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Review

# Digitisation and the Circular Economy: A Review of Current Research and Future Trends

Okechukwu Okorie <sup>1,\*</sup> , Konstantinos Salonitis <sup>1</sup> , Fiona Charnley <sup>2</sup>, Mariale Moreno <sup>2</sup>, Christopher Turner <sup>3</sup> and Ashutosh Tiwari <sup>4</sup>

<sup>1</sup> School of Aerospace, Transport and Manufacturing, Cranfield University, Bedfordshire MK43 0AL, UK; k.salonitis@cranfield.ac.uk

<sup>2</sup> Centre for Competitive Design, School of Water, Energy and Environment, Cranfield University, Bedfordshire MK43 0AL, UK; f.j.chnley@cranfield.ac.uk (F.C.); m.moreno@cranfield.ac.uk (M.M.)

<sup>3</sup> Rik Medik Building, Surrey Business School, University of Surrey, Surrey GU2 7XH, UK; christopher.turner@surrey.ac.uk

<sup>4</sup> Amy Johnson Building, Department of Automatic Control & Systems Engineering, The University of Sheffield, Portobello Street, Sheffield S1 3JD, UK; a.tiwari@sheffield.ac.uk

\* Correspondence: o.s.okorie@cranfield.ac.uk; Tel.: +44-7859153124

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**Abstract:** Since it first appeared in literature in the early nineties, the Circular Economy (CE) has grown in significance amongst academic, policymaking, and industry groups. The latest developments in the CE field have included the interrogation of CE as a paradigm, and its relationship with sustainability and other concepts, including iterative definitions. Research has also identified a significant opportunity to apply circular approaches to our rapidly changing industrial system, including manufacturing processes and Industry 4.0 (I4.0) which, with data, is enabling the latest advances in digital technologies (DT). Research which fuses these two areas has not been extensively explored. This is the first paper to provide a synergistic and integrative CE-DT framework which offers directions for policymakers and guidance for future research through a review of the integrated fields of CE and I4.0. To achieve this, a Systematic Literature Review (SLR;  $n = 174$ ) of the empirical literature related to digital technologies, I4.0, and circular approaches is conducted. The SLR is based on peer-reviewed articles published between 2000 and early 2018. This paper also summarizes the current trends in CE research related to manufacturing. The findings confirm that while CE research has been on the increase, research on digital technologies to enable a CE is still relatively untouched. While the “interdisciplinarity” of CE research is well-known, the findings reveal that a substantial percentage is engineering-focused. The paper concludes by proposing a synergistic and integrative CE-DT framework for future research developed from the gaps in the current research landscape.

**Keywords:** circular economy; industry 4.0; data; 9Rs; digital technologies; digital intelligence

## 1. Introduction

### 1.1. Background of Study

Multiple factors have driven the need for the transition towards more sustainable, intelligent sociotechnical systems. These include economic challenges and uncertainty amongst individual companies and across entire economies [1], a rising global population which has put pressure on already scarce resources [2], and environmental challenges such as biodiversity loss and the depletion of important natural resources [3,4]. Other challenges include social issues, such as high unemployment in certain parts of the world and poor working conditions [5]. Systematic investigations concerning the impact of these challenges on society and its sustainability have indicated tension in existing

systems [6], raising questions about the sustenance of prosperity trends in society [7]. It is evident that the prevailing economic model of “take, make, use and dispose”—or the linear economy—is now incompatible with social sustenance and sustainable economic growth.

Dating back to the Industrial Revolution of 1760–1820, the linear economic model is framed largely around “consumption”, where the product is “consumed” in use and then disposed of; a unidirectional model of production [8]. Thus, it could be described as linear or, as in Figure 1 [9], as an incomplete circle which starts at the point of extraction and “ends” at the point of disposal. The product resource is extracted as much as possible during its useful life; product efficiency and lifespan are not prioritised in a linear economic model. Research shows that this model is unsustainable as the current consumption rate is 50% faster than replacement [10]. At the current growth rate, the global middle class is predicted to double by 2030 [10], hence with the increase in population] driving demand for resource-intensive goods requiring more than two planets worth of natural resources [8]. This trajectory is clearly unsustainable.



**Figure 1.** (L-R) Linear economy concept indicating an incomplete loop where the plant provides the extracted resources and receives the waste after the resources have been used. The Circular Economy concept keeps the product in use for as long as possible and is recycled at the end of its life. Adapted from Suave et al., (2015) [9].

### 1.1.1. The Circular Economy

The factors mentioned above and the unsustainability of the linear economy drove the development and implementation of the Circular Economy (CE) as an alternative resource model where economic growth is decoupled from virgin resource consumption. Defining the “Circular Economy” is not without its complexities; Kirchherr et al., (2017) [11] gathered 114 definitions of the CE which were analysed for their associated factors and dimensions. Key differences in CE definitions appear to derive from the fact that the concept is employed by different stakeholders. As CE is of interest to academia, industry, and policymakers [12], different definitions have been proffered which emphasise the different viewpoints of each stakeholder group. Hence, as argued in [13,14], blurring of the concept of CE has occurred since it is used in different ways. Furthermore, [15] argued that “there are various possibilities for defining [CE]” due to its complex and trans-disciplinary nature [9]. CE, is not a new concept; [16] reminds us that the term has been in existence since the 1970s, while [17] states that it appeared in academic literature in 1990 by Pearce & Turner (1990) [18], where the linkages between the environment and economic activities were analysed. The 3R principles of “Reduce”, “Reuse”, and “Recycle” are highlighted in [19], and have been studied and highlighted in academic literature since the early 1950’s and many other existing bodies of literature, while concepts such as “Remanufacture” [20], “Reverse Logistics”, and “Refurbishment” gained increasing traction in academic literature from 1984 onwards [20], commonly referred to as “Circular Approaches”. As there is no commonly accepted definition [21] of CE, for the purpose of this paper, the definition provided by [22] will be adopted, which suggests that the Circular Economy (CE) is “an economic

system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and material loops, and facilitate sustainable development". As well as being concise, this definition leverages the broader (and much cited) definition of The Ellen MacArthur Foundation [23].

#### 1.1.2. Industry 4.0

Industry 4.0 (I4.0) or the Fourth Industrial Revolution, is a phenomenon driven by both an application pull and a technology push [24]. It is the latest industrial system which functions through an integration of manufacturing operation systems and information and communication technologies (ICT), thus creating the much nuanced Cyber-Physical Systems (CPS) [25,26]. As a goal, Industry 4.0 aims to achieve a higher level of operational efficiency and productivity, as well as a higher level of automation [27]. Thus, following Germany's coining of the term and adoption of Industry 4.0 initiative into its "High-Tech Strategy 2020 Action Plan", after recognizing its potential [24], other countries followed with their own version of Industry 4.0. These include, the USA, China, Japan, the UK, Brazil, France, and South Korea [28]. According to [29], "application pull" refers to the opportunities for differentiation and competitive advantage which are enabled by the more intelligent, automated, flexible, and agile production processes manufacturers can adopt. In terms of "Technology push", Industry 4.0 is enabled by a number of converging technological developments [24]. These include the wide-spread Internet connectivity and increasing miniaturization, cost effectiveness, and capability of hardware such as sensors and actuators [30].

While largely separate topics, it can be argued that an integration of CE principles and I4.0 possesses potential benefits for industry and academia. The integration of I4.0 has been previously explored in other areas, such as the hospitality sector and management practices in informing the service sector [31]; in the deployment of I4.0 techniques in the textile industry [32]; and in supply chain and reverse logistics solutions, where I4.0 technologies were utilized in tackling energy efficiency and environmental issues [33]. Similarly, the possibility of integrating CE principles and I4.0 can be seen in already existing product models, such as the tracking of products during use and post-consumption in order to recover components [34] or extension of the life of components. Existing literature that models the framework which integrates these two concepts is very limited as these two ideas tend to be researched separately. This paper seeks to add to the existing gap, as well as to propose a synergistic and integrative CE-DT framework for future research.

#### 1.2. Relevance of the Theme

With the recent report by the International Panel on Climate Change (IPCC) which puts global warming at 1.5 °C above pre-industrial levels [35], the difficulty in meeting the 2030 UN Agenda for Sustainable Development cannot be overemphasized [36]. Thus, concepts that support the transformation of a linear economy to a CE, with net zero emissions, resource efficiency, and conservation, have been the focus of academic research [37]. The concepts of sustainability and the CE, however, have been observed to be ambiguous in similarities and differences [2]. Studies have shown that the world economy is only 9.1% circular [38]. This leaves a massive circularity gap of 91.9% in number; a gap which is currently occupied by the linear economy model of "take, use, and dispose". Within this circularity gap is an ecosystem consisting of a growing middle class (1 billion new consumers by 2020 [39]) with an increasing consumption pattern and a monumental amount of municipal solid waste generated globally (1.3 billion tonnes per year) [40]. Companies acknowledge that the linear system increases their exposure to incremental risks, due to the environmental costs associated with the depletion of natural capital, resulting in price volatility and higher resources [41]. For industry and academia, it is hence important and urgent to address the unsustainability of the current system.

To aid the transition towards a circular economy, The Ellen MacArthur Foundation (2012) [41] proposes three fundamental principles to aid this transition. Relevant to this research is the second

principle, which focuses on “optimising resource yields by circulating products, components and materials at the highest utility at times in both technical and biological cycles: by designing for remanufacturing, refurbishing and recycling to keep technical components and materials circulating in the economy, preserving embedded energy and other value”. Understanding and enabling circular approaches, such as remanufacturing, refurbishing, and recycling, is necessary for the transition towards a CE. Whilst there is an abundance of research in both the areas of CE and I4.0, an integration of the two research areas has not yet been presented. A SCOPUS search of “industry 4.0” and “circular economy”, yields only nine results, spread between 2017 and 2018. In addition, the I4.0 technological field is highly heterogeneous [42], leading to confusion, as observed by stakeholders [42]. In proposing a research framework for future CE-I4.0 research, this paper aims to provide some clarity to I4.0 research beset with challenges of heterogeneity and CE research with its own challenges of complexity. Thus, the research theme’s relevance cuts across industry and academia needs, as well as the urgency to bridge the circularity gap.

### 1.3. Contributions of Review Papers

Table 1 provides a list of the most recent reviews of the CE paradigm. Ghiselli et al., (2016) [43] reviewed the CE studies of the last two decades. Their study showed evidence that CE origins are mainly rooted in ecological and environmental economics and industrial ecology, evident in China, the EU, Japan, and the United States. Murray et al., (2013), in tracing the conceptualizations and origins of the CE, argued that [44] a complete CE definition should include the social dimensions inherent in sustainable development. Utilizing the manufacturing industry, Lieder and Rashid (2016) [45] provided a comprehensive CE framework that emphasizes a combined view of three main aspects; that is, the environment, resources, and economic benefits. Studies by Lewandowski (2016) [46] employed a literature review that identified and classified the CE variables according to a business model structure, identifying two new components—the “take-back system” and “adoption factors”. Geissdoerfer et al., (2017) [2] identified eight differences in the relationship between sustainability and circular economy. Sauve et al., (2016) [9] clarified the relationship between the concepts of CE, environmental sciences, and sustainable development. A research review by Blomsma and Brennan (2017) [47] articulated the catalytic function of the CE to waste and resource management discourse. Studies by Su et al., (2012) [48] relating to the China region identified underlying problems and challenges for China’s CE national strategy by examining statistical results from the implementation policies of Beijing, Shanghai, and Tianjin. Kirzherr et al., (2017) [11] conceptualized the CE by its aims (economic prosperity, environmental quality, and impact on social equity) through the analysis of 114 definitions. Nobre & Tavares, (2017) conducted a bibliometric study of big data and Internet of Things (IoTs) on the CE, identifying China and the USA as countries most keen on this integrated area, with Brazil and Russia, large producers of greenhouse gas emissions (GHG), still lacking research in this area. Finally, Masi et al., (2017) [49], in their review of supply chain configurations in the CE, found that there remain differences in CE definitions which result in distinct research streams.

**Table 1.** Most recent reviews of the circular economy (CE) paradigm.

##	Authors	Focus	Journal	Circ. Approach in Keywords/Sections
1	Ghiselli et al., (2016) [43]	Review of 155 articles on the CE	Journal of Cleaner Production	Recycling, Reuse, Remanufacturing
2	Murray et al., (2017) [44]	Comparison of CE concept and sustainable business	Journal of Business Ethics	Recycling
3	Lieder and Rashid (2016) [45]	A review of CE in the context of manufacturing industry	Journal of Cleaner Production	Reduction, Reuse, Remanufacturing
4	Lewandowski (2016) [46]	A review (conceptualisation) of business models for CE	Sustainability MDPI	-
5	Geissdoerfer et al., (2017) [2]	A review of CE and sustainability	Journal of Cleaner Production	-
6	Sauvé et al., (2016) [9]	Comparison of CE concept and sustainable business	Environmental Development	-
7	Blomsma and Brennan (2017) [47]	Explanation of the emergence of the CE concept	Journal of Industrial Ecology	-
8	Su et al., (2012) [48]	Review of CE implementation	Journal of Cleaner Production	-
9	Kirchher et al., (2017) [11]	Comparison and analysis of 114 CE definitions	Resources, Conservation & Recycling	Reduce, Reuse, Recycle, Recover
10	Nobre et al., (2017) [16]	Big data and IOT	Scientometrics	-
11	Masi et al., (2017) [49]	Supply Chain	Sustainability	-
12	Nunez-Cacho et al., (2018) [50]	Family business and transitioning to a CE Model	Sustainability	Reuse, Reduce, Recycle, Recover

#### 1.4. Problem Description

In this study, we examine trends in CE research and I4.0 research to investigate possibilities for integrated research for a quicker transition to a more circular economy. Analyses conducted by the Ellen MacArthur Foundation, SUN, and McKinsey & Co indicate that embedded in a more circular economy includes opportunities such as improved economic growth, reduced CO<sub>2</sub> emissions and primary material consumption, substantial net material cost savings, the creation of employment opportunities, and increased innovation, with regions such as the European Union being estimated to have an 11% GDP increase by 2030 [51].

The transition to a CE is achieved through circular and innovative business models, digital technologies, and enabling capabilities that supports these systems [19,23]. However, the CE is currently populated by diverging approaches [52], which has hampered the dissemination of the CE field. Digital technologies and the wider field of I4.0 have been suggested as having the potential to play a leading role in enabling and scaling the CE [19]. These include, through smarter asset use, managing physical resource flows and optimizing the performance of running systems that have the potential to contribute to longer product lifecycles, a higher efficiency, and the development of “remanufacture” or “repair” as a better competitive solution than “replace”, [19,53]. The circularity gap currently straining the environment and the world economy [38] suggests that there has been little change in circularity since the emergence of the CE as an academic concept in 1990 [38]. Against this background, while there is more that I4.0 and digital technologies can do in accelerating the transition towards a CE, little research exists which proposes an integrative approach to these two emerging research areas [34]. With these circumstances in mind, this research examines the CE and I4.0 within an integrated framework, observing current trends and proposing avenues for future research.

#### 1.5. Research Question and Novelty of Research

Growing attention has been paid to the CE and I4.0 over the last decade, largely through independent and separate research of both fields. I4.0 has been widely accepted to be an enabler of the CE [34] and, more specifically, the introduction of digital technologies and connected objects is agreed to have the potential to promote resource reduction and the facilitation of circular systems [54]. Despite this wide acceptance, there is still a lack of clarity on how I4.0 can enable a transition to a CE. To address this, the following research questions are proposed:

- How can the synthesis of digital technologies with circular approaches support I4.0 in enabling the transition towards a CE?
- How can a synergistic and integrative CE-DT framework offer direction for policymakers and industrialists and guidance to academia for future CE-I4.0 research?

These research questions are developed from the assumption that, owing to the dynamic nature of both CE and I4.0 research fields, the heterogeneity of I4.0 technologies [25], and the complexities and comprehensiveness of CE research [45], there would be difficulty and limitations in integrating both research fields. This research mitigates these limitations by focusing on key enablers of both fields, circular approaches and digital technologies as seen in Figure 2, in order to understand the behaviour of the whole. The novelty in this research hence lies in this synergistic and integrated framework developed from an SLR of CE approaches and digital technologies from I4.0.

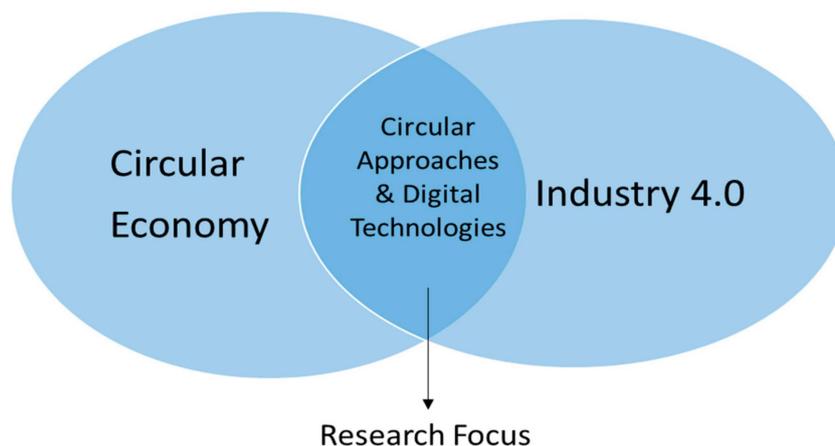


Figure 2. Research Focus for Research Paper.

### 1.6. Objective of Paper

Table 1 is a collection of recent reviews of the CE concept obtained from SCOPUS and Science Direct databases. While the CE concept has received massive promotion by academia, governments, and policymakers alike, review research on CE has largely centered on analysis of the CE definitions, sustainability, and the CE within various supply chains. The interdisciplinary context of the CE is also evident in research, with the CE gaining grounds in the fields of business and business models, management, strategy and strategy implementation, and value-thinking [45,55,56]. Manufacturing-related review research on the CE has included exploring the different ideas, motivation for research, and the context of manufacturing within CE [45].

Despite the widely acknowledged possibilities that an integration of the CE and I4.0 can offer [34], there are no papers that examine this at a comprehensive review level. Thus, for these two emerging and beneficial fields of knowledge, current research has been pursued in isolation of each other. For example, a SCOPUS search on “industry 4.0” set between the years 2012 and early 2018 produced 3034 initial results; a SCOPUS search of “circular economy” set between the same period yielded 2318 initial results. Out of the nine initial results obtained from a SCOPUS search that integrates “circular economy” and “industry 4.0”, set between the same search periods, none contained review research. Similarly, a search for “circular economy” and “industry 4.0” as separate elements on Web of Science produced an initial result of 1856 and 1792 for “circular economy” and “industry 4.0”, respectively. Only six results were produced on Web of Science for the same search period when the two terms were integrated.

There are possible reasons for the research gap. According to [34], the topic nature of both subjects would suggest the reason for the gap in research. It was suggested [55] that this omission is due to “gaps in operational data-driven and 3Rs optimization solutions”, while arguing for the imperativeness of this research as big data (a component of I4.0 with the potential to drive industrial symbiosis within a CE). Other authors such as Antikainen et al., (2018) [56] and Pagoropoulous et al., (2017) [57] acknowledge the emergent role of digital technologies in the circular economy and the gap in integrated research, but fail to suggest reasons for this gap of research. Thus, the objectives of this paper are as follows:

- To provide a precise investigation of the development of Industry 4.0 and CE in research by conducting a systematic literature review integrating key terms from CE and I4.0.
- To identify trends and gaps from the systematic literature review and research to develop a synergistic and integrative framework to provide an overview for future research.
- To present identified suggestions to academia, industry, and policymakers for future CE-I4.0 research.

The relevance of integrative research of two emerging and complementary agendas can be seen in similar integrative research. [58] explored the integration of two emerging research areas of green

human resource management (GHRM) and green supply chain management (GSCM). It was found that an integrated GHRM-GSCM had implications for scholars, managers, and practitioners in both areas in terms of organizational sustainability and truly sustainable supply chains [59]. Similarly, other works [60–63] from the perspective of organizational sustainability argue for the need for integrative research.

Methodologically, this study is based on the following main assumptions:

- Integrative research is critical to multidisciplinary research areas, such as the CE and I4.0 [41,64,65].
- I4.0 and digitization are critical in boosting the transformation towards a more sustainable CE, [34,58] and supporting specific circular approaches [63].
- As I4.0 contains a variety and growing number of sub-groups, domains, and technologies [28,50] and the CE possesses a number of approaches (Reuse, Reduce, Remanufacturing, Recycling, Repurpose, Recover, Repair, Refurbish, and Refuse) [11], it is important to refer to key concepts relating to I4.0 and CE in order to synthesize and build a consistent and integrative framework.
- The CE and I4.0 possess similar attributes and complexities and are both emerging concepts [47]. An integrative and synergistic framework may be able to provide simplicity and direction for future research [58].
- As I4.0 domains and technologies advance, their uses within the CE increase further.

The concepts of I4.0 can enable the CE by building visibility and intelligence into products and assets, such as the real-time condition, location, and availability of assets [56]. The utilization of artificial intelligence or blockchain technology, for example, bringing novel was to improve traceability and transparency throughout a product's lifetime [65].

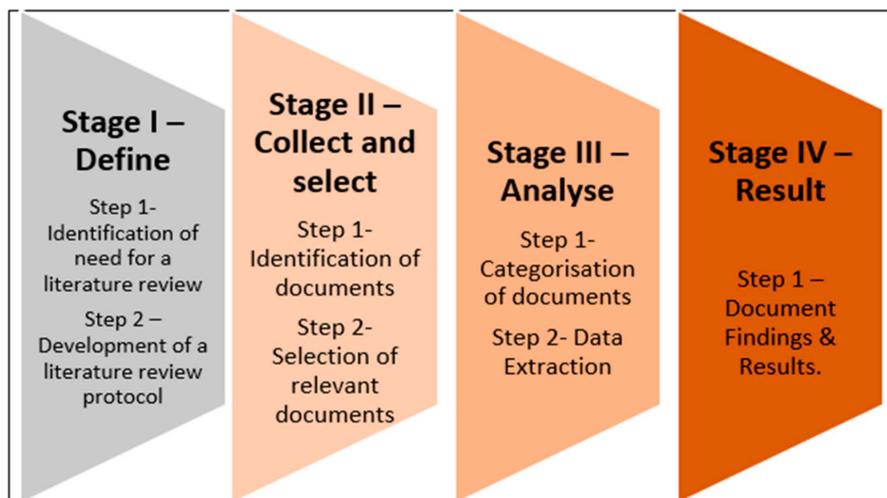
### 1.7. Structure of Paper

The remainder of this paper is structured as follows: Section 2 describes the method and analytical design employed in this SLR. The process of paper selection is described in Section 3. Section 4 presents and categorises the descriptive analysis of the literature. In Section 5, the content from Section 4 is analysed and a framework is proposed for further research on the topic. Section 6 contains the conclusions of this paper, limitations, and recommendations for future study.

## 2. Review Methodology

This research shall be based on a Systematic Literature Review, or SLR. Thus, the sections and the review methodology shall be designed according to the SLR method, as highlighted in [66–70]. In conducting this research, requirements such as thoroughness and depth were deemed as important to this research. Traditional methods of research have been criticized for lacking these requirements [66]. The SLR has been proposed as a detailed type of research which takes into consideration the broad foundation [16], as well as being transparent, explanatory, heuristic [67], context-sensitive, and able to achieve evidence-informed reviews and decisions [66]. Thus, the need for an SLR in the review of data-driven circular approaches in manufacturing for digital technologies is predicated on the view that SLR can help this research identify research trends, future work in the area, and the tools used in solving the problems being addressed [68]. Figure 2 on the next page describes the systematic literature review phases.

The SLR process was conducted in four stages, as shown in Figure 3. Stage 1 is defined as “*Define*”; here, the need for a literature review is identified (as presented in the Introduction) and a literature review protocol is developed. Stage 2 is the “*Collect and select*”; here, documents for research are identified and from the pool of identified documents, relevant documents are selected.



**Figure 3.** Systematic literature review phases. As adapted from Tranfield et al. [66].

Stage 3 is the “Analyse” stage; here, documents selected in Stage 2 are categorized and data is extracted from it. Stage 4 is the “Result” stage; here, the trends and data are analyzed and reported as findings [66].

For this research, Scopus is utilized. Various reasons exist for this choice of database. SCOPUS has been described as a viable alternative to Eugene Garfield’s Science Citation Index [69] and has been consistently found to have a greater overall coverage of academic journals, [71–75]. Scopus also presents best practice in terms of comprehensiveness [69]. This “comprehensiveness” of SCOPUS over Web of Science can be seen in this example: When the search string (“Industry 4.0” OR “digital technolog\*” OR “manufactur\* data” OR “digital intelligen\*”) AND (“circular econom\*”) was entered into both databases, Web of Science returned four results and SCOPUS returned 14 results for the period selected “All Years”. Google Scholar was not utilized as valid questions still persist in terms of its suitability for research evaluation due to the low data quality found in Google Scholar [70]. As this research specifically focuses on *understanding trends* and not a *comparison of research trends* from scholarly databases, it will be justified to focus on one identified comprehensive database, SCOPUS, despite the cited drawbacks of SCOPUS, such as its unsuitability for humanities and social science-type research [70].

The literature review protocol is detailed in Table 2. First, the period 2000 to early 2018 is set as the focus period of the literature review. The systematic literature review study starts with the identification of keywords, applied as search strings. These keywords and search arguments are developed from the scoping study of the research, and the literature is consulted and finally agreed upon by the research team. As corroborated in [68], it is an iterative process that requires protocol refinement for approval. This is shown in Figure 4.

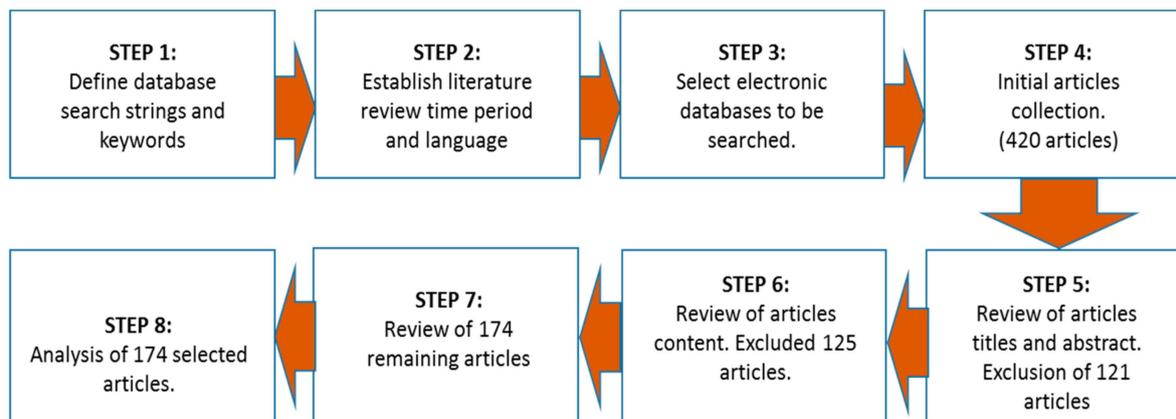
Boolean operators “AND” and “OR” were utilized, as these helped to produce more focused and strategic results [71]. Defining the search string, however, was slightly less straightforward. The keywords used for this search related to I4.0 were “Industry 4.0”, “digital technologies”, “digital intelligence”, and “manufacturing data”. The decision to utilize these keywords stemmed from the fact that they have been defined to be members of the “top 25 most frequent words related to Industry 4.0” [28].

“Circular Economy” is also defined as a search string, as this is the key theme of this research. Circular approaches, however, were slightly more problematic due to the many “Rs” in the literature. Lacy and Rutqvist (2016) [19] referred to the three Rs of “Reduce”, “Reuse”, and “Recycle” [19], which has also been cited in a number of literature studies [22,48,56,57,76–78]. Other “R” frameworks include the 4R framework of “Reduce”, “Reuse”, “Recycle”, and “Recover” [11], and the 6Rs as first proposed by Joshi in 2006; these are “Reduce”, “Reuse”, “Recycle”, “Recover”, “Redesign”, and

“Remanufacture” [72]. Other scholars [64] have extended the frameworks into the 9Rs, which are “Refuse”, “Rethink”, “Reduce”, “Reuse”, “Repair”, “Refurbish”, “Remanufacture”, “Repurpose”, “Recycle”, and Recover”. The 3R framework is proposed as the most prominent R framework [11] and is at the core of many CE implementation drives in countries, including the 2008 CE Promotion Law of the People’s Republic of China.

**Table 2.** Literature Review Protocol.

Item	Description
Time Period	January 2000 to June 2018 (Search was performed in June, 2018)
Boolean Operators	AND between keywords; OR between Database search fields.
Search fields	“Industry 4.0”; “Digital Technologies”; “Digital Intelligence”; “Circular Economy”; “Reuse”; “Recycl*”; “Remanufacture”; “Repair”; “Repurpose”; “Rethink”; “Recover”; “Recover Energy”; “Refuse”; “Refurbish”; “Reduce”
Language	English
Availability	Articles available online as full text
Research Discipline	Engineering; Business; the Sciences excluding Medical Science.
Exclusion Criteria	Articles unrelated to search words;
Publication type	Peer-reviewed academic journals; conference papers.



**Figure 4.** Flow Diagram indicating the Review Process.

The 3R’s have been argued to relate to mainly waste management policies, [43]; hence the 4R’s, 6R’s, and 9R’s were proposed as a more comprehensive and integrated framework for circularity, with the 9R’s possibly being the most nuanced one [11]. In selecting the circular approach to utilize as the search string, it is important to note two facts; firstly, the conference paper [73] already utilizes “reuse”, “recycling”, “remanufacturing”, and “sustainability” as search strings; hence, for this research, a more comprehensive list of approaches is needed. Also, it is important to understand that all new varieties of the R framework move in order of increasing circularity—from the linear economy to the circular economy, where “refuse”, “rethink”, and “reduce”, strategies were observed to be more useful in smarter product use and manufacture. However, the gradations of circularity make it clear that “refuse” (preventing the use of raw materials) is the first option for circularity and “recover energy” or “recover” is the final option for extracting value from resources [74]. Thus, while recycling and energy-recovery are at the heart of circularity gradations, a comprehensive review of the circular economy must include the options in the middle. Thus, the 9R’s will be utilized as search strings.

The language of the search is restricted to English as this is the language with the largest number of publications and universality, and is hence more likely to offer useful papers. The search string was defined in this manner: (“Industry 4.0” OR “Digital Technolog\*” OR “Digital Intelligence”) AND (“Circular Econom\*”).

This search string did not guarantee that only papers within the research topic would be returned; hence, exclusion criteria were defined. The returned papers were subjectively examined by

reading through their titles and abstracts, ensuring the exclusion of papers that did not address the research area.

While studies show that journal papers, especially higher rated journals, are considered to provide a high quality of research [75], research into circular economy and industry 4.0 and its concepts has been described as “emerging research” in [34,57]. Thus, it was important to consider for this research, new discussions around industry 4.0 and circular approaches from all sources, including conference papers. The next section describes the process employed in the selection of relevant papers.

### 3. Paper Selection Methodology

Inclusion and exclusion criteria chiefly describe the paper selection process in any methodological review. According to Pittaway et al., (2004) [76] and Roehrich, et al., (2014) [77], defining inclusion and exclusion criteria is important in generating an unbiased review of literature, which also focuses on the context of the research [78]. In their research focusing on energy efficiency and environmental sustainability in the supply chain management context, Pittaway et al., (2004) [76] and Roehrich, et al., (2014) [77] go on to propose three selection criteria which shall be adopted in this work to produce the paper selection criteria. Table 3 describes the paper selection criteria utilized to identify useful papers for CE-I4.0 integrated research.

**Table 3.** Papers Selection Criteria.

Selection Criteria	Tasks Performed
1st selection criterion: Focus of abstract	The focus is on the title and abstract in materials which relate to the research context identified for this research. Papers outside this criterion were removed.
2nd selection criterion: focus of paper	Papers focusing on Circular Economy and each of the 9R's were identified and considered. Papers with a missing abstract, broken links, were excluded.
3rd selection criterion: citation method	Papers not included in the selected academic database (SCOPUS) but cited in the literature found on industry 4.0, circular economy, and circular approaches were considered.

It is important to define keywords utilized as search strings, to ensure that keywords are understood in their proper context. Figure 5, as adopted from [64], defines the terms in 9Rs. Table 4 gives the paper selection before and after the selection exclusion criteria were applied.

When the search string (“Industry 4.0” OR “Digital Technolog\*” OR “Digital Intelligence” OR “Digital Manufactur\*” AND (“Reduce”)) was applied, 488 results were yielded. This is due to the possibility that the word “reduce” was likely to appear in articles where it was not used as a circular approach. Thus, the search string (“Industry 4.0” OR “Digital Technolog\*” OR “Digital Intelligence” OR “Digital Manufactur\*” AND (“Reduce”) AND (“Circular Economy”)) was applied and this yielded an initial result of three articles, further reduced to two after the exclusion terms had been applied.

Thus, a total of 174 papers were selected from 420 papers after assessing the title and abstract of the articles and applying the exclusion criteria in Table 3. This is a discard percentage of over 100%; according to [79], a high discard rate after an initial literature review is not uncommon. The text was analyzed carefully and the final 174 articles were eligible for SLR, as shown in Table 4. A second search string was deployed with (“Circular Economy”) AND the Circular Approaches in the 9Rs in order to ascertain articles which examined the 9R's within the specific context of circular economy research. The initial result was seven papers and a total of four papers after the exclusion criteria were applied. More importantly, this was not spread across all of the approaches as some of them returned zero results. The implication of this is discussed in the next section.

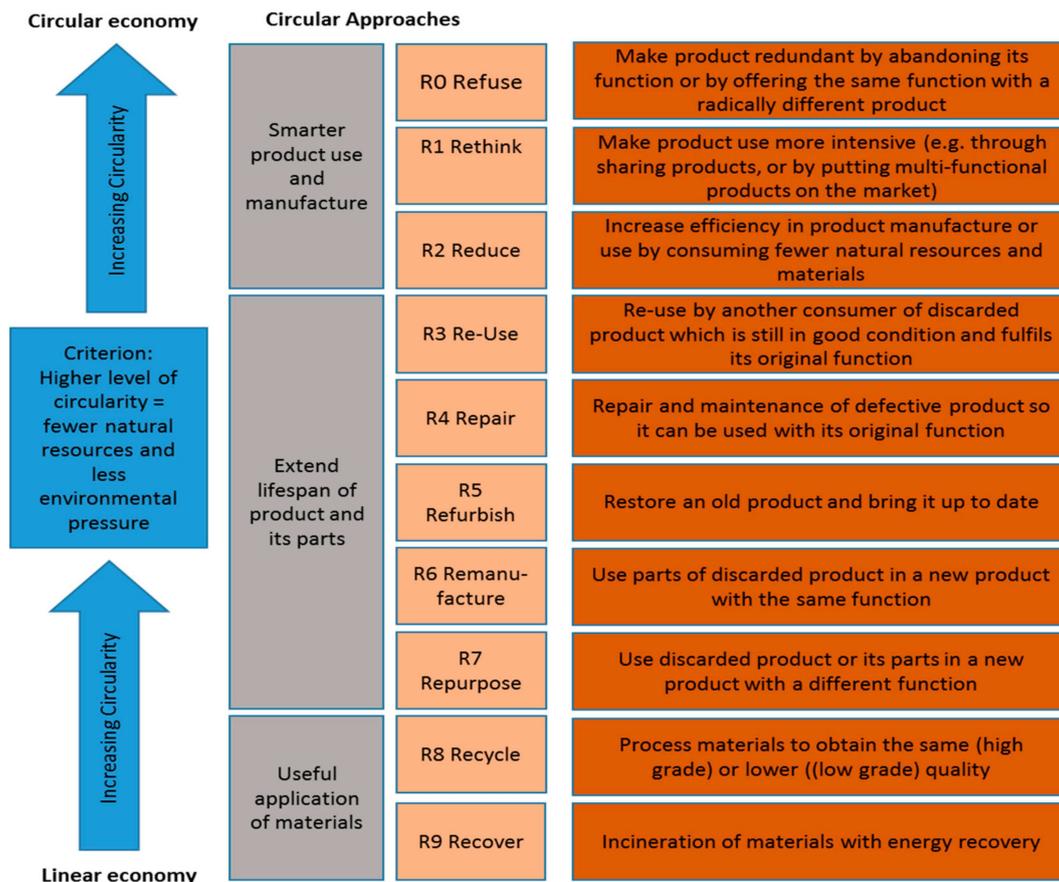


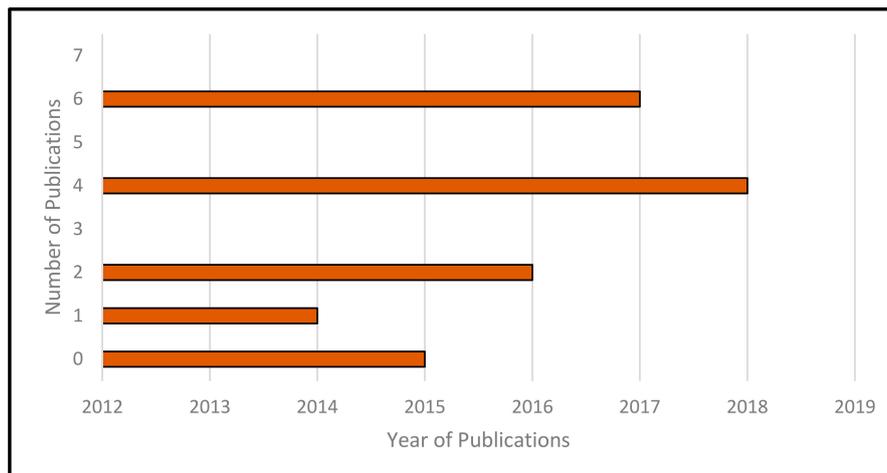
Figure 5. The 9R Framework of Circular Approaches with the production chain in order of priority. Source: Adapted from Potting et al., (2017, p. 5) [64].

Table 4. Paper selection with search strings.

Search String Keyword	Initial Result	After Exclusion Criteria
“Circular Econom*”	15	12
“Remanufactur*”	9	7
“Reuse”	59	35
“Recycl*”	44	18
“Recover” OR “Recover Energy”	137	49
“Repair”	65	27
“Reduc*” AND “Circular Economy”	3	2
“Refuse”	4	0
“Repurpose”	0	0
“Rethink”	66	11
“Refurbish*”	18	13

#### 4. Descriptive Analysis of the Literature

Descriptive analysis of the papers is employed to give a mainstream view analysis of the selected articles for the research area involving I4.0 and circular approaches. The aim is to examine 9R’s as captured in Potting et al. [64]. The results and trends from the 174 papers are combined in Figure 6 and 7. Thus, in order to describe the trend in a year, the 9R’s are combined in a single graph instead of analyzing each approach in nine different graphs. In total, 174 selected papers are evaluated according to the following identified perspectives: (1) Circular economy papers across years; (2) circular approaches papers across years; (3) papers across journals and conference papers; (4) papers by geographical distribution; and (5) papers by subject area.



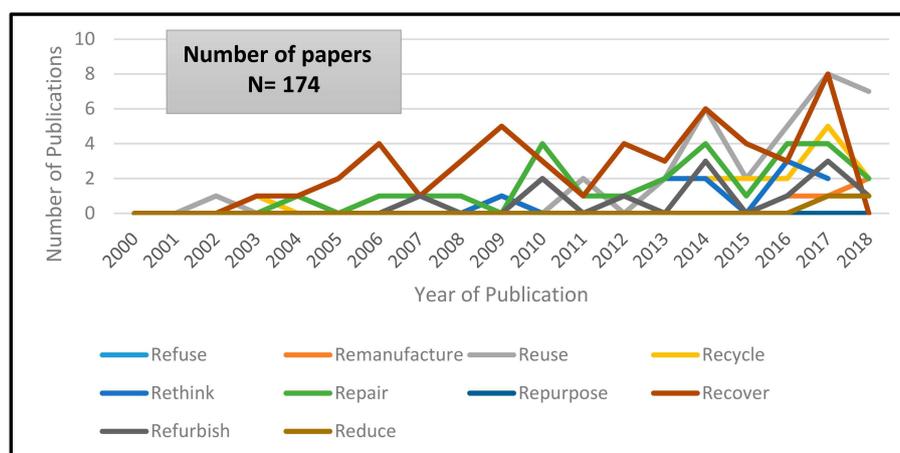
**Figure 6.** Number of Publications vs. Year of Publications for circular economy and Industry 4.0.

#### 4.1. Circular Economy Papers Across Period under Review

The time distribution for the research was set at 2000–2018, representing an 18-year span. 2000 was set as the beginning of the time distribution as an evolution in CE studies and models has been observed since the early 2000s [55]. According to the distribution over a period of time, there were no identified relevant papers on Scopus from 2000 to 2014 which focused on Industry 4.0 and the CE. Specifically, papers on this subject only emerged in 2014 (one paper) and peaked in 2017 with six identified papers. In the paper by Jabbour et al. [34], examining a viable research agenda for I4.0 and the CE, identified technologies for I4.0 were highlighted in papers published in 2015, 2016, and 2017, confirming the recentness of the research. Thus, the trend of the research indicates a research area which is new and steadily growing.

#### 4.2. Circular Approaches Papers Across Years of Publication

The distribution of the selected papers across the years 2000–2018 has been analyzed for the following circular approaches in Figure 7: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. Despite being described as 9R's, as first coined in [64], it must be observed that this list contains 10 different approaches.



**Figure 7.** Number of Publications vs. Year of Publications for circular approaches and Industry 4.0.

The reason for this, as put forward in [64], is that R0 (*Refuse*) and R1 (*Rethink*) only decrease the consumption of natural resources and materials applied in a product chain by less of the product being needed (or reused) for the same function. The circular approaches are combined in a single graph,

as illustrated in Figure 7 below. Research into data-driven/I4.0 enabled circular approaches shows a general increase, with peaks in 2014 and 2017. The focus in literature, however, is observed to be on recycling, recover, and reuse within the context of I4.0, while approaches such as remanufacturing appear to be slower in comparison. There are several possible reasons for this; papers on energy where devices employed in the energy sector are increasingly fitted with sensors and other data collection devices [34]; recycling is still viewed as important by policymakers (resource efficiency specialists at WRAP estimate that only 117 million tons out of 540 million tons of products entering the UK annually get recycled [80]) and hence the continued research in academia [81], while remanufacturing is still being traditionally driven [20] as disassembly, cleaning, refurbishment of component parts, and reassembly are labor-intensive processes where the experience of the workers is more important than the use of sensors in machines, for example [20]. It is noted that refuse and repurpose do not make up any part of the selected articles. A possible reason for this is that “refuse” refers to the product no longer needed in the product chain and “repurpose” is still viewed as a major strategy in the linear economy [64]. However, the major conclusion from the analyzed publications is that the trend of papers is one of continued growth in recent years.

### 4.3. Papers across Journals and Conference Papers

The types of paper reviewed were selected by the identified subject areas. The functionalities provided by the SCImago Journal Rank (SJR) platform helped identify nine subject areas relevant to the research. These include: “Engineering”, “Energy”, “Computer Sciences”, “Decision Sciences”, “Mathematics”, “Business, Management and Accounting”, “Chemical Engineering”, “Material Science”, and “Environmental Science”. This wide range of subject area reflects the multidisciplinary nature of the research.

Articles selected included journal papers, conference papers, book chapters, and review papers, which are denoted by “others”. Figure 8 illustrates the type and quantity of articles across the various circular approaches. Figure 8 highlights (and reiterates) two important aspects of this research. Firstly, conference papers make up about 70% of all literature found in this research area, across the 9R’s, while journal papers make up 19% of selected literature. Several possible reasons for this emerge. These include the relative novelty of this research area [34], leading to researchers focusing on conferences where the matrix of CE, Industry 4.0, and CE approaches are the focus. According to Roets & Botma [82], while conference papers form the basis of a subsequent journal publication, many challenges prevent this happening. Access to data and industry collaboration are highlighted as key [83] reasons as these are required for article submissions to high quality journals. The second aspect of this research is the prevalence of remanufacturing within journal articles (42.90%) and conference papers (57.10%). Thus, a conclusion that can be reached on this is that research focusing on enabling CE and remanufacturing with I4.0 is of equal importance to academics and industry.

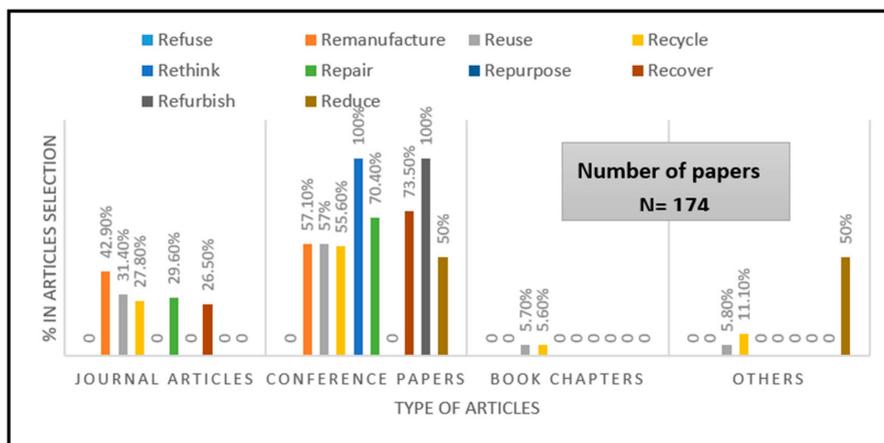
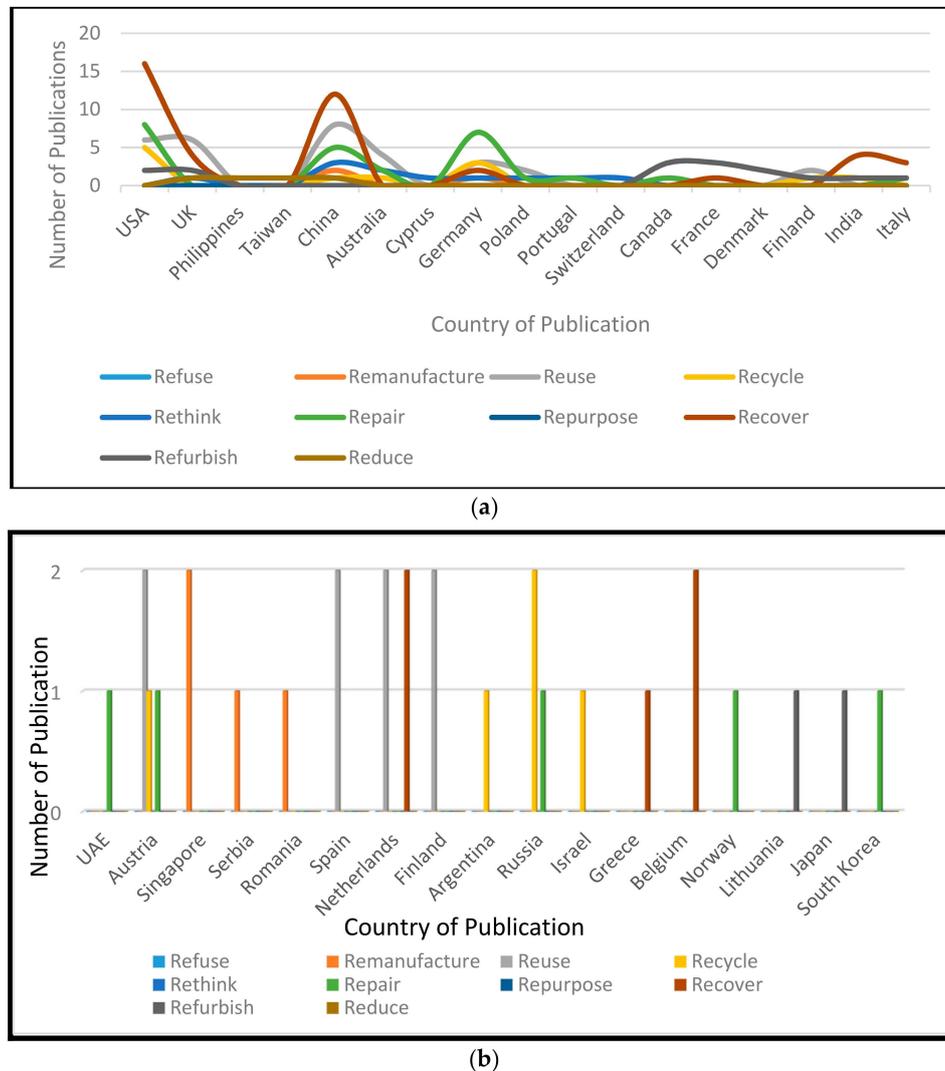


Figure 8. Papers distribution across Journals and Conference papers by numbers.

#### 4.4. Papers by Geographical Distribution

Research publications were drawn out of 34 countries, with the USA providing the most publications. Figure 9a,b shows the paper distribution across countries of publications.



**Figure 9.** Papers distribution across countries of publication (a); Papers distribution across countries of publication (b).

Besides the USA, China, the UK, and Germany predominate in terms of total research. The reasons for this are varied; since being launched in 2008, the CE is a sustainable development strategy proposed by the central government in China [48] with the aim of improving the efficiency of materials and energy use, [84]; research into utilizing sensors to recover energy has been consistent in the USA since the 1980's [20], but this interest appears to have diminished in remanufacturing in the USA, [85] as evident in the graph. CE research and enabling the CE through digital manufacturing and digital intelligence is a key strategy in the UK largely driven by the Engineering and Physical Sciences Research Council's (EPSRC) research funding council [86]. However, the low number of publications in this research area largely indicates that the objectives of these policies, especially using I4.0 to enable the CE, have not fully been achieved. A sectoral analysis of the chart by region indicates that most of the research is coming from Europe (20 out of 34 of the countries). As the European Commission has specifically adopted a CE package to drive Europe's transition towards a CE, this level of interest is not unexpected [87].

#### 4.5. Papers Across Subject Area

Eight functional subject areas in this research area were identified based on the number of papers published. These include: “Engineering”, “Energy”, “Computer Sciences”, “Decision Sciences”, “Material Science”, “Business, Management and Accounting”, “Chemical Engineering”, and “Environmental Science”. Other subject areas (designated as “others” in Figure 10) include agricultural science, economics, physics, and mathematics. Thus, this area of research can be classified as “multidisciplinary” owing to an abundance of academic areas. Figure 10 illustrates these academic areas as a proportion of the number of papers found.

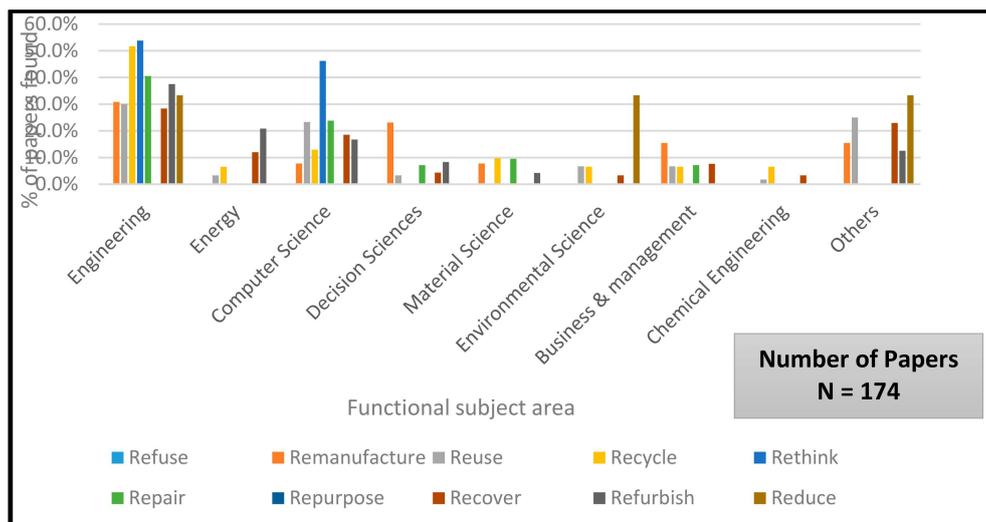


Figure 10. Papers distribution across subject area and circular approach.

Predominant subject areas in this research include engineering and computer sciences, which are also populated with the most circular approaches in this research. Research on “rethink”, “recycle”, and “repair”, respectively, make up 54%, 52%, and 41% of papers under the engineering subject area. Research on “rethink” and “repair” make up 46% and 24% of papers in computer sciences, respectively. There were no subject areas for the circular approaches, “repurpose”, and “refuse”.

## 5. Content Analysis and Framework Design

In this section, the aim is to provide a content analysis of the 174 selected papers in a manner which provides detailed clarity on observations from the previous sections. A detailed content analysis of the selected papers is utilized to propose a framework for future CE research in manufacturing for digital technologies. The following sections shall examine the observations of the research.

### 5.1. Analyzing the Aspect of Multidisciplinary Research in I4.0 for CE Research

Interdisciplinary research or multidisciplinary research has been observed to be a key feature from the systematic literature analysis in the previous section. Also referred to as “transdisciplinary or interdisciplinary research” [88], one definition for transdisciplinary research is research which is aimed at achieving a holistic and comprehensive picture of the problem at stake, requiring an open and complex research design [89]. Driven by collaborations [88], multidisciplinary research is important for research solutions which are both complex and demand innovative solutions [90]. However, Huutonemi et al. [91] argue that a single definition for multidisciplinary is tricky since the inherent complexity in multidisciplinary research stems from the many parts and stakeholders involved in the research. Thus, while no consensus exists on how to measure multidisciplinary research in practice [92], certain indicators are proposed for this in [91].

These include the “*scope of interdisciplinarity*” (the subject area, topic area) and the “*type of interdisciplinary reaction*” between fields and projects (topic areas are subsets of subject areas). Figure 11 indicates observations of multidisciplinary in the research area under review. Interdisciplinary research has been observed to be a key ingredient in CE research. As observed in [43,52], implementation strategies, business modelling, and policy making for CE must be multidisciplinary-driven for sustainable goals to be realized. Current CE research in dissemination of the CE, according to [52], is being hampered by diverging approaches and there is little focus on multidisciplinary in circularity implementation. There are other areas of this research where this aspect has been seen to be important. Sheng et al. [92] argue for the case of multidisciplinary in big data research. According to [92], a few scholars have suggested an integrated multidisciplinary approach in research and understanding of big data, for a more comprehensive research outcome. Multidisciplinary has also been argued in research elements involving the Internet of Things, or IoT. The Internet of Things is described by Atzori et al. [93] as a concept of billions of interconnected smart devices (sensors, controllers, machines, autonomous vehicles, etc.) that allow any participatory object to be sensed and controlled remotely across existing network infrastructure. Thus, unlimited opportunities are created through the automatic collection and exchange of data [94]. Two key contributions are highlighted in [90] which drive the multidisciplinary of research in IoT. These include smart applications [95] and future IoT system challenges [90].

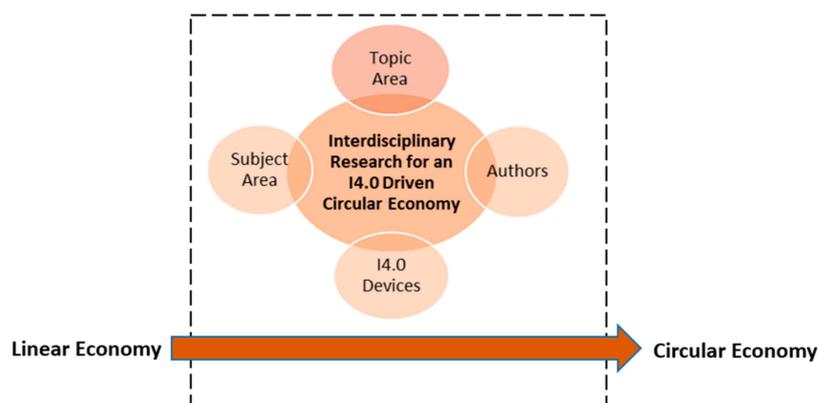


Figure 11. Multidisciplinary in Industry 4.0 for CE research.

Multidisciplinary is evident in the outcomes of this research. These are included, in a subject area which had eight main subjects and six other sub areas, described in Figure 10, as “others”. These include “*Physics*”, “*Mathematics*”, “*Earth and Planetary Science*”, “*Economics*”, “*Biochemistry*”, and “*Agricultural Science*”. Topic areas considered under the 9R’s also suggest a multidisciplinary content of the research. A cursory look at the subject areas suggests that research on using I4.0 and digital technologies to drive the CE is still domiciled within the engineering and sciences as only “*Economics*”, and “*Business & Management*” can be argued to be outside this category. This also suggests why over 50% of the authors across the selected articles are affiliated to institutions of technology.

## 5.2. Industry 4.0 and Digital Technologies

I4.0 (also defined as smart manufacturing [34]) is a common feature from the SLR. The main framework supporting I4.0 was first published by Kagermann in 2011 and thereafter by the German National Academy of Science in 2013 [96]. A simple definition for this is: “manufacturing systems driven by information technology” [29]. However, as I4.0 is based on three key paradigms of the *Smart Product*, the *Smart Machine*, and the *Augmented Operator* [97], a concise definition becomes imperative. Thus, as elaborated in [34], I4.0 involves a “combination of smart factories and products and the Internet of Things that aims to provide real time information on production, machines and flow of components, integrating this information in order to help managers to make decisions,

monitor performance and track parts and products” [98]. Table 5 gives an overview of the functional technologies encompassing I4.0.

**Table 5.** Overview of the functional technologies of Industry 4.0. (Adapted from Kang et al., 2016 [99]).

Technology	Description	Resources in Use
Cyber-physical systems	Enables automation, monitoring and control of processes and objects in real time [26]	Controllers and sensor systems [26]
Cloud Manufacturing	Virtual portals which create a shared network of manufacturing resources and capabilities offered as services [100]	The Internet
Internet of Things (IoT)	A computational system which collects and exchanges data acquired from electronic devices [99]	Radio-frequency identification (RFID) technology tags, sensors, barcodes, smartphones [100,101]
Additive Manufacturing	Represents agile and connected prototyping of parts of products on a large scale, enabling customization [102]	3D printers

Thus, in addition to the key technologies of I4.0 identified in [99], cyber-physical systems are listed as cloud manufacturing, internet of things, additive manufacturing, and big data as key technologies of I4.0. This research is developed from the argument that I4.0 technologies, also referred to as “digital technologies”, are able to enable circular approaches and hence, the CE. For example, tracking products post-production by the use of sensors in order to recover components [34] or inform end of life strategy [73]. As outlined in a research survey conducted by PriceWaterhouseCoopers on 235 German industrial companies [103], while enabling products with digital devices requires considerable investments, there is clear economic potential for products post-production and the larger CE. When companies from the following industries: manufacturing and engineering, automotive suppliers, process industry, electronics and electrical systems, information and communications [103], were interviewed and the results analyzed, it was concluded that, while the digitization of value chains was the top priority for all companies irrespective of size, the benefits for the CE per company was a degree of the extent of digitization deployed on products, their production, and development.

### 5.3. Analysis of Trend by Means of Technology Life Cycle (TLC)

The product life cycle is based on an economic viewpoint showing turnover, as well as costs, profits, and loss [104]. The hypothesis of the product life cycle (PLC) is established both empirically and theoretically in various literature ([105,106]). When the concept of PLC is applied to technological revolution, the technological life cycle (TLC) is birth. Often, the terms “product life cycle”, “industry life cycle”, and “technology life cycle”, are used interchangeably and ambiguously [107], leading to arguments portraying the inconsistencies of the TLC, such as “there is no single strong, unified theory of technological evolution” [108]. Comparatively, while PLC is generally concerned with the individual product, service, or industry [109], technology life cycles depict the development over time for the different stages of technological change [110].

Thus, each generation of technology is expected to comply with a PLC-style life cycle [109]. A multitude of related products and/or services can be allocated to a level/levels within a generation of technology, each of which follows its own PLC. Hence, for research that integrates CE into Industry 4.0 by means of understanding the utilized technologies, it can be argued that a macro-level perspective is needed when exploring this theme through the dynamics of the TLC [109]. The macro view of TLC understands that technological evolution, technological progression, and technological progression within industries and industry evolution are central to the technology evolution model [111,112]. The macro model of TLC incorporates technological discontinuity (a breakthrough innovation which affects both products and/or processes) [107]. According to [112], these are technologies that are also described within industry and academia as revolutionary, radical, breakthrough, emergent, step-function technologies. Within the context of this research paper, I4.0 technologies can be appropriately classified as this. These will include technologies within cloud manufacturing, cyber-physical systems, internet of things, additive manufacturing, flexible manufacturing lines, big data collection and analysis, digital automation with sensors, and simulation/analysis of virtual models [98].

The era of ferment variation follows the period of technological discontinuity. In this period, a dominant, single configuration takes place after a period where rivalry and competition among variations of the original breakthrough occur [113]. As indicated in Figure 12, this dominant design becomes the industry standard. Earlier figures (Figure 9a,b) show the US and China leading in terms of the areas where most research on circular approaches is most dominant. The dominant subject area according to this context is “engineering”, as indicated in Figure 10. This brings an interesting perspective to any proposed framework. The next step in this cycle is the era of evolution where incremental changes are made for the selected technology. Refs. [112,113] describes these changes as evolutionary, continuous, incremental, or ‘nuts and bolts’ technologies. The continuity of this cycle of variation begins with a further discontinuity at the point of technological discontinuity [114]. There are a number of reasons why TLC is utilized in order to develop an integrative framework for the CE-I4.0 from a systematic literature review. First, the initial phase of the technology life cycle is presented by scientific publications drawn from general databases [115]. Based on [116], scientific publications, patents, start-up companies, and reported product launches make up technology life cycle indicators. Furthermore, ref. [117] goes on to elaborate that digital technologies and sustainable technologies can be classified as “patents” within “start-up companies”. In addition, ref. [118] suggests that within this TLC framework, “technological frames” which capture how stakeholders categorize a technology relative to other technologies can be understood. Such performance criteria which are used to evaluate a new technology are important for emerging technologies in I4.0. For stakeholders, the deployed technological frame ensures that they have the right interpretation of that particular digital technology and gives them a better understanding of its usefulness to their field Thus, these points give sufficient reasons to explore CE-I4.0 within the TLC framework.

According to [119], understanding the long-term composition of innovation in energy technologies is important for technology forecasting and public policy planning in the context of climate change. This is also important in the context of the CE [107] as CE-I4.0 integration will require a focus on innovative activities, as well as emerging digital technologies [120].

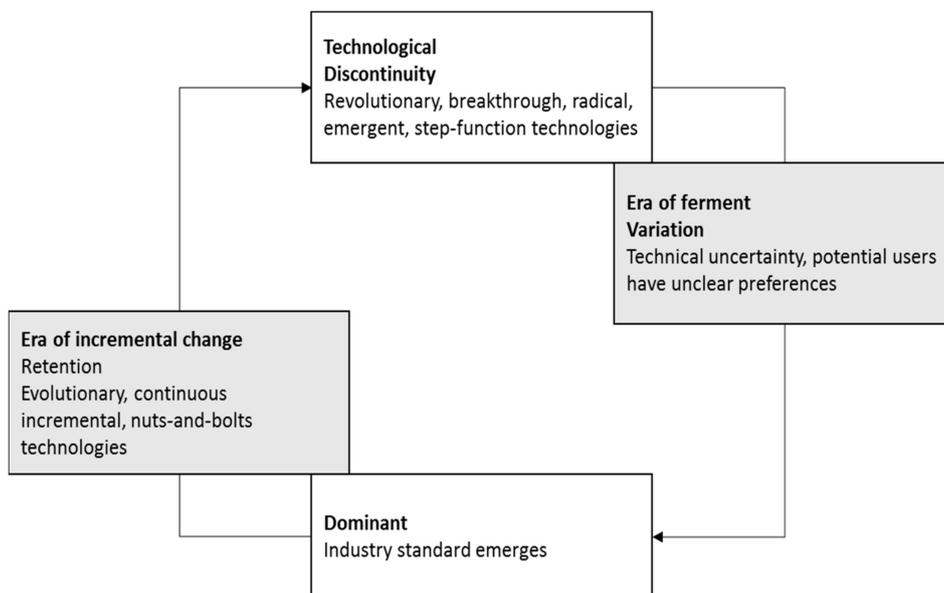


Figure 12. Macro TLC (Adapted from Taylor & Taylor, 2012; [107]).

**RQ 1: How can the synthesis of digital technologies with circular approaches support I4.0 in enabling the transition towards a CE?**

The papers reviewed showed a growing number of digital technologies already utilized in specific circular approaches. These include: (recycling and reuse) digital tracking and modelling devices used

in the steel industry [121], sensors employed for thin-film photovoltaic (PV) technologies [122] and on buildings [123], sensing devices and programmable logic controllers for a steel industrial complex for water [124], hybrid genetic algorithms employed on household appliances [125], and automated optical sorting for recycled glass [126].

For *remanufacture*, digital sensors are being employed in vehicle engines [127], within mechanical equipment industry [127], on waste electrical and electronic equipment [128], and as hybrid generic algorithms for certain manufacturing systems [129]. In the *reuse* circular approach, digital sensors are seen to be employed in metal forming [130], in the manufacturing industry [131], for virtual engineering objects [132], and for computer aided technologies (CAx) systems within the aerospace industry [133]. Also included in this circular approach category are digital sensors using a big data model in smart computing [134], RFID in the manufacturing industry [135], and real-time distributed embedded control software in the manufacturing industry [136].

Thus, there is growing evidence that I4.0 domains and technologies are employed in specific circular approaches. In some cases, these technologies apply to more than one circular approach [124].

The Ellen MacArthur Foundation, a key global charity involved in pursuing CE objectives amongst key stakeholders, proposed the ReSOLVE framework [137] of *Regenerate, Share, Optimize, Loop, Virtualize and Exchange* as six key business actions to aid organizations in implementing the principles of the CE. While this framework is elaborate in definition, it can be argued that it does not fully appreciate the emerging technologies that can transform both service- and product-oriented businesses. Also, while these actions all increase the utilization of physical assets, prolonging their life and shift resource use from finite to renewable sources [138], there is little focus on the experiences and feedback of the user, as it lists businesses, the government, and academia as decision-makers [137]. Within I4.0, especially in the domain of the Internet of Things, data production is essential [139]. Studies by Liao et al., (2017) show that “data” appeared 229 times as part of the 25 most frequent words related to Industry 4.0, when 224 related papers were analyzed [28]. With the amount of data produced by personal, home, and industrial devices, data and data ownership will influence the transition to a CE [139].

The proposed framework attempts to create a bridge between the three principles that govern the CE cycles and users as stakeholders. This is captured in Table 6. The *technological perspective*, *economic perspective*, and *organizational perspective* are covered within the CE cycle principles of (1) conservation of natural capital, (2) increasing the lifespan of resources through technical and biological cycles, and (3) reduction of the negative effects of production systems [139]. The cognitive perspective takes into account *users* as a key stakeholder in any CE-DT integrated framework. Users of CE-I4.0 tools are expected to develop different interpretations of new technologies as they use them in practice, which can drive additional variation [140] and functions in the original design stage, for example, design for remanufactured DfRem. According to [139], “lead users” (users with experience) will have to be created for high technology products as potential users may not have the experience needed to evaluate or understand the attribute of a new product. Potential users, as argued in [139], make their interpretations based on their technological frames and on comparisons with interpretations made by other users. Following this, ref. [118] shows that in adopting a new technology at the time, Lotus Notes, users imposed their assumptions about familiar technologies on the new product, where they made comparisons with word processing and spreadsheet programs. The same research results show that in the same firm, variation in framing caused different Lotus Notes implementations. Users with experience in a technology—the lead users—are also able to shape subsequent technology development (than those originally intended) for further CE-I4.0 integration [140]. As I4.0 presents a number of specialist domains and technologies within cyber-physical systems, cloud computing/manufacturing, additive manufacturing, and the Internet of Things [34], which are rapidly evolving, the synthesis of I4.0 and CE approaches will be driven by various actors: academia, the government, industry, and end-users of which there would be users and *lead-users* [141].

**Table 6.** Synergistic and integrative CE-DT framework through TLC (As adapted from Kaplan & Tripsas, 2008; [140]).

	<b>Era of Ferment</b>	<b>Dominant Design</b>	<b>Era of Incremental Change</b>	<b>Discontinuity</b>
Technological perspective	Greater or lesser variation takes place on product or process. Specific I4.0 domains are introduced, e.g., sensor-enabled product to enable recycling.	A dominant design is achieved or not. A particular technology becomes dominant over others in specific CE approaches.	Dominant design from SLR includes reuse, recycle, remanufacture, and repair. Inertia develops around these CE approaches.	A new I4.0 technology emerges or not [140].
Economic perspective	<b>Mechanism</b> <b>Mechanism:</b> Technical breakthroughs in CE-DT integrated areas are likely to come from areas where research is highest. <b>Predicted Outcomes:</b> Variation here is not random but strategic.	<b>Mechanism:</b> A dominant design linking I4.0 domain to CE approach will be driven by economies of scale, interdisciplinary interaction, and industry. <b>Predicted outcomes:</b> Dominant technology for CE approach.	<b>Predicted Outcomes:</b> I4.0 technology linked to CE approach is expected to remain dominant. Future technologies and research are expected to be built around this outcome.	When existing I4.0 to CE approach technology reaches a point of diminishing returns, a new technology will emerge [140], e.g., from Bar code to RFID.
Organizational perspective	<b>Mechanism:</b> Technical variety is driven by exogenous stochastic technological advances [141]. <b>Predicted Outcome:</b> Variation is random.	<b>Mechanism:</b> emergence of dominant design is driven by subject area (engineering and computer sciences Figure 9). <b>Predicted Outcomes:</b> Dominant design sponsored by a dominant community is expected.	<b>Mechanism:</b> CE-DT results from industry-academic demand, existing CE approach, and procedures. Technological progress is expected to rapidly increase due to the competing stakeholders and countries.	<b>Mechanism:</b> Stakeholders from academia, industry, and government bring capabilities to bear. <b>Predicted outcome:</b> As evident by number of papers in Figure 6, research in CE-DT research will grow, with technologies outpacing CE approaches
Cognitive perspective (framework adaptation)	<b>Mechanisms:</b> Technical variation is driven by agents such as academia, industry, government policy-makers, and customer. End-users guide the design and interpretation of various CE-DT technologies and trends.	<b>Mechanisms:</b> The prerequisite for achieving a dominant design is end-user feedback. Why should this CE-DT device be used? Is it user friendly? How would the device interact with other users? Has the data collection & analysis been defined?	<b>Mechanisms:</b> Adoption and flexibility of I4.0 technologies may be fairly easy across dominant CE approaches.	<b>Mechanisms:</b> CE and I4.0 are emerging research areas, hence any discontinuity of existing technology will be due to a newer, more efficient technology.

#### 5.4. Technological Infrastructure Important for a CE-DT Integration

According to [142], technological infrastructure can be described as the solutions required to complete or fulfil a technological process, usually in a component-based fashion [143]. These include distributed IT solutions, Information Systems Development (ISD) methodologies, and other functionalities provided by collaborative and workflow technologies [142] that will allow organizations to evolve quickly in the face of changing business requirements. Within a CE-DT framework, these will include research facilities in academia and industry required for successful CE-I4.0 implementation, as this platform must be assembled, scaled appropriately, documented, and monitored for key improvements [144], which would be enhanced as required.

Key reasons exist which emphasize the need for known technological infrastructure to support CE-DT integration. These include the turbulent and competitive markets [142] which industries and CE stakeholders operate from [140], the increasingly complex IT environment which organizations deal with, data complexity, and interconnected data networks [145]. In research to examine the technological infrastructure important for organizations which solely depend on information systems [142], the concept of “Process-Based Information Systems” or PBIS was developed. This contained a set of solutions that simplify the integration of new IT artefacts and aid companies in responding to changing business requirements [142]. This framework is developed by integrating activities and technologies at two defined levels; the coordination level and the operation level, unifying all the computational resources of a company into a single global infrastructure.

To drive the development of a related technological infrastructure for a CE-DT integration would be multidisciplinary already identified in I4.0 and the CE research. A comprehensive technological infrastructure will involve an understanding of the technological nutrient within a CE for individual circular approaches, as identified in [146], as well as the incorporation of technological, business, sustainability, and organizational aspects which multidisciplinary can drive.

#### 5.5. Digital Intelligence to Enable a CE-I4.0 Integration

While integration of digital intelligence within CE approaches can potentially provide opportunities to distribute knowledge, structure, ownership and different levels of customization [56], this has largely being unexplored in available CE research. A SCOPUS search, for example, yields two papers when “Circular Economy” and “Digital Intelligence” are utilized as search strings. In [53] an integrative literature review was used to explore if re-distributed manufacturing and digital intelligence can enable a regenerative economy. Following this [147], opportunities for digital intelligence as an enabler of a CE was investigated. It can be seen that, through qualitative systemic analysis and analysis of consumer good production, there are opportunities for circularity through implementation of digital intelligence and distributed models of consumption and production [147].

Stemming from Gardner’s intelligence classification scheme [148], a new form of intelligence known as “digital intelligence” was proposed as a response to the cultural change brought about by digital technologies [149]. “Digital Intelligence” however, like the CE, experiences the challenge of lack of a concise definition. Considering the definition of “intelligence” as the ability to learn and solve problems [150], “digital intelligence” is conceptualized as the “ability to understand and relevantly use digital/online concepts and solve technological, informational and communicational online problems” [151]. Following this [152] introduces the notion of “digital fluency”, arguing that the intelligence gap which users of products fill and deploy in order to utilize new technologies can be said to be digital intelligence. Hence the concepts of “digital intelligence” and “digital technologies” have been observed to be used interchangeably in research [57]. However, according to [153] the rise of artificially modified human intelligences and the changes brought about by ICTs suggests that “digital intelligence” lies in the embedded intelligence in the digital device and not in the user. Following this, products are said to be “digital” [103] when “intelligence” are directly integrated into the products itself. Examples include the modern anti-block systems which have embedded electronic control units and other automotive components with embedded sensors [103].

Available definitions are unanimous in the assertion that in practice, digital intelligence must be driven by intelligence, information, algorithms or coding which are not independent from the product or user. This *intelligence* is thus critical for a faster transition to a CE and for enabling an effective CE-I4.0 integration. Digital intelligence is also important for strengthening circular business models [147] through automated monitoring, control and optimization of resources and material flows [53]. Digital intelligence, for example has been seen to enable premium customized services within circular business models [154]. From this, it is concluded that digital intelligence relating to the perspectives as captured in Table 6 as well as in the product and business models is important for an effective CE-I4.0 integration.

## 6. Conclusions

This paper presents a synergistic and integrative CE-DT framework utilizing the technology life cycle concept based on results from a systematic literature review of 174 papers. Currently, papers on the two emerging concepts of the “Circular Economy” and “Industry 4.0” largely follow an independent direction in research, with the two areas barely interacting, despite the acknowledged support that I4.0 gives in the transition to a CE. This section presents and discusses the results of the paper.

### 6.1. Implication for Academia, Policy Makers, Industry and End-Users

**RQ 2: How can a synergistic and integrative CE-DT framework offer directions for policymakers and guidance to academia for future CE-I4.0 research?**

Several relevant pieces of literature have stressed the need for a research agenda and processes as a critical success factor in any implementation of I4.0 techniques [155], as concepts within I4.0 such as Internet of Things, Additive Manufacturing, Cyber Physical Systems, or Cloud-Based Manufacturing can be inherently disruptive [24]. Within the new actor introduced from the framework, the end-user, research shows that a limited number of end-users have a clear understanding of the implementation techniques of I4.0 [156]. In integrating CE approaches and I4.0 technology with the aim of enabling a CE, the prospects for further confusion on this subject is high. The research and industry implications are presented in Table 7.

**Table 7.** Research trends for various stakeholders for future research.

Stakeholder	A Concise Definition	Research Trend for Integrated CE-I4.0 Future Research
Academia	Research institutions, universities, scholarly institutes	(a) To investigate and map CE approaches to specific I4.0 technology; (b) to investigate, capture, categorize, and rank value from CE-I4.0 implementation within industry; (c) to identify possible barriers to CE-I4.0 implementation and suggest ways of overcoming these barriers; (d) to identify opportunities for I4.0 to support each of the 9R’s CE approach; (e) to provide a definition for the CE within an integrative CE-I4.0 context; (f) future research in this area could include intersecting (and important) research areas such as supply chain and cybersecurity; (g) to study CE-I4.0 development within selected areas, for example, countries and regions.
Industry	Manufacturing, environmental, health-related industries, etc. Research and Development units within industries.	(a) To identify and categorize various emerging I4.0 devices and intelligence under the technologies (smart manufacturing) as identified in [99] and link them to use in CE approach; (b) to identify links between CE approaches, I4.0, and environmental implications; (c) identification of dominant design where industry standards emerge; (d) to investigate CE-I4.0 implementation at theoretical, practical, and strategic level.
Policy-makers	National governments, regional governmental units, policy-making institutions (e.g., the United Nations, UN)	(a) To clarify data ownership with Industry and academia. (b) As done with CE research to synthesize a common template and industrial policy for CE-I4.0 used. (c) To drive for multidisciplinary research for CE-I4.0 research
End-User	User of product or service. Customer who has purchased and shall use product or service.	(a) Can help in carrying out interviews, surveys in order to define “lead-user” and “potential users”; (b) various support shall be implemented to ensure that used and operational data is captured by user in order to implement circularity on products or services (for example, product manual).

## 6.2. Research Conclusions

Empirical studies show an increasing trend in publications in the CE and I4.0 when viewed as individual research areas, especially during the last six years (2012–2018). Research on an integrated study of CE-I4.0 within the period under review is still limited. When viewed as independent circular approaches (9R's) and selected I4.0-related words, however, the results show that the research area has been part of mainstream research in academia. Efforts should be made (see Table 7) to link these research areas as part of the wider CE research/transition to a CE. Currently, the USA and China lead in this research area, with the main subject areas in Engineering and Computer Science. Within Europe and Asia (outside China), Germany and India recorded the highest number of papers found. Research in recycling, refurbishment, remanufacturing, and reuse recorded the highest ratio of results when their final results (after exclusion) were compared to the results from the initial search. The review revealed that most articles published in this research area were conference papers. Stronger multidisciplinary research is recommended to ensure that a higher number of journal papers are published. Multidisciplinary research in the CE-I4.0 integrated research area is expected to increase results within all CE approaches and bring greater visibility in terms of links between CE strategies and specific digital technologies.

I4.0 paradigms and digital technologies were identified to have driven CE-related research in engineering and the computer sciences, and less in environmental sciences, business and management, material science, and chemical engineering research areas. This paucity of research implies that much is unknown in academia in these areas, especially in terms of the opportunities for I4.0 in these areas. The rise of I4.0 has led to the rapid growth of data volume (hence the term, Big Data) [63]. From the reviewed papers, it is observed that current I4.0-CE strategies research situates its focus on digital sensors and sensor devices. Big data, however, is not pronounced in the papers reviewed, despite its many uses and opportunities [157]. It is also concluded that digital intelligence important for an effective CE-I4.0 integration extends beyond the product but also the intelligence within the technological, economical, cognitive and organization perspective within a CE-I4.0 framework.

The research utilized the technology life cycle (TLC) framework in developing an integrative framework for future research. From this, it was discovered that “end-users” are not clearly identified and captured in current CE frameworks. Thus, a synthesized framework which can enable the transition to a CE would include all the identified key stakeholders: academia, industry, policy makers, and end-user.

## 6.3. Limitations and Recommendations for Future Study

This research could be improved further in order to overcome some identified limitations. Technology life cycle (TLC) was utilized in the development of an integrative framework. This can be argued to be focused on the technical aspects of the research and the end-user. Furthermore, TLC has been highlighted in literature as “confused” and incomplete” [107], a misunderstanding which has been attributed to the similarities between the terms “*industry life cycle*”, “*product life cycle*”, and “*technology life cycle*”. In light of this limitation, it is suggested that a future CE-I4.0 integrated study is modelled with other existing frameworks within CE, product end-of-life, or sustainability literature.

While a comparison between the integrative framework and the ReSOLVE framework was made, it is suggested that for a future study, both frameworks are exhaustively utilized. The research focused on implementing an SLR on the 9R's, as identified in [64]. For future research, it is recommended that important circular approaches are identified (from the 9R's) and a detailed SLR performed on this in order to yield strategic results. There is a need to examine the various methodologies employed in CE-I4.0 research in order to highlight methodologies that drive the selection of a particular circular approach to an identified digital technology. Implementing an SLR on 9R's in order to find these methodologies can be challenging. Hence, it is recommended that smaller units of these circular approaches be used in the determination of these methodologies (for example, limiting the search to the 3R's of Reuse, Recycle, and Remanufacture). These methodologies could produce some useful

results for industry and manufacturers, especially towards designing a CE. There is also the need to investigate the concept and applicability of what are considered technological nutrients within the CE for specific circular strategies. Future studies in this area should include conceptualization of a workable definition for digital intelligence for a CE as well as exploration of the concept within CE strategies.

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