sustainability

MDPI

Article

Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda

Gianmarco Bressanelli [1,*], Federico Adrodegari [1], Daniela C. A. Pigosso [2] and Vinit Parida [3,4]

[1] RISE Laboratory, Department of Mechanical and Industrial Engineering, University of Brescia, 25123 Brescia, Italy; federico.adrodegari@unibs.it
[2] Section of Engineering Design and Product Development, Department of Mechanical Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark; danpi@mek.dtu.dk
[3] Department of Business Administration, Technology and Social Sciences, Lulea University of Technology, 97187 Lulea, Sweden; vinit.parida@ltu.se
[4] Department of Business, History and Social Science, USN School of Business, University of South-Eastern Norway, 3679 Notodden, Norway
* Correspondence: gianmarco.bressanelli@unibs.it

Abstract: The digital age we live in offers companies many opportunities to jointly advance sustainability and competitiveness. New digital technologies can, in fact, support the incorporation of circular economy principles into businesses, enabling new business models and facilitating the redesign of products and value chains. Despite this considerable potential, the convergence between the circular economy and these technologies is still underinvestigated. By reviewing the literature, this paper aims to provide a definition and a conceptual framework, which systematize the smart circular economy paradigm as an industrial system that uses digital technologies during the product life-cycle phases to implement circular strategies and practices aimed at value creation. Following this conceptualization, the classical, underlying circular economy principle, 'waste equals food', is reshaped into an equation more fitting for the digital age—that is to say, '*waste + data = resource*'. Lastly, this paper provides promising research directions to further develop this field. To advance knowledge on the smart circular economy paradigm, researchers and practitioners are advised to: (i) develop research from exploratory and descriptive to confirmatory and prescriptive purposes, relying on a wide spectrum of research methodologies; (ii) move the focus from single organizations to the entire ecosystem and value chain of stakeholders; (iii) combine different enabling digital technologies to leverage their synergistic potential; and (iv) assess the environmental impact of digital technologies to prevent potential rebound effects.

Keywords: circular economy; digitalization; industry 4.0; literature review; business models; sustainability

check for updates

Citation: Bressanelli, G.; Adrodegari, F.; Pigosso, D.C.A.; Parida, V. Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda. *Sustainability* **2022**, *14*, 4960. https://doi.org/10.3390/su14094960

Academic Editor: Antonella Petrillo

Received: 17 February 2022
Accepted: 18 April 2022
Published: 20 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. The Relevance of the Digital Age to the Circular Economy

The circular economy is recognized by industries, scholars, and policy makers as a promising approach to jointly advance the sustainability and competitiveness of value chains, given its ability to decouple economic growth from resource consumption and waste generation [1–3]. Moving companies towards the circular economy involves fundamental changes in industrial ecosystems and a systemic redesign of products, production processes, business models, value chains, and consumption patterns [4,5]. By doing so, several 'R' strategies (sometimes called R hierarchies or imperatives) may be pursued. For instance, the European Council in 2008 issued the Directive 2008/98/EC to define a priority order and a waste management hierarchy that lays its foundation on the 3Rs [6]. They are reduce (through prevention), reuse, and recycle. Other researchers then proposed a framework based on the work of Potting et al. [7], grouping several 'R' strategies into three categories: (i) refuse, rethink, and reduce to find smarter manufacturing methods or product usages;

(ii) reuse, repair, refurbish, remanufacture, and repurpose to extend product and component lifespan; and (iii) recycle and recover to find useful applications for materials [8]. This categorization has been reframed in other scientific articles [9,10]. Other scholars summarize the divergent perspectives on 'R' strategies by proposing 10R typologies [11]. Recently, other authors have proposed limiting the categories of 'R' strategies to a 4R scheme, to make it more comprehensible for managers and companies, based on reduce (increase material and energy efficiency), reuse products, remanufacture components, and recycle materials [12].

However, in making the significant transformation towards the circular economy, several technical, organizational, cultural, and financial challenges arise [13–17]. For example, products designed to last are unable to respond to fashion and technological changes. The collection of end-of-use products leads to uncertainties regarding quantity, quality, time, and place of return, reducing the probability of achieving economic scale and decreasing the profitability of reuse and remanufacture. In addition, remanufactured products can cannibalize the sales of existing ones, affecting traditional revenue streams. Furthermore, regulation, taxation, and policy systems are usually not aligned with the aim and scope of the circular economy. Low awareness and resistance to change often limit how the circular economy is embraced, especially given the prevalent linear mindset of industries and consumers. As a result, the implementation of circular economy projects requires large investments and often leads to longer and more uncertain payback times than traditional projects.

Against this backdrop, the digital age offers companies many new opportunities to overcome these transformational challenges and to jointly advance sustainability and competitiveness [18]. In fact, digital technologies provide incentives for businesses to implement circular economy principles by enabling new business models as well as the redesign of products and value chains to conform to a new smart circular economy paradigm [19–21]. For instance, Michelin implemented the Internet of things (IoT) technology to collect tire-related data and to enable a tire-as-a-service business model, in which fuel consumption and downtime are minimized [22]. Groupe SEB leveraged 3D printing to print spare parts on demand, virtualizing its provision and overall technical assistance processes, thus reducing overstocking, transport needs, and emissions [23]. Walmart tested the IBM Food Trust blockchain to track the origin, real-time location, and status of food products in its supply chain network, to prevent food waste and support consumer choice of sustainable patterns [24]. Rolls-Royce took advantage of big data collected through the IoT on jet engine conditions, to improve the design of engines for optimal performance and for predictive maintenance [25].

Despite these technological projects and their substantial potential, the convergence between the circular economy and digital technologies is still underinvestigated, and commercial applications in companies remain limited [26,27]. More specifically, the literature continues to struggle to understand how these technologies might contribute to value creation in the implementation of the circular economy [28]. A new smart circular economy paradigm is emerging [20], but the literature still lacks a clear definition and conceptualization of this development as well as an integrative framework on how to approach the transformation required. Thus, the aim of this paper is to define, conceptualize, and discuss the smart circular economy paradigm as a new emergent phenomenon. The intent is to discuss how digital technologies can help to realize the different aspects of the smart circular economy and to identify promising research directions that will advance research in this field.

The paper is structured as follows. In Section 2, the research methodology and the theoretical background are provided. Based on the literature review, a definition and a framework for the emergent smart circular economy paradigm are conceptualized in Section 3. Here, the usefulness of the framework is demonstrated by applying the model to the seven contributions published in the special issue, 'Circular Economy in The Digital Age'. Section 4 proposes promising research directions to advance academic discussion on how companies can leverage digital technologies in transitioning to the smart circular economy paradigm. Lastly, in Section 5, the study's conclusions are presented.

2. Research Methodology and Theoretical Background

2.1. Research Methodology

This paper is centered on a literature review and on developing a conceptual framework. To address the research gap, a literature review on the emergence of the smart circular economy paradigm has been carried out, according to the steps represented in Figure 1. More specifically, scientific articles dealing with the intersection of the circular economy and digitalization have been searched on the Scopus database. The keyword 'circular economy' has been combined with several terms identifying the digitalization phenomenon, such as 'digital technologies', 'smart', and 'digitalization'. The search was carried out in December 2021 and updated in March 2022. The search string TITLE-ABS-KEY ('circular economy') AND TITLE-ABS-KEY ('digital technologies' OR 'digitalization' OR 'smart') led to the extraction of 641 documents. A first screening was carried out to exclude articles written in languages other than English. An important decision was also taken regarding the type of article: considering the scientific nature of the research, we decided to include only articles published in international, peer-reviewed scientific journals, as a measure to ensure the quality of the publications selected. As a consequence, conference proceedings and book chapters were discarded in this step. A total of 402 articles advanced to the next step, title and abstract reading, to determine the eligibility of the articles. Given the objective of the research (i.e., to define, describe, and conceptualize the smart circular economy paradigm), we decided to focus only on research articles reporting a definition and/or a conceptualization of the smart circular economy for the manufacturing industry. After this step, a total of 75 documents remained. The same criterion was applied for inclusion during the full-text reading step. As a result, a final set of 44 documents was used as the basis for this research. The results of this analysis and a collection of the definitions/conceptualizations are provided in Sections 2.2 and 2.3.

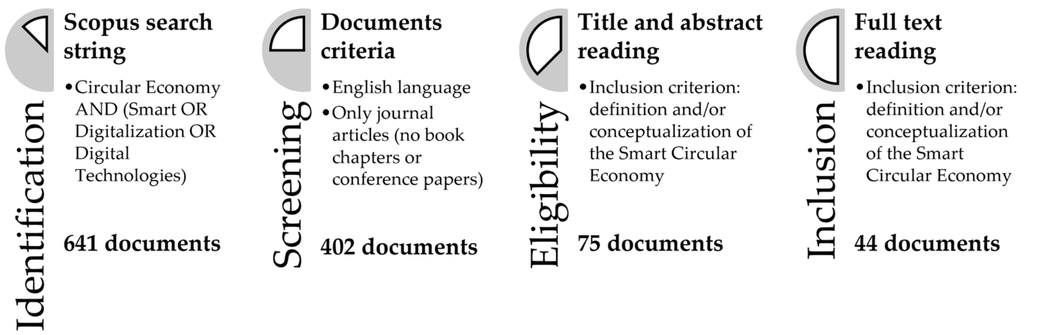

Figure 1. Literature Review methodology.

Building on the previous literature, we provide a definition of the emergent smart circular economy paradigm and a framework comprising the main concepts underlying it. Our intention is to use the framework to describe—and prescribe—the enabling role and effects of digital technologies in achieving sustainability under the smart circular economy paradigm. To test the framework and to demonstrate its usefulness, we decided to apply it to the seven contributions published in the special issue, 'Circular Economy in The Digital Age'. Lastly, based on the literature review and on the application of the framework, promising research directions to advance the academic discussion on how companies can leverage digital technologies to transition towards the smart circular economy paradigm have been drafted.

2.2. The Emergence of the Smart Circular Economy Paradigm

Industries are witnessing a digital age as society enters a fourth industrial revolution (often called industry 4.0 [29]), which is revolutionizing business by capitalizing on digitalization, innovation, and collaboration in industrial ecosystems [18]. In this context, and as discussed later in this paper, digital technologies (e.g., the IoT, big data and advanced analytics, 3D printing, blockchain, and virtual and augmented reality) can have a direct impact on the adoption of sustainability practices [30], thus enabling the transition towards a smart circular economy [31–34]. In fact, digital technologies can enable several functionalities, from data collection and integration to data analysis and data automation [35]. Nevertheless, their enabling role is currently fragmented in the scientific literature, and a clear definition and conceptualization of the smart circular economy paradigm is still lacking [27,34,36].

Previous research attempted to conceptualize the smart circular economy paradigm in a scattered way (Table 1). Alcayaga et al. conceptualized smart circular systems as industrial systems that are restorative or regenerative by intention and design, where smart use, maintenance, reuse, remanufacturing, and recycling are included in the business models of product-service systems, enabled by digital technologies [37]. Kristoffersen et al. conceptualized the smart circular economy as a framework that bonds together data transformation (from smart products to data, information, knowledge, and wisdom), resource optimization capabilities (descriptive, diagnostic, discovery, predictive, and prescriptive), and data flow processes (hierarchical structure of data collection, data integration, and data analysis) to enable the implementation of circular strategies [20]. To implement a smart circular economy, organizations should leverage digital business practices on value creation [36]. Dahmani et al. proposed the synergistic combination of lean/eco-design and industry 4.0 to enable a smart circular product design. Their innovative model promoted sustainability throughout the product life cycle by adopting reduce, reuse, and recycle strategies [38]. On the other hand, Kayikci et al. emphasized the role of smart circular supply chains, which would be established by combining the circular economy with smart enablers (including digital technologies) to provide firms with a competitive advantage. This outcome would be achieved by managing products effectively, preventing pollution, and supporting the achievement of the sustainable development goals [39]. Lastly, Lobo et al. defined the smart circular economy as an industrial system that uses digital technologies to implement circular strategies such as reduce, reuse, remanufacture, and recycle [40].The studies listed above make useful contributions to the field, but there is still a lack of clear definition and conceptualization of the smart circular economy.

Table 1. Previous conceptualizations of the smart circular economy paradigm.

Article	Year	Smart Circular Economy Definition and Conceptualization
Towards a framework of smart circular systems: An integrative literature review [37]	2019	Smart circular systems are conceptualized as industrial systems that are restorative or regenerative by intention and design, where smart use, maintenance, reuse, remanufacturing, and recycling are included in product-service systems' business models, enabled by digital technologies.
The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies [20]	2020	The smart circular economy is conceptualized in a framework that combines data transformation, resource optimization capabilities, and data flow processes to enable circular strategies.
Smart circular product design strategies towards eco-effective production systems: A lean eco-design industry 4.0 framework [38]	2021	Smart circular product design is conceptualized as the synergistic combination of lean/eco-design and industry 4.0 to promote sustainability throughout the product life cycle using reduce, reuse, and recycle strategies.

Table 1. *Cont.*

Article	Year	Smart Circular Economy Definition and Conceptualization
Smart circular supply chains to achieving SDGs for post-pandemic preparedness [39]	2021	The establishment of smart circular supply chains is conceptualized as the combination of the circular economy and smart enablers, to provide firms with a competitive advantage by managing products effectively and preventing pollution.
Towards a business analytics capability for the circular economy [36]	2021	The smart circular economy is conceptualized as a more efficient and effective economy, where organizations leverage digital business practices on value creation.
Barriers to transitioning towards the smart circular economy: A systematic literature review [40]	2022	The smart circular economy is defined as an industrial system that uses digital technologies to implement circular strategies such as reduce, reuse, remanufacture, and recycle.

2.3. The Enabling Role of Digital Technologies in the Smart Circular Economy Paradigm

As discussed above, several digital technologies can facilitate the transition towards a smart circular economy in several ways. We decided to confine our focus to five main digital technologies (i.e., the IoT, big data and analytics, 3D printing, blockchain, and augmented and virtual reality) given their relevance and potential for the circular economy [4,30,41]. Their enabling role in the smart circular economy paradigm is discussed in the following segment.

The IoT, as a technology, describes a network of connected physical objects that are embedded with sensors (such as radio frequency identification (RFID), printed circuits, or electronics) [42]. Products embedded with sensors can share information and communicate with other systems through the Internet. Thus, they become active participants in the network. The IoT enables a circular economy by facilitating access to the data of products over their life span (from design and manufacturing to distribution, usage, and end of use) to support their life-cycle management [26,37]. During manufacturing, the monitoring of operational data through the IoT expedites the achievement of operational excellence by reducing scrap rates and equipment wear and tear, with a lower environmental footprint compared to conventional manufacturing processes [18]. In addition, the IoT enables the provision of product-as-a-service circular business models (such as sharing or pay per use). It allows products to become *smart*, thus facilitating tracking, monitoring for billing purposes, and the provision of full-service contracts, including repair and maintenance [19,43]. Finally, from usage to the end of use, the IoT helps to track product flows, capture product lifetime information, and minimize the uncertainties involved in recovery strategies—in particular, with regard to the quality and condition of each product/part/component prior to disassembly. Consequently, the IoT promotes better managerial decision-making about alternative circular strategies such as reusing, remanufacturing, and recycling [37].

Big data and analytics are based on extremely large amounts of unstructured data, which are generated in a continuous stream and are characterized by their large volume, velocity, and variety. Big data are usually analyzed computationally through data mining and advanced analytics to identify new information, trends, patterns, and associations. In this context, artificial intelligence techniques may be employed for both data collection and data analysis [44]. In fact, big data are commonly used to feed and train machine learning and deep learning algorithms. Therefore, advanced analytics can be defined as the ability to transform data into valuable information to increase knowledge [45]. Big data and analytics serve the circular economy through their potential to optimize processes and enhance decision-making, using the data collected from the IoT to improve resource management across the entire product life cycle, from manufacturing to end of use [20,46]. Artificial intelligence can also be an effective tool in helping managers to identify hidden patterns [47]. For instance, the exploitation of data-driven decision-support platforms may provide efficient and reliable tools for decision-making in sustainable logistics systems [48]. In this context, digital modeling and simulation are used to support decision-making in several circular economy areas [49]. For instance, big data may provide valuable information on how customer usage patterns can be used to improve product design for circularity. Big data and analytics can generate an enhanced understanding of user behavior and provide useful (and often missing) feedback from the product usage phase back to design [26,50]. In addition, data mining and advanced statistical analysis enable the provision of preventive, predictive, and condition-based maintenance [20,51], including the realization of completely automated workflows where smart and connected products can predict failures and automatically schedule future maintenance activities [37].

3D printing as an additive manufacturing technique is used to create three-dimensional objects, layer by layer, starting from a digital computer-aided design (CAD). Products are manufactured through additive processes—that is to say, the opposite of subtractive manufacturing processes—where pieces of plastics or metals are cut out by milling, drilling, and turning machines. Additive manufacturing is a more comprehensive concept than 3D printing, since the former is a broader term encompassing more processes than 3D printing. In contrast, 3D printing empowers the circular economy by allowing a circular design to manufacture, repair, reuse, and recycle products [52,53]; 3D printing enables the circular design of products because recycled materials (plastics and metal powder), instead of virgin ones, can be used as input in additive manufacturing processes [54,55]. In this process, the effects of thermal cycles on the mechanical properties of products should be carefully taken into account because they could impose limits on the reuse of recycled powder [52]. Moreover, they significantly increase the personalization of products, thus improving the bond between the customer and the product itself, enhancing emotional attachment to the products, and averting their early retirement [56]. Regarding circular manufacturing, 3D printing enables local, on-demand, efficient, and real-time production. In contrast to conventional subtractive techniques, 3D printing avoids material losses, scraps, and waste during production, achieving resource efficiency by employing complex geometries without the need for special equipment [56,57]. Since 3D printing draws on economies of scope rather than on economies of scale, it reduces the need to maintain a large inventory [54]. In addition, 3D printing reduces the need for transportation (and its related economic and environmental impact) because it supports local production through distributed manufacturing in small-scale plants [54]. Finally, 3D printing enables the on-demand production of spare parts for repair and upgrading purposes, leading to an extension of the lifetime of products [58]. In this context, spare parts are stored digitally and are only produced when a repair is needed, thus reducing inventory size [56].

Blockchain is a system of recording information that draws on a digital, distributed ledger of transactions. This ledger is stored, shared, and replicated with multiple participants across a decentralized network in a way that prevents changing, hacking, or cheating the system. Some studies have shown how blockchain can potentially increase firm performance, by adopting circular practices in procurement, design, remanufacturing, and recycling processes [59]. From a practical point of view, blockchain aids the circular economy in several ways [60,61]. First, blockchain technology ensures trust, transparency, traceability, security, and reliability in the value chain, given its distributed digital characteristics [62–64]. In fact, all blockchain participants can easily view the ledgers and analyze transactions, thanks to decentralization. In addition, blockchain incorporates encrypted information and consensus mechanisms (proof of work) that reduce the risks of cyber attacks and system failures [60]. These features allow products to be tracked in the value chain, including relevant information on their environmental and social conditions at each stage (such as the materials' source, the actors involved, the processes carried out, and the energy consumed) [62]. Thus, blockchain can be used to ensure that purportedly circular products are environmentally friendly, driving consumer choices and avoiding greenwashing—namely, the disinformation provided by organizations to present a (false) environmentally responsible public image. Furthermore, blockchain technology allows the smart execution of transactions because it connects users without the need for intermediaries. This is achieved through the execution of smart contracts, leading to greater efficiency in operational processes [60]. Lastly, blockchain supports—and may facilitate the design of—incentive mechanisms (e.g., in the form of bitcoin or other cryptocurrencies) to direct user behavior towards specific actions, such as participation in recycling schemes (e.g., bitcoins received in exchange for depositing old cans) [47,60,62].

Augmented and virtual reality (AR-VR) are technologies that enable a superior version of the real, physical world by adding digital elements to provide an enhanced user experience [41]. While augmented reality just adds digital elements to a live view, virtual reality is based on full computer-generated simulations of three-dimensional environments. Users interact with AR-VR environments through special electronic equipment, such as smart glasses or gloves equipped with sensors. AR-VR supports the circular economy thanks to virtualization. In fact, virtualization facilitates the redesign of more repairable and modular products because of the easier simulation of alternative concepts [20]. In this context, virtual design and simulation are enabled by generating the so-called digital twin of a product—that is to say, a virtual representation that works as the digital counterpart of a physical object [65]. Lastly, AR-VR systems can encourage people to work more flexibly, providing remote assistance and guidance during service and maintenance activities, thus reducing transportation needs [42].

Table 2 summarizes the role of digital technologies in the smart circular economy paradigm on the life-cycle phases of a general product, from design to the end of use.

Table 2. The role of digital technologies in the smart circular economy paradigm.

Digital Technology	Product Life-Cycle Phase					References
	Design	Manufacturing	Distribution	Usage	End of Use	
Internet of Things		Monitoring of data to achieve operational excellence by reducing scraps and equipment wear and tear.	Enabling the provision of circular product-as-a-service business models (pay per use, sharing).		Tracking products to increase collection rate.	[18,19,26,37,42,43]
Big Data and Analytics	Transforming product-in-use data into valuable information to improve product design for circularity.			Enabling the provision of preventive and predictive maintenance.	Informing better decision-making for reuse, remanufacturing, and recycling.	[19,20,26,37,44,46,47,49–51]
3D Printing	Increasing the use of recycled materials (recycled plastic polymers or metal powders). Increasing product personalization to avoid the early retirement of products.	Minimizing material losses, scraps, and waste (additive, not subtractive process). Reducing the need to hold large inventories.	Reducing the need for transportation.	Enabling the local and on-demand production of spare parts for repair and upgrades.		[54,56–58]
Blockchain		Ensuring trust, transparency, traceability, security, and reliability in the value chain to drive green consumer choices and prevent greenwashing.		Allowing automated transactions (e.g., smart contracts), leading to greater efficiency.	Financial incentivization to drive users' behavior towards increased recycling.	[47,60–63]
Augmented and Virtual Reality	Facilitating the redesign of products to improve circularity.			Providing remote assistance and guidance for maintenance activities.		[20,41,42,65]

3. Towards the Smart Circular Economy Paradigm

3.1. Smart Circular Economy: A Definition and Research Framework

Given the scarcity of existing contributions and building on the studies listed in Table 1, we define the Smart Circular Economy paradigm as:

> *an industrial system that uses digital technologies during the product life-cycle phases to implement circular strategies and practices, aiming at value creation through increased environmental, social, and economic performance.*

On the basis of our definition, we propose a framework that consolidates the main concepts and enables users to organize and classify the existing literature as well as new contributions, according to the smart circular economy paradigm (Figure 2). The framework considers five main dimensions, which are affected by the transition towards a smart circular economy:

1. The underlying digital technologies, such as the Internet of things, big data and analytics, 3D printing, blockchain, and augmented/virtual reality;
2. The life-cycle phases of a generic product affected by this transformation, ranging from design to the end of use;
3. The circular economy strategies of reducing, reusing, remanufacturing, and recycling, according to [12];
4. The circular economy practices—that is to say, the managerial levers that can be employed to support the implementation of the circular economy in companies regarding product design, business model, and value chain, according to [4];
5. The targeted creation of value, achievable through an increase in environmental performance classified according to the triple bottom-line perspective of economic, environmental, and social benefits.

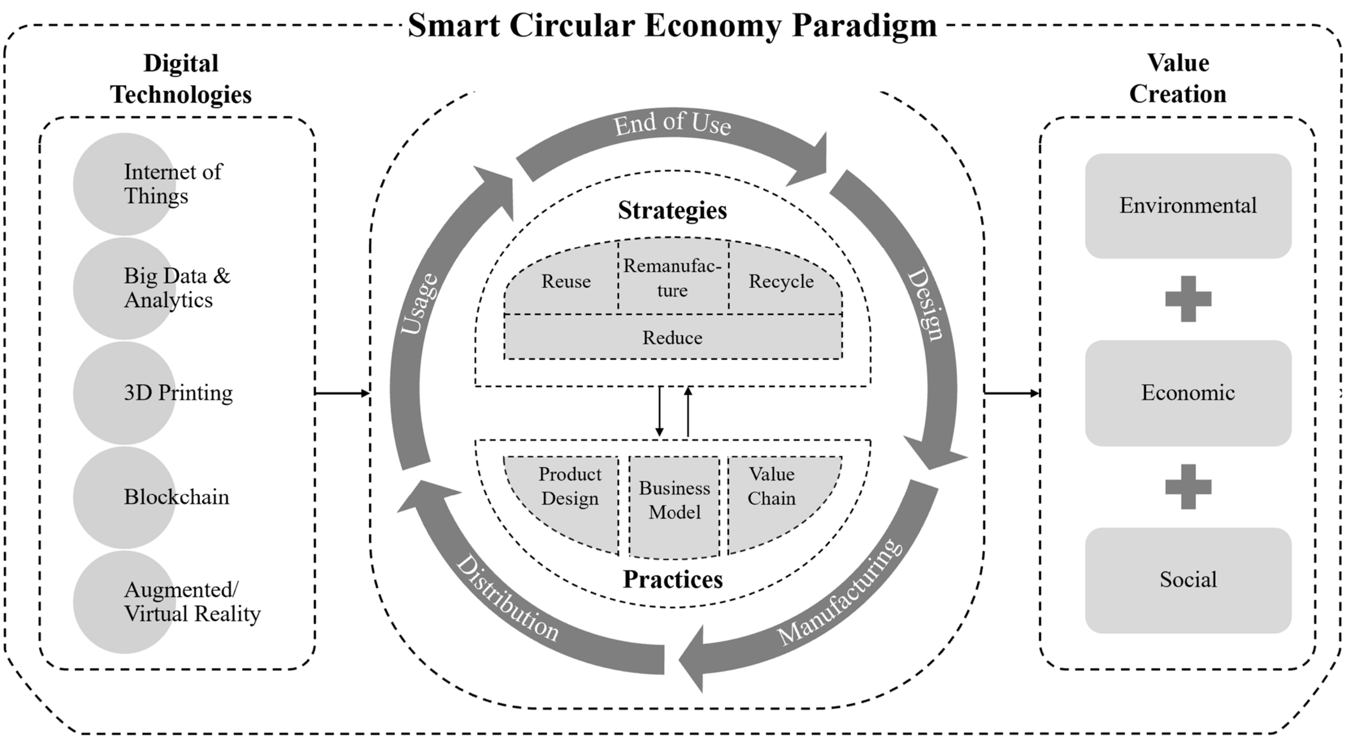

Figure 2. A research framework for the smart circular economy paradigm.

The framework clearly shows the linkages between digital technologies, circular strategies and practices, and sustainability performance. The framework logic suggests that digitalization, fueled by the application of a diverse range of digital technologies, enables a systemic redesign of products, business models, and value chains, impacting all the life-cycle phases of products to reduce material and energy consumption, reuse products, remanufacture components, and recycle materials. This, in turn, promotes value creation and the achievement of enhanced sustainability performance in terms of environmental, economic, and social benefits.

The underlying principle is that, in a smart circular economy, physical flows should be progressively replaced by informational flows. The aim is to make a better use of data to reduce the use of materials, which otherwise would lead to over-production, over-stock, over-transportation, and over-waste in industrial systems. In other words, a smart circular economy *makes information work*, providing relevant information to the right actor at the right time, which enables a better utilization of materials. Lastly, the framework shows that digital technologies are not an end in themselves, but, rather, they are *the means through which* the systemic redesign of products, business models, and supply chains are enabled for the circular economy. Consequently, digitalization for the circular economy is much more than the mere introduction of digital technologies. In fact, digitalization alone will not automatically lead to better performance and a lower environmental impact. It is, however, the redesign of products, business models, and supply chains to introduce circular 4R strategies that will (hopefully) facilitate this, as underscored in the following section.

3.2. Applying the Framework to a Sample of Articles

With the aim of applying the smart circular economy framework to the fresh, new circular economy literature, we took the seven articles recently published in the Sustainability special issue, 'Circular Economy in the Digital Age', and categorized them according to the framework (Table 3).

Table 3. Application of the framework to the seven contributions of the Sustainability special issue 'Circular Economy in the Digital Age'.

Article	Digital Technology	Lifecycle Phase	Circular Economy 4R Strategy	Circular Economy Practice	Sustainability Performance
Green Transition: The Frontier of the Digicircular Economy Evidenced from a Systematic Literature Review [66]	Internet of Things Big Data and Analytics (based on quantum computing)	Design Manufacturing Usage End of use	Reduce Recycling	Eco-design New business models based on servitization Value chain reconfiguration	Reduce the pace of emissions to a value lower than the rate at which natural systems can absorb them. Recycle resources at a pace higher than waste generation.
Digital Twins for the Circular Economy [67]	Digital Twins	Design Manufacturing Distribution Usage End of Use	Reuse Remanufacturing Recycling	Product design Servitized business models (sharing) Circular value chain coordination	Reduce the consumption of natural resources by optimizing product design based on digital twins. Reduce waste generation by increasing remanufacturing and recycling, thanks to improved decision-making enabled by digital twins. Economic benefits from the optimization of resources during the product life cycle.
Omni-Chanel Network Design towards Circular Economy under Inventory Share Policies [68]	Internet of Things	Distribution	Reduce	Value chain optimization	Savings in holding and transportation costs due to the optimization of inventory share policies. Reduce CO_2 over-production and transportation emissions due to the optimization of inventory share policies.
Circularity for Electric and Electronic Equipment (EEE), the Edge and Distributed Ledger (Edge and DL) Model [69]	Blockchain	Manufacturing Distribution End of use	Remanufacturing Recycling	Value chain	Reduce waste generation, especially for electrical and electronic equipment (WEEE).

Table 3. *Cont.*

Article	Digital Technology	Lifecycle Phase	Circular Economy 4R Strategy	Circular Economy Practice	Sustainability Performance
Circular Digital Built Environment: An Emerging Framework [70]	Internet of Things Big Data and Analytics 3D Printing Blockchain	Design Manufacturing (construction and assembly) Usage End of use	Reduce Reuse Recycling	Design for green buildings (long life, reversibility, improvements in efficiency) Circular value chain collaboration	Regenerate resources (using renewable resources). Narrow resource flows (resource efficiency). Slow resource loops (intensify usage and extend service life). Close the loop.
Using Internet of Things and Distributed Ledger Technology for Digital Circular Economy Enablement: The Case of Electronic Equipment [71]	Internet of Things Blockchain Big Data and Analytics	Distribution Usage End of use	Reduce Reuse Remanufacturing Recycling	Servitized business models Value chain management coordination	Prevent electronic waste generation. Prevent adverse environmental and human health effects due to inappropriate disposal and recycling of WEEE (e.g., related to the illegal exportation of e-waste to developing countries that use child labor and whose dismantling practices create hazardous pollution). Increase compliance with legislative requirements, such as the WEEE directive.
Industry 4.0 and Smart Data as Enablers of the Circular Economy in Manufacturing: Product Re-engineering with Circular Eco-design [72]	Internet of Things Big Data and Analytics	Design Manufacturing Distribution	Reduce	Eco-design	Reduce the environmental impact of the product (ceramic tiles), thanks to eco-design informed by the IoT and Big Data Analytics.

The paper by De Felice and Petrillo [66] investigated how digital technologies can support a circular economy, identifying the current state of the art and defining future research developments in this field. They investigated: (i) the role of the IoT as well as big data and analytics (based on quantum computing) in implementing product eco-design, (ii) new business models based on servitization and supply chain reconfiguration to improve the use of natural resources, (iii) reduction in the pace of emissions to a value lower than the rate at which natural systems can absorb them, and (iv) the recycling of resources at a pace higher than waste generation. The paper by Preut, Kopka, and Clausen [67] presented the potential contributions of digital twins to the management of circular supply chains and the circularity of resources. They investigated how digital twins can be employed to design products and share business models, and to coordinate a circular supply chain across the life-cycle stages of manufacturing, distribution, usage, and end of use. In this way, digital twins can reduce the consumption of natural resources by optimizing product design, and they can lessen waste generation by increasing remanufacturing and recycling as a result of improved decision-making. The paper by Izmirli, Ekren, Kumar, and Pongsakornrungsilp [68] studied different lateral inventory share policies in a digitalized omni-channel supply chain, in which each network shares real-time inventory data and demand information with each other, enabled by the IoT. In this work, the authors stressed how supply chain optimization, employing the IoT in logistics and distribution processes, helps to achieve savings in holding and transportation costs and, at the same time, reduce CO_2 over-production and transportation emissions (from optimizing inventory share policies). The paper by Andersen and Jæger [69] investigated how manufacturers of electrical and electronic equipment can build on extended producer responsibility to increase the circularity of products. They explained how the adoption of blockchain in supply chains can increase remanufacturing and recycling to reduce waste generation, especially in electrical and electronic equipment. The paper by Çetin, De Wolf, and Bocken [70] examined which digital technologies have the potential to expand the circular economy into the built environment, exploring different methods and implementation paths. More specifically, several digital technologies (the IoT, big data and analytics, 3D printing, and blockchain) can be employed to enable circular supply chain coordination and design for green building practices, such as long life, reversibility, and improvements in building efficiency. In this way, it is possible to achieve sustainability performances by regenerating resources (e.g., using renewable resources) and by narrowing, slowing, and closing resources loops. The study by Magrini, Nicolas, Berg, Bellini, Paolini, Vincenti, Campadello, and Bonoli [71] discussed the application of the IoT and distributed ledger technologies based on blockchain in the context of enabling different circular economy strategies for the professional electronic equipment industry. Using a case study of five Italian companies in the electronics supply chain, the authors explained the enabling role of the IoT, blockchain, and big data and analytics in implementing servitized business models and in providing better coordination of the overall supply chain during distribution, usage, and end-of-use processes. Results vary from the prevention of electronic waste generation to the prevention of adverse environmental and human health effects from the inappropriate disposal and recycling of WEEE (e.g., from the illegal exportation of e-waste to developing countries that use child labor and whose dismantling practices cause hazardous pollution). In addition, an increase in compliance with legislative requirements, such as the WEEE directive, is registered. Lastly, the research by Vacchi, Siligardi, Cedillo-Gonzalez, Ferrari, and Settembre-Blundo [72] developed and applied eco-design principles based on the integration of the IoT, big data, life cycle assessment, and material microstructural analysis in the Italian ceramic tile manufacturing industry. More specifically, eco-design practices were enabled by the IoT as well as big data and analytics to reduce the environmental impact of the ceramic tile product.

4. A Research Agenda for the Smart Circular Economy Paradigm

Although existing studies have provided relevant contributions to the literature, they have failed to encompass the full range of research perspectives in the domain of the smart circular economy paradigm. Therefore, several areas remain open for further research. We have identified four research directions, which constitute promising avenues for future research.

4.1. Develop the Research Objectives and Methodologies from Exploratory to Confirmatory Purposes, and from Descriptive to Prescriptive Frameworks (Research Perspective)

The current literature has largely limited itself to exploring the potential of digital technologies for the circular economy, through literature reviews and single case studies. However, significant movement towards a mature theory on the smart circular economy paradigm will require the development of research objectives and methodologies to generate hypotheses and constructs for such a theory, and to statistically test them with quantitative methods. Future research should, thus, focus on models and frameworks that support prescriptive decision-making activities, relying on a variety of research objectives and methods. See, for instance, the work of Di Maria et al. [28], who investigated the mediating role of supply chain integration at the nexus of industry 4.0 and the circular economy using a quantitative regression model, or the work of Nayal et al. [73], who investigated the relationships between digital technology adoption, the circular economy, and firm performance by using structural equation modelling.

4.2. Move the Focus from Single Organizations to the Entire Ecosystem of Stakeholders (Business Strategy and Organizational Perspective)

Research on the topic of the smart circular economy paradigm should not be confined to advancements in technological fields. Instead, innovation should be related to the innovation of organizational and business models paradigms, aligned with the proposed move towards industry 5.0, with the focus on human progress and well-being [74]. However, current research often takes a single firm-centric view rather than an ecosystem perspective involving the full spectrum of stakeholders participating in a circular value chain. Therefore, new research should move away from the confines of single organizations and extend the research scope to the entire network of actors. This enlargement should extend to the global level because no organization or nation is sovereign when it comes to the circular economy and sustainability. Digital technologies have been proven to be a strong enabler of connection and cooperation in circular value chains in diverse markets. This may call for the intra-organizational revision of roles and responsibilities between the customer-facing 'front end' and the headquarters-based 'back end'. Nevertheless, information managed through digital technologies is rarely shared along the value chain, principally because of issues concerning the disclosure of sensitive information, data security, and data protection. Future research should, therefore, focus on defining incentives (e.g., financial) and requirements (e.g., legislative) to encourage cooperation and information sharing in circular value chains. Digital technologies have the potential to enable the transition to the circular economy in entire industrial ecosystems, but the path towards achieving circularity differs a lot depending on the involvement of a supply chain led by circular economy native companies (e.g., start-ups specifically born to seize Circular Economy opportunities) rather than circular economy adopters (e.g., large multinationals pushed to embrace Circular Economy by external pressures). See, in this regard, the work of Bressanelli et al. [58]. Thus, a promising avenue for future research is to deepen the different circular-economy-enabling roles of digital technologies for both native companies and adopters, highlighting differences and similarities. Moreover, we encourage future studies to look closely into the digital technology adoption process in different contexts. For example, the adoption process will vary between larger firms and SMEs, as it depends on different industrial contexts (see, for instance, the work of Chaudhuri et al. [53]).

4.3. Combine Different Enabling Digital Technologies and Study Their Interlinked Effects on the Circular Economy (Technology Perspective)

The previous literature investigated only a few digital technologies at a time, perhaps focusing on one or a limited set. However, most digital technologies should interact with each other to perform circular economy tasks. Therefore, future research should provide a more comprehensive picture of the combined role and impact of different digital technologies in the circular economy, leveraging the synergistic potential of the IoT, big data and analytics, 3D printing, blockchain, AR-VR, and so forth. In addition to studying the effects of their combined enabling role, researchers are called to further address the practical lack of interoperable solutions and communication protocols, which hinders the integration of heterogeneous systems. Thus, new research should focus on the development of common standards and communication protocols that allow for the integration of different technologies. The combination of different technologies should also advance the debate between edge computing and cloud computing. In fact, the IoT normally operates at the edge of the network, while data sharing usually occurs through the cloud. Big data analytics is sometimes carried out at the edge; at other times, it is executed in the cloud. New research should, therefore, focus on highlighting which operations are best executed at the edge and which operations should be performed in the cloud, weighing the pros and cons of each (vertical or hybrid) architecture.

4.4. Assess the Environmental Impact of Digital Technologies on the Circular Economy to Show That Environmental Gains Offset Their Intrinsic Environmental Cost (Assessment Perspective)

Previous research has mainly focused on highlighting the potential benefits associated with the introduction of digital technologies to achieve a circular economy. This paper is no exception. However, digital technologies come at a cost to the environment in terms of resource depletion (we rely on raw materials to produce their hardware, and these materials are often critical in terms of availability and supply), energy consumption (digital technologies need energy to function, which is largely produced from fossil fuels), and waste generation (the hardware connected to digital technologies is usually dumped in landfill, and its reuse, remanufacturing, and recycling rates are still low worldwide). For instance, a common sustainability tension in blockchain is its very energy-intensive operation. The same holds for data centers behind the IoT as well as big data and analytics activities. The belief that the circular economy results achieved through digital technologies will offset their intrinsic environmental costs is yet to be investigated (and proven). Therefore, future research should deepen our understanding of the environmental impact of digital technologies—see, for instance, Obringer et al. [75]—in relation to the potential benefits achieved through the circular economy by analyzing, quantifying, and comparing environmental gains and pains using life cycle assessment to consider potential trade-offs and rebound effects connected to the implementation of such digital technologies [76]. Thus, we encourage future studies to closely examine how digitalization provides a higher degree of transparency through the sharing of data across organizations, leading to the communication of sustainability performance and benefits.

The research directions are summarized in Table 4.

Table 4. A research agenda for advancing the smart circular economy paradigm.

Research Direction	Perspective	Highly Promising Avenues
§1 Develop the research objectives and methodologies from exploratory to confirmatory purposes, and from descriptive to prescriptive frameworks.	Research objectives and methodologies	1.1 Develop research objectives and methodologies to generate hypotheses and constructs of the smart circular economy theory and statistically test them. 1.2 Develop models and frameworks to support prescriptive decision-making activities. 1.3 Rely on a variety of research objectives and methods.
§2 Move the focus from single organizations to the entire ecosystem of stakeholders.	Business strategy and organization	2.1 Shift away from the confines of single organizations, extending the research scope to the entire network of actors. 2.2 Focus on defining incentives (e.g., financial ones) and requirements (e.g., legislative ones) to encourage cooperation and information sharing in circular value chains. 2.3 Deepen the different circular-economy-enabling roles of digital technologies for both native companies and adopters, highlighting differences and similarities.
§3 Combine different enabling digital technologies and study their interlinked effects on the circular economy	Technology	3.1 Provide a more comprehensive picture of the combined role of different digital technologies in the circular economy, leveraging their synergistic potential. 3.2 Address the practical lack of interoperable solutions and communication protocols through the development of common standards and communication protocols. 3.3 Advance the debate between edge computing and cloud computing, highlighting which operations should be executed at the edge and which operations should be carried out in the cloud architecture.
§4 Assess the environmental impact of digital technologies on the circular economy to show that environmental gains offset their intrinsic environmental cost.	Assessment and evaluation	4.1 Deepen knowledge on the environmental impact of digital technologies in relation to the potential benefits achieved through the circular economy by analyzing, quantifying, and comparing environmental gains and pains through life cycle assessment, so as to consider potential trade-offs and rebound effects connected to the implementation of such digital technologies. 4.2 Explain how digital technologies can be used to provide transparency about sustainability benefits across a value chain.

5. Conclusions

By reviewing the literature and by making use of conceptual development, this paper provides a systemic understanding of the broad topic of the smart circular economy paradigm. The framework clearly shows that digitalization is not primarily associated with the adoption of some specific technology but is rather built on a combination of different techniques. The framework also shows that digital technologies are not an end in themselves, but, rather, they are the means through which the systemic redesign of products, business models, and supply chains are enabled for the circular economy. This conceptualization takes the view that digitalization for the smart circular economy is much more than the mere introduction of digital technologies, and that digitalization alone will not automatically lead to a higher sustainability performance. We, therefore, propose to adapt the underlying principle of the classical circular economy, 'waste equals food', to an equation more fitted to the digital age we are living in, namely:

$$waste + data = resource$$

In other words, the disruptive potential of digital technologies should be unleashed to turn waste into a resource, leveraging data as an essential raw material from which information and knowledge can be derived to generate sustainable value [77]. Finally, we sought to provide promising research directions to advance research on the smart circular economy paradigm (see Table 4) regarding the need to: (i) develop the research objectives from exploratory and descriptive to confirmatory and prescriptive purposes, relying on a wide spectrum of research methodologies; (ii) move the focus from single organizations to the entire ecosystem of stakeholders; (iii) combine different enabling digital technologies; and (iv) assess the environmental impact of digital technologies to prevent rebound effects. These research directions will help future researchers to sharpen the academic focus and avoid saturating research in the field of the smart circular economy.

This work carries certain managerial implications. It provides decision-makers with a framework that illustrates the relations between digital technologies, product life-cycle phases, circular strategies, circular economy practices, and potential benefits. Besides being a useful way to organize and map existing studies (as shown in Section 3), the framework can support managers in the analysis and categorization of potential smart circular economy projects. In particular, the proposed framework provides a conceptual structure on how to move towards a smart circular economy. It can, therefore, act as a powerful guide delineating the state of the art of a portfolio of smart circular economy projects, and what needs to be further developed. When putting the smart circular economy paradigm into practice, it might be useful for managers and policymakers alike to understand all the possible interrelations among digital technologies, circular strategies, and circular practices, so that value creation can be highlighted in terms of the potential benefits for both managerial and policy projects.

Lastly, this work has certain limitations. Strict criteria have been applied during the literature review process to refine article selection and analysis. Although this decision was taken to better focus on the smart circular economy as an emergent phenomenon, some (potentially relevant) articles dealing with sustainability and industry 4.0 may have been overlooked. In addition, our analysis was limited to a pre-defined set of digital technologies—namely, the IoT, big data and analytics, 3D printing, blockchain, and augmented and virtual reality. These technologies have been selected on the basis of their simultaneous academic relevance and implementation potential. Future studies should consider the potential of other digital technologies (e.g., for the smart circular economy paradigm). Lastly, our research mainly adopted a managerial perspective, focusing on the functionalities enabled by digital technologies rather than on the technologies themselves.

Author Contributions: Conceptualization, G.B., F.A., D.C.A.P., and V.P.; methodology, G.B., F.A., D.C.A.P. and V.P.; validation, G.B., F.A., D.C.A.P. and V.P.; formal analysis, G.B.; investigation, G.B.; data curation, G.B.; writing–original draft preparation, G.B.; writing–review and editing, G.B., F.A., D.C.A.P. and V.P.; visualization, G.B.; supervision, G.B., F.A., D.C.A.P. and V.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research Council of Norway (Project no: 326087), by Formas (Project no: 2018-01417), and by the Swedish Energy Agency (Project no: 52742-1).

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ellen MacArthur Foundation. *Towards a Circular Economy-Economic and Business Rationale for an Accelerated Transition*; Ellen MacArthur Foundation: Cowes, UK, 2012.
2. Calzolari, T.; Genovese, A.; Brint, A. The adoption of circular economy practices in supply chains—An assessment of European Multi-National Enterprises. *J. Clean. Prod.* **2021**, *312*, 127616. [CrossRef]
3. Blomsma, F.; Pieroni, M.; Kravchenko, M.; Pigosso, D.C.A.; Hildenbrand, J.; Kristinsdottir, A.R.; Kristoffersen, E.; Shahbazi, S.; Nielsen, K.D.; Jönbrink, A.-K.; et al. Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *J. Clean. Prod.* **2019**, *241*, 118271. [CrossRef]
4. Bressanelli, G.; Pigosso, D.C.A.; Saccani, N.; Perona, M. Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: A literature review. *J. Clean. Prod.* **2021**, *298*, 126819. [CrossRef]
5. Pigosso, D.C.A.; McAloone, T.C. Making the transition to a circular economy within manufacturing companies: The development and implementation of a self-assessment readiness tool. *Sustain. Prod. Consum.* **2021**, *28*, 346–358. [CrossRef]
6. *European Council Directive 2008/98/EC on Waste (Waste Framework Directive)-Environment-European Commission*; European Environment Agency: Copenhagen, Denmark, 2008.
7. Potting, J.; Hekkert, M.; Worrell, E.; Hanemaaijer, A. *Circular Economy: Measuring Innovation in the Product Chain-Policy Report*; PBL Netherlands Environmental Assessment Agency: The Hague, The Netherlands, 2017.
8. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
9. Lakatos, E.S.; Yong, G.; Szilagyi, A.; Clinci, D.S.; Georgescu, L.; Iticescu, C.; Cioca, L.I. Conceptualizing core aspects on circular economy in cities. *Sustainability* **2021**, *13*, 7549. [CrossRef]
10. Morseletto, P. Targets for a circular economy. *Resour. Conserv. Recycl.* **2020**, *153*, 104553. [CrossRef]
11. Reike, D.; Vermeulen, W.J.V.; Witjes, S. The circular economy: New or Refurbished as CE 3.0?—Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resour. Conserv. Recycl.* **2018**, *135*, 246–264. [CrossRef]
12. Bressanelli, G.; Saccani, N.; Pigosso, D.C.A.; Perona, M. Circular Economy in the WEEE industry: A systematic literature review and a research agenda. *Sustain. Prod. Consum.* **2020**, *23*, 174–188. [CrossRef]
13. Bressanelli, G.; Perona, M.; Saccani, N. Challenges in supply chain redesign for the Circular Economy: A literature review and a multiple case study. *Int. J. Prod. Res.* **2019**, *57*, 7395–7422. [CrossRef]
14. Bockholt, M.T.; Hemdrup Kristensen, J.; Colli, M.; Meulengracht Jensen, P.; Vejrum Wæhrens, B. Exploring factors affecting the financial performance of end-of-life take-back program in a discrete manufacturing context. *J. Clean. Prod.* **2020**, *258*, 120916. [CrossRef]
15. Cezarino, L.O.; Liboni, L.B.; Oliveira Stefanelli, N.; Oliveira, B.G.; Stocco, L.C. Diving into emerging economies bottleneck: Industry 4.0 and implications for circular economy. *Manag. Decis.* **2021**, *59*, 1841–1862. [CrossRef]
16. de Lima, F.A.; Seuring, S.; Sauer, P.C. A systematic literature review exploring uncertainty management and sustainability outcomes in circular supply chains. *Int. J. Prod. Res.* **2021**, 1–34, in press. [CrossRef]
17. Bressanelli, G.; Visintin, F.; Saccani, N. Circular Economy and the evolution of industrial districts: A supply chain perspective. *Int. J. Prod. Econ.* **2022**, *243*, 108348. [CrossRef]
18. Parida, V.; Sjödin, D.; Reim, W. Reviewing Literature on Digitalization, Business Model Innovation, and Sustainable Industry: Past Achievements and Future Promises. *Sustainability* **2019**, *11*, 391. [CrossRef]
19. Bressanelli, G.; Adrodegari, F.; Perona, M.; Saccani, N. Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies. *Sustainability* **2018**, *10*, 639. [CrossRef]
20. Kristoffersen, E.; Blomsma, F.; Mikalef, P.; Li, J. The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *J. Bus. Res.* **2020**, *120*, 241–261. [CrossRef]
21. Bag, S.; Yadav, G.; Dhamija, P.; Kataria, K.K. Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study. *J. Clean. Prod.* **2021**, *281*, 125233. [CrossRef]
22. Michelin Services and Solution. Available online: https://www.michelin.com/en/activities/related-services/connected-services-and-solutions/ (accessed on 29 September 2021).
23. Groupe SEB 3D Printing to Improve Repairability. Available online: https://www.groupeseb.com/en/webzine/3d-printing-improve-repairability (accessed on 29 September 2021).
24. IBM IBM Food Trust: A New Era in the World's Food Supply. Available online: https://www.ibm.com/blockchain/solutions/food-trust (accessed on 29 September 2021).
25. Rolls Royce Power by the Hour. Available online: https://www.rolls-royce.com/media/our-stories/discover/2017/totalcare.aspx (accessed on 29 September 2021).
26. Ingemarsdotter, E.; Jamsin, E.; Kortuem, G.; Balkenende, R. Circular Strategies Enabled by the Internet of Things—A Framework and Analysis of Current Practice. *Sustainability* **2019**, *11*, 5689. [CrossRef]
27. Okorie, O.; Salonitis, K.; Charnley, F.; Moreno, M.; Turner, C.; Tiwari, A. Digitisation and the Circular Economy: A Review of Current Research and Future Trends. *Energies* **2018**, *11*, 3009. [CrossRef]
28. Di Maria, E.; De Marchi, V.; Galeazzo, A. Industry 4.0 technologies and circular economy: The mediating role of supply chain integration. *Bus. Strateg. Environ.* **2022**, *31*, 619–632. [CrossRef]

29. Phuyal, S.; Bista, D.; Bista, R. Challenges, Opportunities and Future Directions of Smart Manufacturing: A State of Art Review. *Sustain. Futur.* **2020**, *2*, 100023. [CrossRef]
30. Beltrami, M.; Orzes, G.; Sarkis, J.; Sartor, M. Industry 4.0 and sustainability: Towards conceptualization and theory. *J. Clean. Prod.* **2021**, *312*, 127733. [CrossRef]
31. Rajput, S.; Singh, S.P. Connecting circular economy and industry 4.0. *Int. J. Inf. Manag.* **2019**, *49*, 98–113. [CrossRef]
32. Ranta, V.; Aarikka-Stenroos, L.; Väisänen, J.-M. Digital technologies catalyzing business model innovation for circular economy—Multiple case study. *Resour. Conserv. Recycl.* **2021**, *164*, 105155. [CrossRef]
33. Dantas, T.E.T.; De-Souza, E.D.; Destro, I.R.; Hammes, G.; Rodriguez, C.M.T.; Soares, S.R. How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. *Sustain. Prod. Consum.* **2021**, *26*, 213–227. [CrossRef]
34. Lopes de Sousa Jabbour, A.B.; Jabbour, C.J.C.; Godinho Filho, M.; Roubaud, D. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. *Ann. Oper. Res.* **2018**, *270*, 273–286. [CrossRef]
35. Liu, Q.; Trevisan, A.H.; Yang, M.; Mascarenhas, J. A framework of digital technologies for the circular economy: Digital functions and mechanisms. *Bus. Strateg. Environ.* **2022**, 1–22, in press. [CrossRef]
36. Kristoffersen, E.; Mikalef, P.; Blomsma, F.; Li, J. Towards a business analytics capability for the circular economy. *Technol. Forecast. Soc. Chang.* **2021**, *171*, 120957. [CrossRef]
37. Alcayaga, A.; Wiener, M.; Hansen, E.G. Towards a framework of smart-circular systems: An integrative literature review. *J. Clean. Prod.* **2019**, *221*, 622–634. [CrossRef]
38. Dahmani, N.; Benhida, K.; Belhadi, A.; Kamble, S.; Elfezazi, S.; Jauhar, S.K. Smart circular product design strategies towards eco-effective production systems: A lean eco-design industry 4.0 framework. *J. Clean. Prod.* **2021**, *320*, 128847. [CrossRef]
39. Kayikci, Y.; Kazancoglu, Y.; Lafci, C.; Gozacan-Chase, N.; Mangla, S.K. Smart circular supply chains to achieving SDGs for post-pandemic preparedness. *J. Enterp. Inf. Manag.* **2021**, in press. [CrossRef]
40. Lobo, A.; Trevisan, A.H.; Liu, Q.; Yang, M.; Mascarenhas, J. Barriers to Transitioning towards Smart Circular Economy: A Systematic Literature Review. In *Smart Innovation, Systems and Technologies*; Springer: Berlin/Heidelberg, Germany, 2022; Volume 262 SIST, pp. 245–256. [CrossRef]
41. Cagno, E.; Neri, A.; Negri, M.; Bassani, C.A.; Lampertico, T. The Role of Digital Technologies in Operationalizing the Circular Economy Transition: A Systematic Literature Review. *Appl. Sci.* **2021**, *11*, 3328. [CrossRef]
42. Manavalan, E.; Jayakrishna, K. A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. *Comput. Ind. Eng.* **2019**, *127*, 925–953. [CrossRef]
43. Schwanholz, J.; Leipold, S. Sharing for a circular economy? An analysis of digital sharing platforms' principles and business models. *J. Clean. Prod.* **2020**, *269*, 122327. [CrossRef]
44. Pagoropoulos, A.; Pigosso, D.C.A.; McAloone, T.C. The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Proc. Procedia CIRP* **2017**, *64*, 19–24. [CrossRef]
45. Ardolino, M.; Rapaccini, M.; Saccani, N.; Gaiardelli, P.; Crespi, G.; Ruggeri, C. The role of digital technologies for the service transformation of industrial companies. *Int. J. Prod. Res.* **2018**, *56*, 2116–2132. [CrossRef]
46. Awan, U.; Shamim, S.; Khan, Z.; Zia, N.U.; Shariq, S.M.; Khan, M.N. Big data analytics capability and decision-making: The role of data-driven insight on circular economy performance. *Technol. Forecast. Soc. Chang.* **2021**, *168*, 120766. [CrossRef]
47. Chauhan, C.; Parida, V.; Dhir, A. Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technol. Forecast. Soc. Chang.* **2022**, *177*, 121508. [CrossRef]
48. Sun, X.; Yu, H.; Solvang, W.D.; Wang, Y.; Wang, K. The application of Industry 4.0 technologies in sustainable logistics: A systematic literature review (2012–2020) to explore future research opportunities. *Environ. Sci. Pollut. Res.* **2022**, *29*, 9560–9591. [CrossRef]
49. Charnley, F.; Tiwari, D.; Hutabarat, W.; Moreno, M.; Okorie, O.; Tiwari, A. Simulation to Enable a Data-Driven Circular Economy. *Sustainability* **2019**, *11*, 3379. [CrossRef]
50. Marconi, M.; Germani, M.; Mandolini, M.; Favi, C. Applying data mining technique to disassembly sequence planning: A method to assess effective disassembly time of industrial products. *Int. J. Prod. Res.* **2019**, *57*, 599–623. [CrossRef]
51. Ingemarsdotter, E.; Kambanou, M.L.; Jamsin, E.; Sakao, T.; Balkenende, R. Challenges and solutions in condition-based maintenance implementation—A multiple case study. *J. Clean. Prod.* **2021**, *296*, 126420. [CrossRef]
52. Ponis, S.; Aretoulaki, E.; Maroutas, T.N.; Plakas, G.; Dimogiorgi, K. A systematic literature review on additive manufacturing in the context of circular economy. *Sustainability* **2021**, *13*, 6007. [CrossRef]
53. Chaudhuri, A.; Subramanian, N.; Dora, M. Circular economy and digital capabilities of SMEs for providing value to customers: Combined resource-based view and ambidexterity perspective. *J. Bus. Res.* **2022**, *142*, 32–44. [CrossRef]
54. Despeisse, M.; Baumers, M.; Brown, P.; Charnley, F.; Ford, S.J.; Garmulewicz, A.; Knowles, S.; Minshall, T.H.W.; Mortara, L.; Reed-Tsochas, F.P.; et al. Unlocking value for a circular economy through 3D printing: A research agenda. *Technol. Forecast. Soc. Chang.* **2017**, *115*, 75–84. [CrossRef]
55. Ertz, M.; Sun, S.; Boily, E.; Kubiat, P.; Quenum, G.G.Y. How transitioning to Industry 4.0 promotes circular product lifetimes. *Ind. Mark. Manag.* **2022**, *101*, 125–140. [CrossRef]
56. Sauerwein, M.; Doubrovski, E.; Balkenende, R.; Bakker, C. Exploring the potential of additive manufacturing for product design in a circular economy. *J. Clean. Prod.* **2019**, *226*, 1138–1149. [CrossRef]

57. Nascimento, D.L.M.; Alencastro, V.; Quelhas, O.L.G.; Caiado, R.G.G.; Garza-Reyes, J.A.; Rocha-Lona, L.; Tortorella, G. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context. *J. Manuf. Technol. Manag.* **2019**, *30*, 607–627. [CrossRef]
58. Bressanelli, G.; Saccani, N.; Perona, M.; Baccanelli, I. Towards Circular Economy in the Household Appliance Industry: An Overview of Cases. *Resources* **2020**, *9*, 128. [CrossRef]
59. Khan, S.A.R.; Zia-ul-haq, H.M.; Umar, M.; Yu, Z. Digital technology and circular economy practices: An strategy to improve organizational performance. *Bus. Strateg. Dev.* **2021**, *4*, 482–490. [CrossRef]
60. Kouhizadeh, M.; Zhu, Q.; Sarkis, J. Blockchain and the circular economy: Potential tensions and critical reflections from practice. *Prod. Plan. Control* **2020**, *31*, 950–966. [CrossRef]
61. Centobelli, P.; Cerchione, R.; Del Vecchio, P.; Oropallo, E.; Secundo, G. Blockchain technology for bridging trust, traceability and transparency in circular supply chain. *Inf. Manag.* **2021**, 103508, in press. [CrossRef]
62. Saberi, S.; Kouhizadeh, M.; Sarkis, J.; Shen, L. Blockchain technology and its relationships to sustainable supply chain management. *Int. J. Prod. Res.* **2019**, *57*, 2117–2135. [CrossRef]
63. Upadhyay, A.; Mukhuty, S.; Kumar, V.; Kazancoglu, Y. Blockchain technology and the circular economy: Implications for sustainability and social responsibility. *J. Clean. Prod.* **2021**, *293*, 126130. [CrossRef]
64. Böckel, A.; Nuzum, A.K.; Weissbrod, I. Blockchain for the Circular Economy: Analysis of the Research-Practice Gap. *Sustain. Prod. Consum.* **2021**, *25*, 525–539. [CrossRef]
65. Birkel, H.; Müller, J.M. Potentials of industry 4.0 for supply chain management within the triple bottom line of sustainability—A systematic literature review. *J. Clean. Prod.* **2021**, *289*, 125612. [CrossRef]
66. De Felice, F.; Petrillo, A. Green Transition: The Frontier of the Digicircular Economy Evidenced from a Systematic Literature Review. *Sustainability* **2021**, *13*, 11068. [CrossRef]
67. Preut, A.; Kopka, J.-P.; Clausen, U. Digital Twins for the Circular Economy. *Sustainability* **2021**, *13*, 10467. [CrossRef]
68. İzmirli, D.; Ekren, B.Y.; Kumar, V.; Pongsakornrungsilp, S. Omni-Chanel Network Design towards Circular Economy under Inventory Share Policies. *Sustainability* **2021**, *13*, 2875. [CrossRef]
69. Andersen, T.; Jæger, B. Circularity for Electric and Electronic Equipment (EEE), the Edge and Distributed Ledger (Edge & DL) Model. *Sustainability* **2021**, *13*, 9924. [CrossRef]
70. Çetin, S.; De Wolf, C.; Bocken, N. Circular Digital Built Environment: An Emerging Framework. *Sustainability* **2021**, *13*, 6348. [CrossRef]
71. Magrini, C.; Nicolas, J.; Berg, H.; Bellini, A.; Paolini, E.; Vincenti, N.; Campadello, L.; Bonoli, A. Using Internet of Things and Distributed Ledger Technology for Digital Circular Economy Enablement: The Case of Electronic Equipment. *Sustainability* **2021**, *13*, 4982. [CrossRef]
72. Vacchi, M.; Siligardi, C.; Cedillo-González, E.I.; Ferrari, A.M.; Settembre-Blundo, D. Industry 4.0 and Smart Data as Enablers of the Circular Economy in Manufacturing: Product Re-Engineering with Circular Eco-Design. *Sustainability* **2021**, *13*, 10366. [CrossRef]
73. Nayal, K.; Kumar, S.; Raut, R.D.; Queiroz, M.M.; Priyadarshinee, P.; Narkhede, B.E. Supply chain firm performance in circular economy and digital era to achieve sustainable development goals. *Bus. Strateg. Environ.* **2022**, *31*, 1058–1073. [CrossRef]
74. European Commission. *Transformative Vision for Europe ESIR Policy Brief No. 3*; European Commission: Brussels, Belgium, 2021.
75. Obringer, R.; Rachunok, B.; Maia-Silva, D.; Arbabzadeh, M.; Nateghi, R.; Madani, K. The overlooked environmental footprint of increasing Internet use. *Resour. Conserv. Recycl.* **2021**, *167*, 105389. [CrossRef]
76. MahmoumGonbadi, A.; Genovese, A.; Sgalambro, A. Closed-loop supply chain design for the transition towards a circular economy: A systematic literature review of methods, applications and current gaps. *J. Clean. Prod.* **2021**, *323*, 129101. [CrossRef]
77. Aberkane, I.J. From Waste to Kwaste: On the Blue Economy in Terms of Knowledge Flow. In *First Complex Systems Digital Campus World E-Conference 2015*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 283–290.