waste generated in the construction industry: education, documentation, and visualization [38]. AI is often developed and operated in conjunction with other DTs [50], e.g., analyzing data collected by IoT via AI systems, and combining image recognition technology with robots for sorting mixed material streams [51,52]. Further, blockchains protect the technical, instrumental, and policy security of the networked environment and guarantees the confidentiality, integrity, and availability of data [53], which provides a secure and transparent system that minimizes transaction costs and improves communication [54]. As such, organizations can manage the entire supply chain process to reuse end-of-life materials and reduce waste generation [55].

Business Economics

The field of "Business Economics" is predictably centered on "economy", with a focus on 'business models", "firms", "products", and "services", as shown in Figure 10. By increasing the reuse of products, it reduces the impact on the environment and the economy. DTs help to achieve sustainable marketing by playing different roles, considering environmental protection, socio-economic, and corporate governance [4]. Blockchains are widely used in the field of business economics for intra-enterprise collaboration, cross-border payments, transaction security, and data transparency to help organizations establish transparent, secure, and reliable transaction environments, reduce time and resource costs, and improve trust [49,56]. The integration of AI and big data analytics can be used to understand customer needs, manage customer relationships, and make personalized recommendations by predicting trends, and improving customer satisfaction and fraud prevention [16,32].

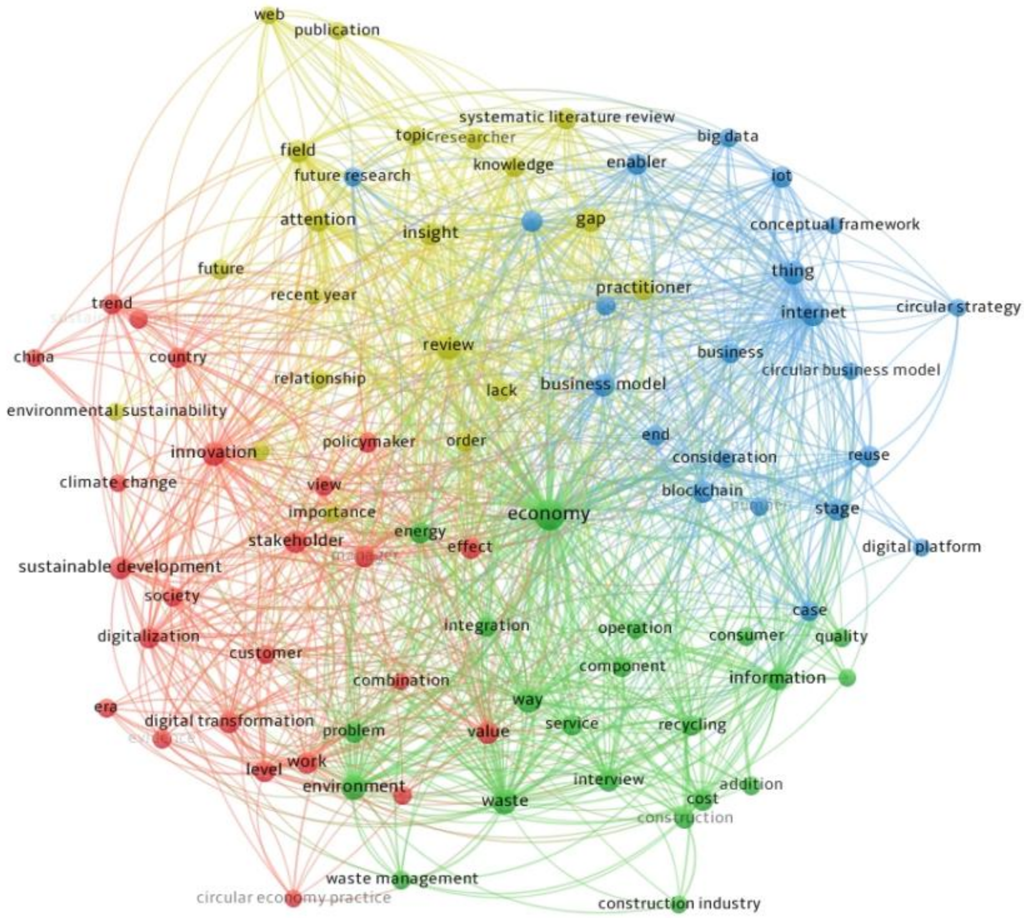


Figure 9. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Science and Technology and Other Topics between 2016 and 2023 (generated by the authors).

Computer Science

As shown in Figure 11, the visualization of the keywords presented in the "Computer Science" field is not ideal. As such, the clustering distribution is not obvious and scattered with regard to the individual DTs, of which the most obvious keyword is "transformation", suggesting that the emergence of changes in thinking, behaviors, and technologies in the field of computer science facilitate the adaptation of the business and organization to the new environments and challenges. In addition to technology, many keywords can be found in relation to stakeholders such as "person", "practitioner", "researcher", "customer", "organization", "company", "government", and "country". Through consumers' use of digital platforms, DTs enable resource sharing and circulation, and facilitates customers' purchase decisions of sustainable products and their direct and indirect participation in the recycling process to improve resource utilization. For enterprises and organizations, DTs help to better the understanding of consumer demand, adjust marketing strategies, and achieve the organic integration of production and consumption [37]. For governments, DTs facilitate the monitoring of the consumption and utilization of resources, grasp the flow of resources and real-time status, and the formulation of measures. For the international community, an international cooperation and exchange platform can be built through the network platform to promote cooperation among countries.

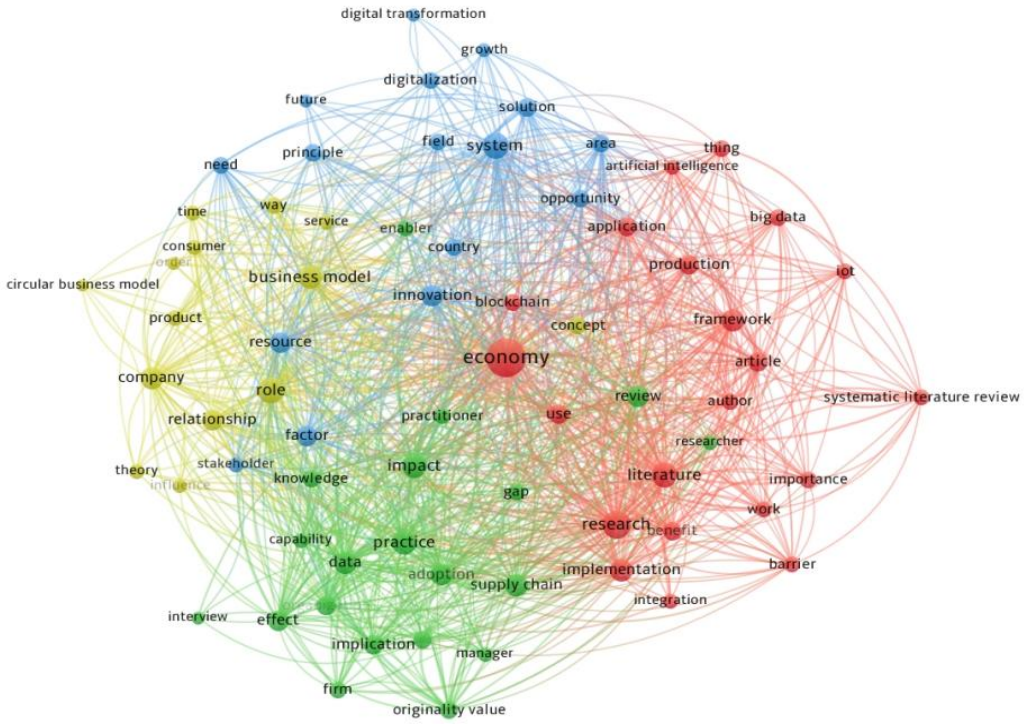


Figure 10. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Business Economics between 2016 and 2023 (generated by the authors).

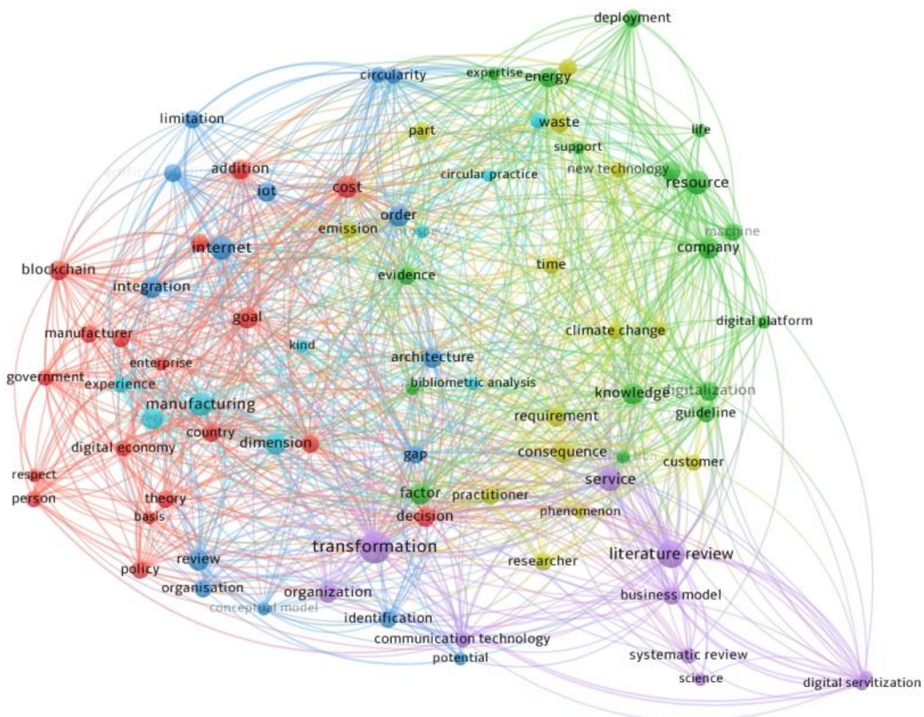


Figure 11. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Computer Science between 2016 and 2023 (generated by the authors).

In addition, big data, through AI, IoT, and cloud computing, connect companies' devices and systems for data collection and analysis, and provide data and train machine learning and algorithms, from which the integration of technologies helps to improve product quality, user and device services, and iterative manufacturing [19,48]. Data visualization is another major aspect, which is mainly achieved through augmented reality and virtual reality allowing for the visualization of infrastructure (i.e., pipelines, and cables) to prevent the damage of underground facilities or economic and environmental impacts [18,57]. Further, IoT is often used in conjunction with other technologies to improve productivity, efficiency, and reliability [58,59], e.g., to form interoperable networks with other technologies such as radio frequency identification systems, and cloud computing [43,60], to send and receive real-time production and process data through interconnected sensors [61].

Operations Research Management Science

The "Operations Research and Management Science" field encompasses two different yet connected subjects: (1) "Operations Research" is a comprehensive subject involving in mathematics, statistics, and computer science to optimize decision making through numerical models and techniques. (2) "Management Science" focuses more on management practices and methodologies to improve business performance and management through systematic analyses, with an emphasis on data-driven decision making and innovation [62]. As shown in Figure 12, the "green" cluster is dominated by "data", including "environment", "organization", "sustainability", and "enterprise". The "red" cluster is related to "application", "information", and includes "service", "circularity", and "food products". The "blue" cluster is associated with "products", and "business models" and the "yellow" cluster is mainly related to DTs.

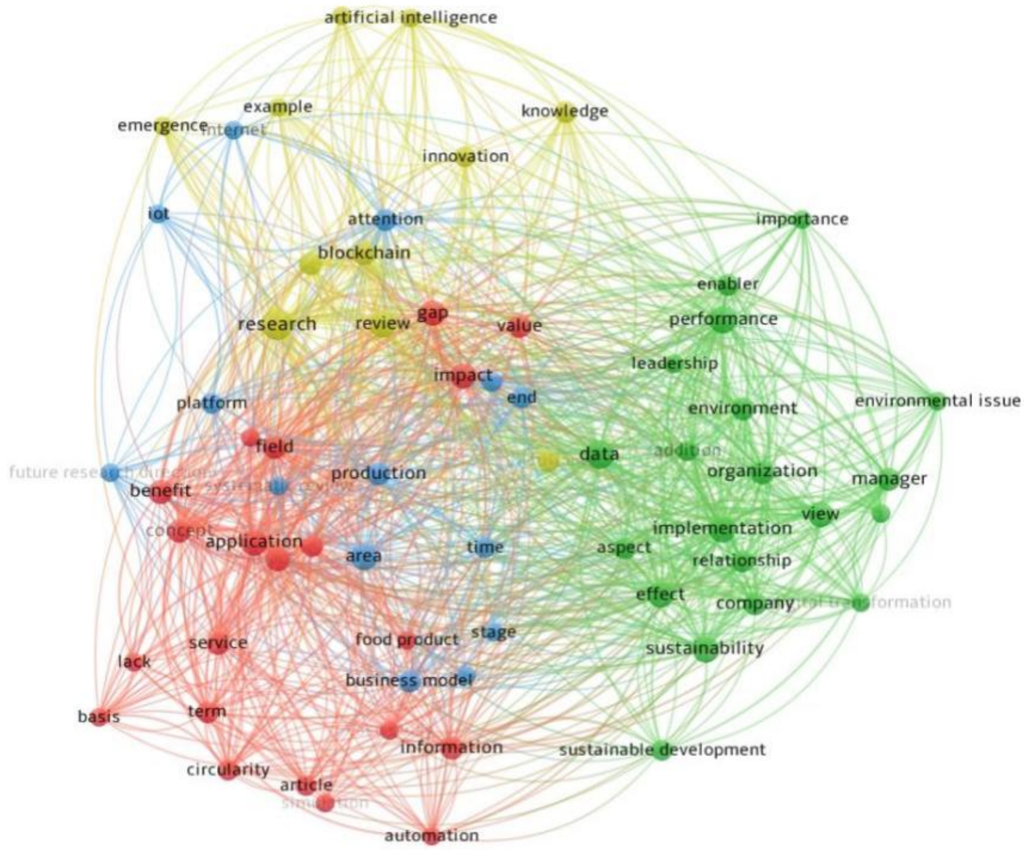


Figure 12. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Operations Research and Management Science between 2016 and 2023 (generated by the authors).

A CE in "Operations Research Management Science" could help with resource management, including the management of waste materials, backlog inventory, and human resources, and improve the flexibility and sustainability of the supply chain. By using machine learning and AI, organizations make smarter decisions, including resource allocation, product design, and market positioning, via cyber–physical systems that connect cyberspace, physical processes, and objects, from which real-time data can be monitored and exchanged for decision making [32,63]. As such, these intelligent decision-support systems improve the competitiveness of organizations.

Construction and Building Technology

As shown in Figure 13, the map of keyword co-occurrence visualization is divided into two clusters, "red" cluster and "green" cluster, by "blue" cluster with "challenge", and "environment" keywords, in which clusters are centered around "construction", "sustainability", "lifecycle" and DTs.

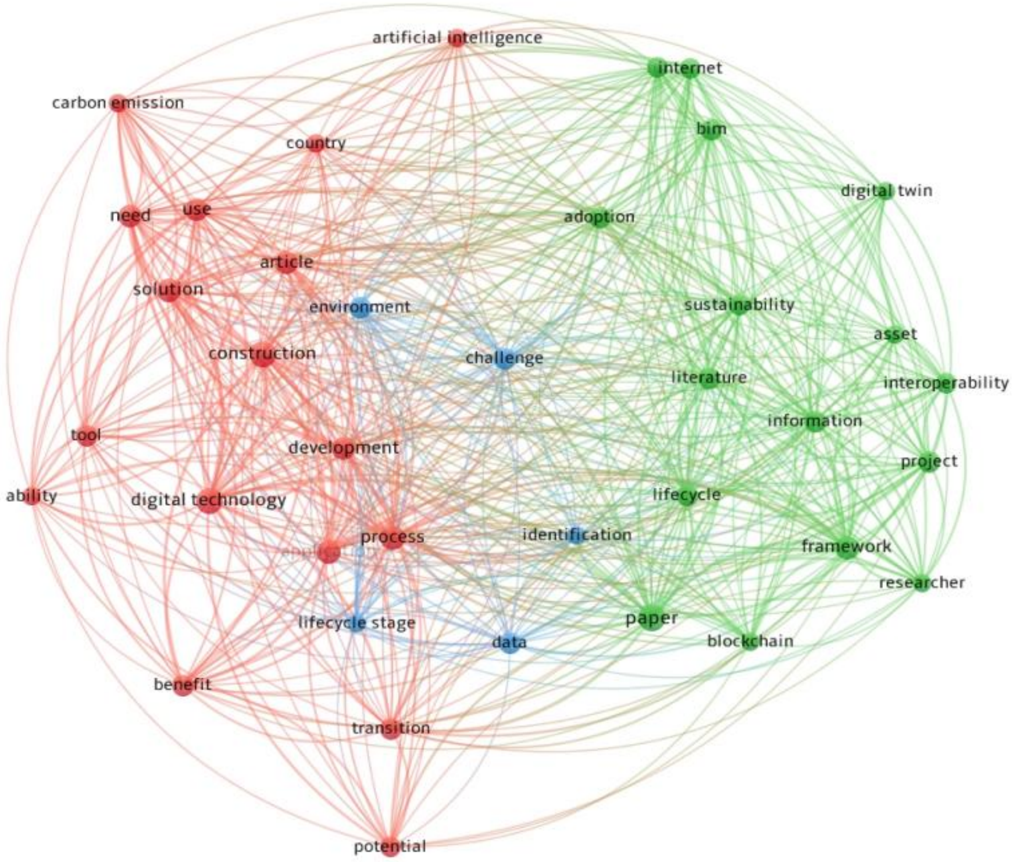


Figure 13. Keyword co-occurrence visualization of articles published on CE and DTs in the field of Construction and Building Technology between 2016 and 2023 (generated by the authors).

Digital twins are currently mostly used in the aerospace and automotive industries, to simulate performance [29], and are also used in the field of the built environment to facilitate the completion of a construction project through the integration of BIM throughout the building lifecycle, i.e., design, construction, operation and maintenance, and demolition. Building information recorded in BIM provides static data for digital twins that can carry out the dynamic processing of the information, which, in the construction domain, can be driven by machine learning capabilities, on the collected data during the building lifecycle [29]. Currently, the integration of CE and digital twins has rarely been investigated in architecture [30], but the technology has been used in different stages of the built environment.

In addition, VR and AR are considered effective tools for more sustainable building design, which can be applied to design review, construction, operations, management, training, and stakeholder engagement [64]. Robots are mainly used for drilling or assembling complex and delicate wood and metal components [65] and casting large-volume projects such as concrete [66]. Additive manufacturing is used in concrete printing and the manufacture of building components [67].

Further, BIM has been used for project databases, data checking, and material development and recycling [29], and is widely adopted in the built environment, where BIM provides comprehensive digital information to help reduce resource wastage at all stages of the lifecycle, and efficiently manage the reuse and recycling of materials and maintenance. BIM that incorporates CE principles helps stakeholders to evaluate the pros and cons of different designs, materials, and processes, assisting management to make informed decisions [35].

4. Discussion

4.1. Current Research State: The Use of Different Digital Technologies (DTs) to Drive Circular Economy (CE)

This paper analyzes the background, current state of research, and key themes of DTs for the CE through a macro-quantitative analysis. The keyword results lead us to conduct a classification analysis on the micro level about the research subject areas, of which many specific DT terms related to the CE were identified. Additionally, this paper uncovers 13 types of DTs used to enhance the CE. These are discussed below.

4.1.1. Digital Twins for CE

The results show that digital twins are strongly linked to "VR", "AR", "BIM", "built environment", and "life cycle". Digital twins are virtualized collections of real-world information and physical assets that can manage information about a specific product throughout its lifecycle, visualizing product design parameters and status data [68]. Digital twins can directly reflect the dynamics of a real product, with near real-time information transfer through sensors, communication networks, and data models [68,69]. Due to the characteristics of digital twins and their ability to collect, organize, and provide effective information [70], it is a reliable DT to support CE research [71].

In addition, the results suggest that, in Construction and Building Technology, the inclusion of digital twins improves transparency and traceability throughout the chain, which accordingly saves unnecessary and repetitive steps at each stage of the lifecycle and enhances collaboration among stakeholders. In the design stage, the information collected in real time helps in the development of new products; and, in the production stage, machine learning capabilities for digital twins facilitate automating the order processing [72]; in the usage stage, digital twins assists the user to use the product correctly in order to improve its lifecycle performance and usability [44]; and, in the post-sale stage, digital twins are associated with making autonomous decisions on whether to reuse/remanufacture or recycle the product [68]. The use of digital twins across the whole lifecycle has the potential to reduce material and energy resources and time, and improve efficiency and accuracy.

4.1.2. Big Data for CE

Big data is a collection of huge amounts of data, referring to the high-velocity emergence of large volumes, variety, value, and veracity [73]. Since "big data is worthless in a vacuum" [74], the value of big data lies in transforming it into meaningful insights through advanced analysis, the insights from which help to add knowledge to support decision making from a cyclical perspective [75,76]. In addition to improving resource management across the product lifecycle, big data analytics enhance the understanding of user behavior, leading to optimized iterations of product design to achieve more effective circularity [49].

In the "Business Economics" field, big data-enhanced decision effectiveness and CE performance were regarded in the reviewed articles as positively correlated. Data-driven decision making enables higher productivity [28]; especially in organizations, big data analytics impacts on more and more business units [16] such as supply chains, logistics, marketing, and even overall economic and business policies [77,78], thus facilitating the application of the CE.

4.1.3. Internet of Things for CE

The Internet of Things is one of the core technologies of Industry 4.0, allowing for the interaction, co-operation, collection, and exchange of data between people, devices, and objects through the use of modern wireless telecommunications [79]. It is mainly oriented towards the problem of communication between objects and systems [80] and used with smart devices to help adjust decisions by responding in real time to the environment [81]. The International Telecommunication Union [82] defines it as "a global infrastructure for the information society, enabling advanced services through interconnected things based on existing and evolving interoperable information and communication technologies".

The findings of this paper show that the integration of IoT and the CE has been demonstrated in a number of areas, ranging from small household products to large smart cities. IoT enables the CE by facilitating the management of product lifecycles, which can better reduce scrap rates and enable lower environmental footprints by supervising operational data, real-time tracking, and the accurate prediction of data [83–86]. Compared to other DTs, IoT essentially facilitates the improvement of resource utilization and extension of the product lifespan by collecting and analyzing product-related data during (re)design, production, maintenance, dismantling and recycling, and adopting CE practices to achieve a higher degree of overall process circularity [19,44,87,88].

4.1.4. Artificial Intelligence for CE

Artificial Intelligence is a new technological science that is simulated by computers or machines, to extend and expand the ability of human thinking [89], and has the ability to reason and develop mental abilities. It assists in the improvement of decision making and develops perception, association, planning, motion control, and deep learning through research in the fields of image processing, natural language processing, and machine learning [90,91].

AI is considered as a technology with great potential to drive CE development, identifying new routes for CE development and improving the quality of processes, including data analytics, predictive analytics, reverse logistics, improved process optimization, and enhanced responsiveness in the transition to a regenerative economic model. In addition, how the AI can positively impact the transition to CE, describing the practical applications of AI in the CE, through examples, has been explored [32], such as iteratively assisted design processes and predictive maintenance to keep products, components and materials at their optimum value, reduce equipment costs, and extend service life [92,93]. Further, the findings reveal that AI could enhance the necessary infrastructure elements in the production phase as well as in the recycling phase, resulting in sustainable ways to optimize resource use to promote circular businesses and practices [50].

4.1.5. Cloud Computing for CE

The findings indicate that there are few studies on cloud computing to support the CE. Cloud computing is an architectural model that pools computer resources and applications to form a resource pool, enabling on-demand network access to shared resources in the pool [94], which has played a catalytic role in the direction of CE, showing great potential to support collaboration in different industries [18,95].

4.1.6. Immersive Technologies for CE

Immersive technologies include VR, AR, MR, and XR. VR is a computer-generated 3D virtual environment that allows users to immerse themselves in a perceptual technology that is isolated from the real environment using their eyes, HMDs, or other display devices [96]. Augmented reality is the addition or removal of computer-generated interactive virtual objects or information from a 3D model in a real environment that is an extension of the real world [47]. Mixed reality is the mixing of real and virtual environments through holograms and can be seen as a mix of VR and AR [39]. Extended Reality (XR) encompasses VR, AR, and MR, and is an umbrella term for immersive technologies [39].

The combination of AR and VR is predominant in the integration of CE, as the results show that both have a high impact on CE principles. Virtualization helps in designing modular products, providing education and training, creating virtual work environments, encouraging people to work more flexibly, providing remote services, and reducing logistical requirements [49,84]. XR has been identified as a technology that can support the CE in a number of ways, such as facilitating the redesign of products to improve circularity [97]. Although there is a lack of harmonized technical and legal standards and clear workflows, XR can be used in a variety of fields such as industrial engineering, acoustic haptics, psychology, software design, hardware engineering, healthcare, and manufacturing [39].

4.1.7. Robotics for CE

Automated robots are robots that are able to operate autonomously and can interact and co-operate with humans [98], which contribute to the automated production of activities related to the decision making process [99], disassembly [100], maintenance [4], and recycling [48]. They are capable of replacing human labor in repetitive, hazardous, and precise work [29], increasing efficiency and reducing costs and resource consumption throughout the life cycle's stages [37].

The results suggest that automated robots have different characteristics within different industries, in which its flexibility and uniqueness can help to support the current practice of the CE that focuses on resource efficiency and eco-design in the production, disassembly, and remanufacturing phases. In the production and manufacturing phases, it is useful to reduce the consumption of plastics, reduce material waste by implementing automated robots [37,48], improve material handling, picking, and packing, improve inspection efficiency, and provide a more sustainable working environment [101]. In the dismantling phase, resources can be maximized and minimal pollution generated when operated efficiently via automated robots [63].

4.1.8. Building Information Modeling for Circular Economy

Since the National Institute of Building Sciences [102] defines BIM as "a digital representation of the physical and functional characteristics of a facility", the concept of BIM as a digital building asset [103] is well-known to most people. BIM is more commonly used in the architectural, engineering, and construction fields for design, visualization, construction, maintenance, and facilities management [29].

In the field of "Construction Building Technology", more and more studies are incorporating CE principles into the building life cycle via BIM to achieve sustainable building design. BIM enables information sharing among all stakeholders to reduce information gaps and duplication of work, and to improve efficiency [104]. Through digital modelling, BIM can help to optimize the design, and to reduce the wastage of resources and the generation of waste [105]. In addition, life cycle assessment (LCA) is one of the most common methods to investigate CE principles [106]. However, there are less studies on the adoption of BIM-based LCAs for the CE in buildings. The majority of these studies focus on the building design phase, while the CE principles are usually used for recycling materials after the use of buildings and components, without providing a full life cycle assessment [107]. There are still barriers to the implementation of BIM for the CE [108], such as barriers in building construction and demolition waste management [109], and barriers in reusing building materials [110]. On the other hand, potential methods have been proposed to overcome the barriers to the CE using BIM, such as circularity assessment and virtual walkthrough [109].

4.1.9. Blockchain for CE

Blockchains are decentralized and cryptographically secure distributed ledgers where any transaction is permanently stored and recorded [84], enabling transparent value transactions without the need for government agencies and banks. The five elements of blockchain security (cryptographic protection), immutability (cannot be altered or deleted), transparency (end-to-end visibility), consensus (eliminating the need for third-party validation), and smart contracts [29], make it an increasingly popular technology in the field of data management and storage [18]. This is also because of the properties of blockchain possesses that may facilitate communication and collaboration among different stakeholders [111], and reduce the inconvenience of poor information.

It has been acknowledged in the reviewed literature that blockchain has the potential to support the CE in several aspects. The use of blockchain in the production phase allows for the identification of quality issues such as defective batches, thus reducing the waste of time and resources to perform a full inspection or eliminate all products [37]. The adoption of blockchain for the CE improves the efficiency of operational processes by executing smart contracts [56], and the consumer understanding of the entire life cycle of a product [112], in which its transparent nature ensures that organizations provide products that are recycled and authentic to demonstrate a responsible public image [49].

In terms of waste management, the findings suggest that the technology enables traceability and thus improves the handling of e-waste, which is essential for material recovery, refurbishment, and recycling. The blockchain is considered as a CE digital enabler [113], due to its effectiveness in the product reuse, remanufacturing, and recycling phases [114–116], and energy saving, material saving, and emission reduction [117].

4.1.10. Additive Manufacturing (3D Printing) for CE

In a narrow sense, additive manufacturing, also known as 3D printing, creates 3D models by adding materials layer by layer [91,118], enabling the manufacture of complex material assemblies and geometric parts that are not possible with traditional manufacturing processes [119].

The implementation of CE principles in additive manufacturing in the "Engineering" field is reflected in the fact that it allows for the use of recycled materials in the life cycle to reduce waste and adapt to real-time needs and different environments to extend the life of the product for the CE. Additive manufacturing is able to achieve efficient on-demand production by avoiding material loss, scrap, and waste in the production process compared to subtractive technologies [120,121].

In fact, additive manufacturing is a broader term that covers a more comprehensive concept and process than 3D printing [49]. The results of this paper indicate that 3D printing enables the circular design of products, not only by using recycled materials, but also by increasing the personalization of the product and thus strengthening the connection between the user and the product to enhance longevity. In the context of a tight economic situation, on-demand production assists in the reduction of the size of inventories and supports local production, reducing the dependence on transport [34,122].

4.1.11. Cyber–Physical Systems and CE

Cyber–Physical Systems (CPSs) are ICT systems integrating computation, control components, and physical processes in different domains [36,63], which provide real-time connectivity between humans and physical or production systems through sensors, the actuators [123].

The findings suggest that CPSs can be collected, shared, stored, and maintained throughout the product lifecycle. CPSs also enable the lifecycle management of products and services in the recycling, remanufacturing, and maintenance phases, making the disassembly and waste materials' recovery process transparent for its reintroduction into new products [5,63]. The integration of CPSs with other DTs optimizes the use of resources by supporting, on the one hand, the recycling of recovered products and, on the other hand, improving the utilization of natural resources by calculating eco-efficiency indices to increase efficiency and reduce waste [124]. It also improves the sustainability of the production cycle, brings benefits to the product life cycle, and is believed to act as an enabler of circular business models [63]. Further, a comprehensive link between CPSs and the various segments of the CE has been established [36], which is not only from the product point of view, but also from the perspective of the consumers, e.g., portable health testing devices.

4.2. Future Development Trends

DTs and the CE are the two emerging hot topics in the world today, in which the CE attempts to address environmental challenges, such as climate change and resource scarcity, while DTs drive the CE to promote the efficient use of resources and reduce waste [4]. Relevant reports are being continuously published all over the world, with the World Economic Forum proposing to accelerate the transition to a CE in order to meet global climate goals by 2050, and highlighting the need to do so through digitalization [125]. After analyzing DTs and CE keywords through visualization and specific literature, The results highlight that there are three DT-driven CE-associated keywords, i.e., “city”, “industry 4.0” and “enterprise”, which are highly appeared.

- Urban Development via DT-Driven CE

DTs are important means to achieve the construction of smart cities, making urban development more efficient, environmentally friendly, and sustainable [126]. CE can not only promote sustainable urban economy, society, and environment [127], but also improves the efficiency of resource utilization, by reducing the consumption of natural resources and recycling a large number of electronic components and materials needed for technology and equipment. The development of CE creates more employment opportunities and demands for highly skilled personnel for technology research and development, equipment manufacturing, and service provision. Since the development of smart cities in turn requires the support of the information industry and the manufacturing and service industries, through the CE, waste arising in different industries can be transformed into new resources and sources of wealth, promoting the upgrading of industries and the transformation of the development mode [128,129].

When collecting and analyzing literature data on smart cities and the CE, the amount of relevant data was found to be unsatisfactory, with the WOSCC database search using (TOPIC (Circular Economy) and TOPIC (Smart Cities)) yielding 169 articles, and a search using (TITLE (Circular Economy) and TITLE (Smart Cities)) yielding 11 strongly relevant articles. Future research could actively look into the digital transformation of the urban market space, which could focus on the construction of digital infrastructure, such as intelligent transport systems and intelligent energy systems, to improve the management and operation efficiency of the city; strengthen information security management through blockchains and cybersecurity technology to provide a more secure information environment; and promote the development of a digital economy and create a digital economic ecosystem to inject new power into cities’ economies. Further, international cooperation will become a trend, and the future development of cities could focus more on international cooperation and promote exchanges and cooperation between cities.

- Industry 4.0 Associated DTs to CE

The results suggest that “industry 4.0” occurs frequently, which is not a type of DTs that has not been explored in the previous sections. Industry 4.0 refers to the process of applying DTs to the manufacturing industry to promote upgrading and innovation through digital transformation. As such, industry 4.0 involves not only the application of DTs, but also the development of smart manufacturing, smart supply chains, and other fields [130,131].

The CE strategy needs to take advantage of the opportunities presented by the technological developments of the fourth industrial revolution [132], to promote a resource-efficient and environmentally friendly economy. Currently, there is a constant focus on reducing resource consumption and waste, which can be approached from four aspects that optimize digital production processes through digital technologies to achieve efficient and accurate production capacity [48], support new material development and digital dismantling processes to increase waste recycling and reuse and improve material remediation [63], develop energy-saving and emission-reduction technologies to reduce environmental pollution, and guide the supply chain to create connected ecosystems that can help to support resources, energy, and transport to achieve the efficient use of resources and reduce waste for sustainable economic development [84].

- The Use of DT-Driven CE in Businesses

Most of the current case studies in the field of Business Economics, Computer Science, and Operations Research and Management Science are based on the actual projects of enterprises, and the development of the CE has been considered as an effective measure for enterprises to cope with environmental pressure. Optimization and innovation in product design and production processes can initially mitigate environmental impacts and reduce resource wastage [17]. In logistics management, the automation of the logistics system improves logistics efficiency through the IoTs and big data analysis. Hence, in the recycling and reuse stage, the amount of waste to landfill can be reduced [37].

In the future, the use of the CE will enhance customer experience and enterprises' competitive advantage, and enterprises could better understand market demand and consumer behavior to accurately predict user demand, plan production, and improve user satisfaction by providing personalized services. In addition, it can enhance financial risk management capabilities, using blockchain and other technologies to help enterprises understand customer credit and historical transaction records, reducing financial risks and management costs [133].

4.3. Challenges to DT-Enabled CE

In terms of the reality of the development of the CE, it is still facing various difficulties and challenges. The current policies of many countries and regions have not been fully adapted to the needs for the development of the CE, and there is a lack of relevant support mechanisms, metrics, and standards. In addition, linear resource consumption remains 'business-as-usual', and most products still cannot be upcycled after being discarded, leading to waste of resources and environmental pollution. Further, although the international community is aware of the importance of the CE, there has not been formed a unified driving force to enhance CE adoption. Moreover, the current CE practice in the "Construction and Building Technology" sector requires interdisciplinary technical support. DTs may face technical difficulties in the application process, in which the quality of the large amount of data collected cannot be guaranteed, and a large capital investment can be a challenge for financially weak organizations.

5. Conclusions

Using a systematic literature review approach, this paper critically examines quantitatively and qualitatively the current status, use, contribution, challenges, and future perspectives of DT-driven CE development. The paper explores nine research objectives, including the background of the topic, the current situation, hotspots, research within the subject area, the use of specific technologies, applications in cities, enterprise, and the integration of Industry 4.0, and concludes challenges for future developments.

The main contributions of this paper are as follows: (1) Methodologically, this study is the first attempt to combine macro-quantitative bibliometric analysis with micro-qualitative analysis methods to explore the topic of a DT-driven CE. (2) In terms of the research technique, two bibliometric analysis software tools, i.e., VOSviewer and Citespace, were used to conduct the network visualization of the keyword co-occurrence and keyword burst detection, to provide a systematic and in-depth insight into the integration of DTs and the CE, leading to a micro-analysis through disciplinary classification and the use of each individual DT to carry out a thematic analysis. (3) The results of the keyword visualization in the macro-analysis via WOSCC revealed seven major research subject areas for the DT-driven CE that embrace Environmental Sciences and Ecology, Engineering, Science and Technology and Other Topics, Business Economics, Computer Science, Operations Research and Management Science, and Construction and Building Technology. Secondly, compared with existing studies, this paper screens 13 DTs, covering digital twins, big data, IoT, AI, cloud computing, VR, AR, XR, robotics, BIM, blockchains, additive manufacturing, 3D printing, and cyber–physical systems, and explores how each of these technologies can be used for CE development. Improving CE adoption and implementation requires opportunities presented by Industry 4.0-associated DTs to promote a resource-efficient and environmentally friendly economy. The impact of the fourth industrial revolution will make DTs widely used in various fields of cities, including manufacturing, services, and industry, helping enterprises to improve their ability for digital transformation, in which the integration with the CE can better optimize the allocation of resources and improve the efficiency of resource use.

This paper provides valuable information for researchers and policy and industry stakeholders in related fields to better understand the current status and future trends of the DT-driven CE. However, this paper has some limitations. Due to the collection of 13 technologies related to the DT-driven CE, it is challenging to achieve 100% accuracy when manually merging synonymous keywords, which may lead to a slight weakness when analyzing the keyword co-occurrence with the VOSviewer and Citespace software tools, although it will not have a devastating effect on the visualization of the main keywords. Further, the visual data reported in this paper is limited to what is contained in the WOSCC database, and future research will consider adding other high-quality databases to provide a more comprehensive picture of the latest results on the DT-driven CE.

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