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Exploring How Digital Technologies Enable a Circular Economy of Products

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Abstract: Recent studies have advocated that digital technologies (DTs) positively affect the transition of a linear economy model to a circular economy (CE) model and facilitate enterprises in implementing circular strategies. Despite this general statement, the literature still overlooks how enterprises should apply various DTs of Industry 4.0 across the entire product lifecycle to operationalize CE-related strategies. To fill this gap, this paper proposes a conceptual framework exploring DTs in terms of CE operationalization from the perspective of the product lifecycle. Based on insights gained through a systematic literature review, we clarify how DTs can facilitate CE performance objectives through the three stages of the product lifecycle: product design, product use, and product recovery or recycling. Furthermore, we study how various Industry 4.0 DTs, such as the Internet of things, big data, and cloud computing, are utilized to operationalize the transition toward a CE. DTs applied to the service-oriented product-service system contributes innovation into circular business models to make full use of idle resources and provide high-quality personalized services. We have adopted three performance objectives: using fewer materials and resources, extending product lifespan, and closing the loop to evaluate the effects of DTs in promoting CE development. By investigating how DTs affect CE performance objectives, the conceptual framework developed in this paper advances the knowledge regarding the role of DTs as an enabler of CE from the product lifecycle. Our findings provide a practical reference enabling researchers and managers to harness the potential of DTs to support CE transition.

Keywords: circular economy; circular business model; product-service system; Industry 4.0; sharing economy; Internet of things; big data; cloud computing; artificial intelligence

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Citation: Han, Y.; Shevchenko, T.; Yannou, B.; Ranjbari, M.; Shams Esfandabadi, Z.; Saidani, M.; Bouillass, G.; Bliumska-Danko, K.; Li, G. Exploring How Digital Technologies Enable a Circular Economy of Products. *Sustainability* **2023**, *15*, 2067. https://doi.org/10.3390/su15032067

Academic Editor: Davide Settembre-Blundo

Received: 17 November 2022
Revised: 7 January 2023
Accepted: 18 January 2023
Published: 21 January 2023

1. Introduction

The circular economy (CE) is a restorative or regenerative industrial system that prompts exploring the reuse of materials or product components. The CE improves efficiency and productivity through circular strategies, such as reduce, reuse, repair, recycle, and restore [1–3]. The CE promotes a "cradle-to-cradle" model of economic operations through innovative frameworks, such as product-service systems (PSSs), and industrial symbiosis. By incorporating the methodology of the 5R strategies (i.e., refuse, reduce, reuse, repurpose, and recycle), the CE can reduce the demand for limited original resources by decreasing the flow of materials and energy into the production and consumption processes and extending the life of products and services [4]. The CE also advocates the protection of biodiversity and habitat by reducing emissions and pollution levels and by not treating the natural environment as a place to dump wastes [5].

The rapid development of digital technologies (DTs), such as the Internet of things (IoT), cyber-physical systems (CPSs), cloud computing, artificial intelligence (AI), big data analytics, and digital twins, mobilizes automation and data exchange in the process of smart manufacturing and production to reduce overconsumption and production errors and improve efficiency, thus driving sustainable development [6]. Many scholars have investigated the relationship between CE and DTs to determine the role of DTs in supporting CE implementation. Ranta et al. [7] conducted a multicase study regarding a DTs-enabled business model innovation. Bressanelli et al. [8] developed a conceptual framework that validates the role of DTs as a CE enabler in usage-focused business models.

The relationship between Industry 4.0 and CE is also a hot research topic in recent literature. Rosa et al. [9] analyzed the overlaps between Industry 4.0 research and CE research and established an innovation framework to highlight the link between the two topics via hybrid categories, such as Circular I4.0 and Digital CE. Pham et al. [10] used electric scooter-sharing platforms to show that Industry 4.0 can provide an enabling framework for implementing the sharing economy and enhancing the sustainability of manufacturing sectors in the CE context. Dev et al. [11] built a real-time decision model for a sustainable reverse logistics system by integrating Industry 4.0 and CE. Yadav et al. [12] developed a framework to overcome the challenges of sustainable supply chain management through Industry 4.0 and CE-based solutions.

Various business model innovation approaches have been proposed to support CE [13]. DTs can achieve circular goals through interrelated monitoring, control, optimization, and automation functions. Ingemarsdotter et al. [14] asserted that the IoT allows companies to track products throughout their lifecycle, which helps support R strategies, such as reuse, remanufacturing, and recycling, as well as product sharing. Guzzo et al. [15] proposed and verified a circular innovation framework using different PSS cases. Alcayaga et al. [16] addressed CE, IoT, and smart PSS from a holistic perspective. They also analyzed and built a smart circularity system framework that examined the binary interrelationships between smart circularity, circular PSS, and smart PSS. Kristoffersen et al. [17] designed a circular strategy framework based on DTs to support the efforts of manufacturing enterprises in meeting the requirements for achieving the 12th Sustainable Development Goal within the United Nations 2030 Agenda for Sustainable Development.

Transforming enterprise thinking from a linear economy to a CE encounters many challenges and requires proper management of sustainable production and consumption patterns, closed-loop supply chains, and PSS. Grafström et al. [18] examined barriers to CE implementation from four angles: technology, market, system, and culture. Rajput et al. [6] used principal component analysis to study the factors linking Industry 4.0 to CE use and identified AI and service and policy frameworks as significant enablers. Abdul-Hamid et al. [19] evaluated the challenges faced by Industry 4.0 in implementing CE and how to address those challenges.

A few recent studies have explored the role of digitalization in circular business creation. Okorie et al. [20] conducted a comprehensive literature review of the connections among CE, DTs, and Industry 4.0. The authors highlighted that, while publications in the field are increasing, only a handful of publications have connected them. Ingemarsdotter et al. [14] outlined how the IoT can theoretically support circular strategies and demonstrated the progress of the application of this technology. Scholars have concluded that while some businesses have utilized the IoT to extend product lifetimes, only a few have used the tool to close the loops. In addition, several case studies have explored this topic from a similar perspective [8,21,22]. Although these studies provide useful insights into the digitalization of circular business models, additional research is required to fully comprehend the effects and functions of DTs in the creation of circular businesses that consider whole lifecycle management, especially in the design and recovery phases. To address this gap, we formulated the main research questions (RQs) of the current study as follows:

RQ1: How can digitally enabled technologies be effectively used to obtain data and use data information in different lifecycle stages and promote product lifecycle management?

RQ2: How can business model innovation support DTs to achieve CE evaluative indicators?

First, given how digitally enabled technologies and Industry 4.0 are so closely linked, we discussed the fundamental concepts of CE and PSSs and illustrated the central role of Industry 4.0 in implementing CE and PSSs. We then determined three leading evaluative indicators for CE by reviewing the CE evaluation index. By assessing the perspective of product lifecycle, including beginning-of-life, middle-of-life, and end-of-life (EoL), we highlighted the importance of digitally enabled technologies in product design, product use, and product recovery for the implementation of CE, which is formalized through the development of a conceptual framework.

This paper is organized as follows. Section 2 presents the research methodology used to clarify the procedure of data collection and methods used. Section 3 briefly shows the review of the main concepts employed in the literature on CE, PSS, and Industry 4.0. Section 4 outlines the role of digitally enabled technologies in applying and facilitating the transition toward a CE in various stages of the product lifecycle and provides the conceptual framework. Section 5 discusses the results by detailing an intelligent bike-sharing system as an example of an access-based PSS (AB-PSS) model. Section 6 provides the concluding remarks.

2. Research Methodology

A critical literature review was conducted to provide inclusive insights into the role of digitally enabled technologies in supporting the CE transition. Combinations of the main keywords "circular economy" and "digital" and their synonyms were extracted from the literature [23–26] to build an effective search string, which we then ran in the Scopus database:

- *Search in title: "circular econom*" OR "circular bioeconom*" OR "circular bio-econom*" OR "circular bio econom*" OR "circular trans*" OR "closed loop supply" OR "closed-loop supply" OR "circular business*"*

  AND

- *Search in title, abstracts, and keywords: "intelligent technolog*" OR "smart technolog*" OR "digital technolog*" OR "digitaliz*" OR "digitally-enabled technolog*" OR "digital business*" OR "digital twin*" OR "Industry 4.0" OR "I4.0" OR "Internet of things" OR "IoT" OR "big data" OR "artificial intelligence" OR "blockchain" OR "ICT" OR "information and communications technolog*" OR "cyber physical system*" OR "machine learning".*

The initial run of the search string, which was last updated on 7 December 2022, returned a total of 621 articles without any time limitations. We set some criteria to acquire the most relevant articles that fit the scope of the current study. First, the search was limited to peer-reviewed journal articles published in English (i.e., non-peer-reviewed documents, including notes, letters, editorials, short surveys, communications, and conference proceedings were excluded from the sample). At this stage, 435 articles remained, and 186 articles were removed. Second, to ensure that only good-quality articles were retrieved and to keep the research focused on its main objective, we excluded research papers that focused on algorithms, optimization, simulation, and modeling approaches from the sample data. On this basis, an inclusive manual screening was performed on the titles and abstracts of the remaining papers to select the most relevant studies. In cases where deciding on selecting or removing the papers was not possible, the entire paper was read to make the decision. As a result, 68 articles were selected for further investigation. Moreover, apart from papers selected based on our structured search string, we manually added 11 other papers by screening references found in the literature via the snowballing technique. Thus, the final number of articles analyzed for this research was 79. Following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) framework [27,28], the data collection process is illustrated in Figure 1.

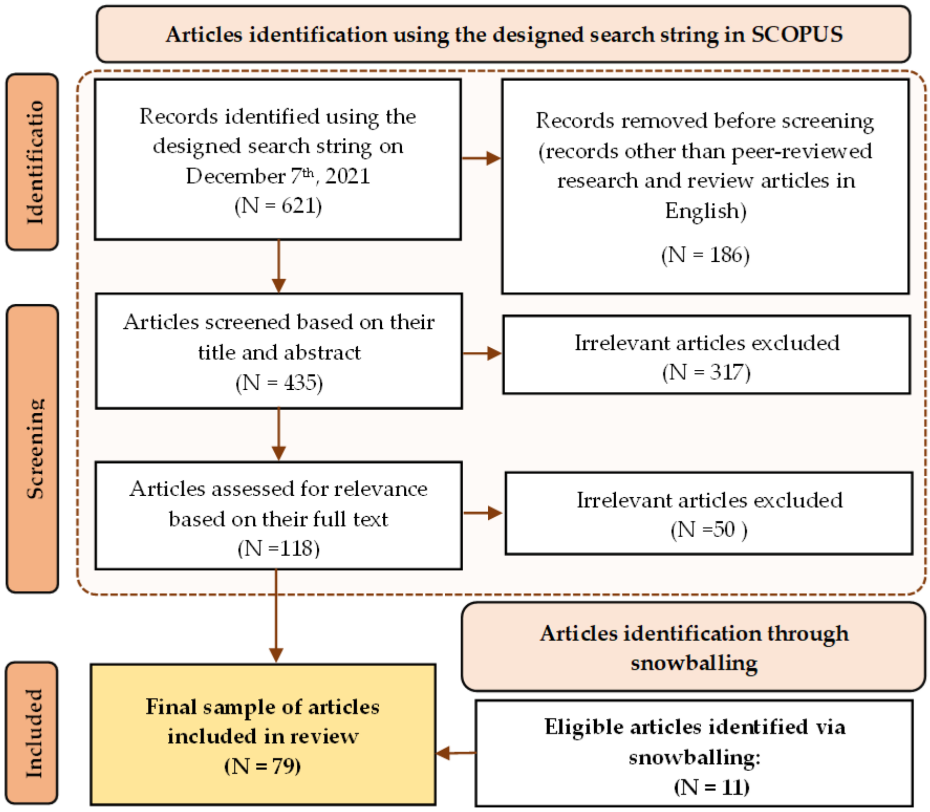

Figure 1. Paper selection process based on the PRISMA framework (adapted from [28]).

3. Literature Review

3.1. Circular Economy as a New Industrial Paradigm

The most widely accepted definition of CE is provided by the Ellen MacArthur Foundation as "a framework for an economy that is restorative and regenerative by design", which aims to preserve the maximum utility and value of products, components, and materials [29]. The CE is different from the cradle-to-grave and governance economies. The CE supports the "cradle-to-cradle" model of economic operation through innovative methods, such as PSSs and industrial symbiosis. Many countries and macroregions are currently promoting CE not to obtain short-term and medium-term benefits, but to achieve long-term sustainable growth and save more resources for upcoming generations. The CE can be considered an optimization of the triple bottom line and can be used to create new business models and jobs.

The effective implementation of the CE can be split into three different levels according to scale and unit of analysis: micro-, meso-, and macro-levels. The micro-level refers not only to the specific measures of a single company's transition to a CE [30], but also to the specific measures taken at the product level. The meso-level extends this to the inter-enterprise level and enables inter-enterprise cooperation to emerge through industrial symbioses, such as eco-industrial parks [31]. The macro-level covers measures implemented by cities, regions, or countries to promote CE at a high level [32].

From a topology perspective, CE is a closed-loop economy, whereas the traditional economic model belongs to an open-loop or linear economy [33]. The CE is composed of several closed-loop cycles, such as reuse, remanufacturing, and recycling, which can help save costs, moderate resource price fluctuations, and achieve economic growth without environmental damage and overuse of precious resources. The closed-loop cycle formed by the different principles of the CE is shown in Figure 2.

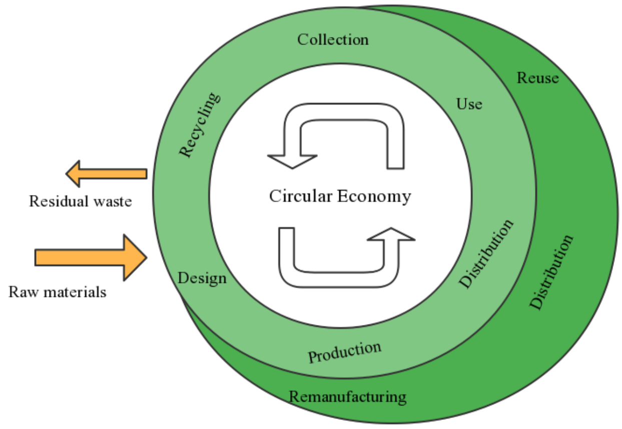

Figure 2. Closed-loop diagram of a circular economy.

The CE pays equal attention to the forward and reverse flows of products, components, and materials through the implementation of reverse logistics and closed-loop supply chains [34]. The environmental impacts of a product are considered upstream at the design stage before manufacture and use. A CE product is designed to be durable, have multiple lifecycles [35], and reconfigure its resource dependencies in a sustainable and systematic way. Several design-for-x strategies can therefore be employed for eco-design [36,37], product life extension [37], modularization [38], remanufacturing [39], standardization, and material selection.

The implementation of a circular strategy must start from the beginning; that is, in the product design stage, fully utilizing the advantages of DTs combined with the idea of circular design. After the product enters the sale-for-use phase, DTs can provide innovation in the business model, allowing enterprises to divorce from the old model of selling products for profit. The CE business model, if appropriately designed, not only provides the enterprise economic and environmental benefits, but also enables it to better deliver its value proposition at the social level. Furthermore, a conceptual framework was designed, as shown in Sections 3.2 and 3.3 below.

3.2. Innovations in Business Models

The business model refers to the value creation function of an enterprise and how it benefits customers and makes profits [40]. An ample amount of literature has analyzed the business models. For example, Wise & Baumgartner [41] identified four types of business models: embedded services, comprehensive services, integrated solutions, and distribution control. This classification is based on service content but does not consider product ownership. Michelini & Razzoli [42] established the concept of product ownership and distinguished several types of services, including whole lifecycle services of tangible assets, leasing services of tangible assets, and the use of shared products. The transaction model dominated by one-off product sales is not conducive for enterprises to carry out technological innovation, and companies do not have access to usage data from product users. To motivate enterprises to adopt CE principles, researchers have proposed a shift from “product sales” to “service provision” [43], in which a company moves toward a service-oriented business model [44] where it owns the products and internalizes product maintenance and updating. Such models are conducive to product management, thereby improving competitiveness and the sustainable development of the company under the condition that the enterprise owns and is responsible for the product [45]. The service-oriented business model can use lifecycle data to improve internal processes, customer relationships, and circularity [46], thus establishing a lasting relationship between suppliers and customers, which are all driven by DTs [47].

Baines & Lightfoot [48] observed three different types of services that the company provides: essential services, which focus on product supply; intermediate services, which focus on maintenance; and advanced services, which focus on the effect of the product. Tukker [45] classified business models into three types: product-oriented, use-oriented, and result-oriented models. Table 1 shows our analysis of PSSs and their relations with CE and the main advantages and drawbacks of each type of PSS.

Table 1. Analysis of product-service systems and their relations with the circular economy (CE).

Product–Service Business Model	Ownership of the Product	Advantages Regarding the CE	Main Drawbacks Regarding the CE	Corresponding References
Product-oriented business model	Customers	The enterprises will provide pre-sale services and corresponding after-sale services	Negative environmental impacts of products, which will probably become wastes	[40,42,45,48]
Use-oriented business model	Enterprises	It avoids the risk of customers holding a large number of fixed assets, increases product utilization rates, and creates additional economic value	Difficult to measure remanufacturing and reconditioning activities and short lifetime of some user-oriented products	[40,42–51]
Result-oriented business model	Enterprises	Customers are provided with the highest degree of service, which can make customers directly evaluate the effect of service and can help enterprises transition to a CE	Difficult to measure results in terms of product/system performance	[40,42,45,47–49]

Product-oriented business models, which incentivize customers to purchase products to maximize product sales, make it challenging to achieve CE goals. These services mainly include pre-sale services for product-related components and quality services during maintenance.

The use-oriented business model is conducive to the improvement of resource-use efficiency, prolonging product lifespan through advanced maintenance and achieving the value of the CE. For instance, the product circulation loop can be closed by signing a recycling agreement. Use-oriented enterprises sell services only via leasing, sharing, or pay-per-use and not through tangible products. Their customers do not need to buy products but must only pay for access [49]. These enterprises provide customers with whole lifecycle services, such as maintenance, repair, and control [50]. As these enterprises retain ownership of the "products", they pay special attention to product design, and the lifecycle is increased by upgrading through easy maintainability and component reuse at the EoL [51].

Result-oriented business models help consumers use products better and improve product usage efficiency by providing consumers with information or services rather than just specific products. The customer pays variable fees according to contractual provisions based on the performance of the product or the results of its use [45]. This business model is conducive for enterprises to minimize operating costs, improve resource efficiency, extend product life, and recycle products for multiple lifecycles, which significantly enhances their market competitiveness. In this model, customers buy performance rather than products and related services [49].

Product-oriented business models may produce additional waste; however, the product/system performance of result-oriented business models is difficult to measure. Here, as our focus is on the advantages of a user-oriented product service business model for CE, we selected a user-oriented PSS for the following analysis. Previous scholars [49,51] have suggested that this model can cause careless product usage by customers, resulting in rapid wear and tear. However, this drawback can be avoided by IoT technologies that, with the user's authorization, can enable the tracking and monitoring of product usage activity. Using the products to control users' activities in a way that prevents inappropriate use behaviors is possible. Use-oriented business models have enormous potential to improve resource efficiency, extend product service life, and close the loop of products through the positive impact of DTs.

3.3. Role of Industry 4.0 in CE

In promoting the transformation from the traditional economy to the CE, DTs has shown good prospects for application via monitoring, control, optimization, and automation in achieving circular goals [52]. The term "Industry 4.0" was first introduced by the German federal government in 2013 as a strategic policy initiative [53]. The "cyber-physical production system" refers to the integration of different systems to achieve a high degree of automation in the manufacturing industry based on customer needs, which is increasingly blurring the boundaries between the virtual world and the real world [53]. The goal of Industry 4.0 is to use disruptive technologies, such as cloud services, IoT, big data and big data analytics, and AI, to interact with one another and improve the manufacture of high-quality products at a minimal cost. Industry 4.0 provides alternatives to sustainable production and consumption that minimize energy losses, resource consumption, and environmental degradation [12]. Industry 4.0 provides a fresh perspective on how manufacturing can use new technologies to create value with maximum output and minimum resource utilization.

The Boston Consulting Group [54] identified the main technologies that help build Industry 4.0: big data analytics, autonomous robots and vehicles, additive manufacturing, simulations, augmented and virtual realities, horizontal/vertical system integration, IoT, cloud, fog, edge computing, and AI, as well as blockchain and network security. According to the literature analysis [54], six technologies have been identified as the main Industry 4.0-based technologies related to CE: CPS, IoT, AI, big data analytics, additive manufacturing, and simulation. Figure 3 shows the digital technologies in Industry 4.0.

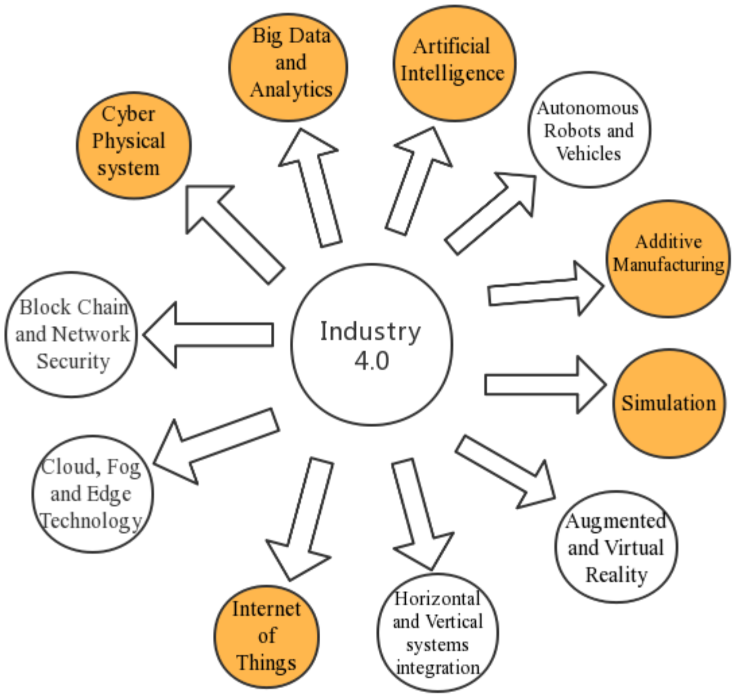

Figure 3. Digital technologies in Industry 4.0 (the six circular economy-relevant technologies are highlighted).

Against the background of the new round of scientific and technological revolutions, many countries have formulated their own national strategic plans to gain a competitive advantage in the manufacturing industry. In 2012, the United States spearheaded the implementation of the "National Strategic Plan for Advanced Manufacturing" to consolidate the US manufacturing industry's world-leading position, optimize its structure, and enhance its global competitiveness [55]. To accelerate the technological transformation of the manufacturing industry, the United Kingdom released "The future of manufacturing: A new era of opportunity and challenge for the UK" in 2013 and established seven high-value manufacturing R&D centers, such as advanced manufacturing and forming technology [56]. China proposed its "Made in China 2025" strategy, which was deployed to drive the implementation of its manufacturing strategy [57]. Through continuous R&D and innovation, China's manufacturing industry has mastered key technologies and filled the gap in the development of high-tech fields. Industry 4.0 is about transforming interactions between technology and the environment.

New DTs have a profound impact on industry. The first is the use of data (big data and open data), connectivity (IoT), and computing power (cloud computing). The second is data analysis, which improves the performance of machinery through "learning" by analyzing collected data [58]. The third is the interaction between humans and machines (data visualization representations and augmented reality). The fourth is the transition from data to reality (additive manufacturing and 3D printing, AI) [59]. The CE model considers the entire lifecycle of products and focuses on the high-level recycling of industrially produced materials. First, in the DTs-enabled design phase for a new product lifecycle, the combination of remanufacturing, reuse, repair, and recycling dramatically changes the cycle characteristics of the production process. Second, IoT technology enables the reintegration of maintenance processes, as well as the reusability of components and products. Finally, digitization enables the optimization of logistics and greatly improves the flexibility and reaction times of industrial and logistics systems.

DTs play a significant role in environmentally sustainable operational decisions, and the synergy and sustainability of Industry 4.0 may further drive a sustainable society [6,60]. Based on the findings of Agrawal et al. [61], integrating Industry 4.0 tools into circular business models can improve logistics, resource efficiency, safety, and product quality and reduce fossil carbon footprints. Several studies [62–66] have indicated that data-driven Industry 4.0 can be used to solve such CE-related issues, as Industry 4.0 features vertical integration, virtualization, automation, traceability, flexibility, and energy management. As part of Industry 4.0, machine learning methods are applied in the CE. Rakhshan et al. [67] determined that advanced supervised machine learning techniques can be used to predict the reuse potential of structural components at the EoL of a building. Uribe-Toril et al. [68] demonstrated the application of deep learning techniques to predict business survival. Arranz et al. [69] combined the regression method with machine learning to explore how institutional pressures affect the development of CE in companies.

This study used the example of a bike-sharing platform to study both DTs and CE. This case has not previously been considered among the fields for application in the literature [62,63]. Abdul-Hamid et al. [62] and Çetin et al. [63] studied the relationship between Industry 4.0 and CE, which is in line with our research; however, they focused on different fields of applied research. Abdul-Hamid et al. [62] selected the palm oil industry to illustrate how the application of Industry 4.0 can improve unsustainable practices. Çetin et al. [63] studied the promotion of DTs for CE in the construction industry. Lopes de Sousa Jabbour et al. [70], Kalogiannidis et al. [64], and Kurniawan et al. [71] collected data from Brazil, Greece, and Indonesia to support a digitalization-based CE, respectively. Here, we considered the real-world situation of bike sharing in China as an example to illustrate how DTs can play an important role in transitioning to CE. Ahmed et al. [65] studied the role of CPS in promoting CE, and Delpla [72] asserted that IoT technology can solve problems in the implementation of closed-loop supply chains. This study employed various DTs in Industry 4.0 as our research object, and we verified the positive role that various DTs play in CE practice from the perspective of the three stages of product lifecycle: product design, product use, and product recovery.

4. Results: Exploring the Conceptual Framework of DTs in the CE in Terms of Product Lifecycle

To measure the effect of DTs on the development of CE, we must define CE performance objectives. The Ellen MacArthur Foundation established three CE performance objectives: increasing resource efficiency, extending the product lifespan, and closing the loop [46]. Bocken et al. [43] proposed narrowing the resource flows by using fewer resources to make each product, reducing the flow of resources by extending the lifetime of the product, and closing the loop of resource flows by redirecting them into raw materials.

This paper adopted the following CE performance objectives: (1) using fewer materials and resources by improving resource efficiency, (2) extending product lifespan, and (3) closing the loop. In this section, we presented a conceptual framework for how DTs can facilitate CE performance objectives in terms of the three stages of product lifecycle: product design, product use, and product recovery.

4.1. Product Design

Intelligent manufacturing is an important way to develop and transform the manufacturing industry, including intelligent design, production, service, management, logistics, and system integration [73]. Among them, intelligent design is the core of intelligent manufacturing and the key point that determines the transformation of the entire intelligent manufacturing system. Products are traditionally designed in a way that does not consider what would happen when they are no longer used and only works to introduce new models to satisfy consumer needs and temptations. As a result, numerous EoL products ultimately end up landfilled, causing not only huge losses of materials, energy, water, and labor, but also damaging the environment. Product design for CE is a complex process that requires a shift in thinking from a product-centric to a system-based design approach. Circular design challenges the next generation of products and materials to minimize the use of primary raw materials [74]. The focus of circular design is to reduce the loss of value by maintaining the closed-loop cycle of these products and materials. These cycles, such as reuse, repair, remanufacture, refurbishment, or recycling, extend the lifecycle of products and improve resource productivity [72,75]. When the product is scrapped, the parts can be recycled and remanufactured, and the materials can be reused through recycling.

The product design phase affects product longevity and reprocessability. Product design is the starting point for fulfilling the challenge of CE; thus, we should use integrated approaches for sustainability assessment to reconfigure our resource dependencies. The CE demands cross-disciplinary collaboration and active communication among designers, materials experts and engineers, environmentalists, economists, and end-users during the design phase [76]. In contrast to current solutions that focus on the "end" of life, we considered and implemented resource challenges from the "beginning" of the lifecycle of products, components, or materials, that is, the design phase.

Research by the UK's Royal Society for the Encouragement of Arts, Manufactures and Commerce found that circular design can be divided into four modes: design for long life, design for lease or service, design for reuse in manufacturing, and design for material recycling [77]. First, design for a long life improves product reliability. Bocken et al. [36] proposed "design for reliability", in which if the manufacturer's instructions for use and maintenance are followed, then the products are highly likely to work failure-free for a certain period of time. Dematerialized designs should also be considered, as they reduce the amount of material required while maintaining core functionality. Second, in "design for leasing/service", which is a business model to provide services to more users, the producer or manufacturer retains ownership of the product. This model has evident benefits for users, as it enables them to use high-spec, high-tech products. In addition, the model of leasing, which sells the results, can also avoid low-priced disposable tools, saving resources and time. Third, in reusable design, damaged product parts are made replaceable. Users can purchase parts through an online ordering system, and manufacturers can provide high-quality and cost-effective maintenance services. Obsolete products are returned from users to manufacturers for remanufacturing through reverse supply chain management [78]. Fourth, the reprocessing of recycled products into new materials in material recycling design requires products to use a single material rather than complex materials and involves the development of a second-hand material certification system [74].

The new technologies and innovations provided by Industry 4.0 have promoted information-oriented and knowledge-oriented business models to achieve economic and sustainable development. Such models require manufacturers to further expand their focus on potential environmental impacts, enhance product design quality, and explore their contribution to sustainable development [63,79]. Additive manufacturing technology innovates traditional processing. It uses computer control to add materials layer by layer to manufacture objects and is thus able to produce an increasingly wide range of goods. It not only enables complex and revolutionary design and manufacturing, such as topology-optimized structural design, complex 3D shape printing, and lightweight design, but also agile, integral, low-cost manufacturing, such as full digitalization, no tooling, and one-shot molding, all while minimizing transport. As a strategic technology trend of Industry 4.0, the digital twin is gradually maturing and becoming a mainstream technology. This tool is essentially a combination of physical entities, and twin models can then optimize continuous processes and help achieve precise control in the real world. Therefore, digital twin is also featured among the core technologies of CPS. The tool can help enterprises reduce costs, resource consumption, and carbon footprints while supporting innovation, business agility, and customer-centric business models that are highly aligned with CE. Using Industry 4.0 for product design is conducive to the realization of CE, as shown in Table 2.

Table 2. List of different product design strategies for circular economy (CE) performance objectives.

Design-for-x Strategies	Analysis of the Strategies	CE Performance Objectives	Function of Digital Technologies
Design for manufacturing	Design for manufacturing helps save resources in product manufacturing and enables rapid high-quality manufacturing	Use fewer materials and resources	Digital design and manufacturing technology provide product design solutions that integrate many advanced technologies, such as CAD/CAPP/CAM
Design for assembly	Design for assembly helps improve efficiency and reduce wear during product assembly	Extend product lifespan	Digital assembly technology uses virtual reality to plan and simulate the actual product assembly process
Design for disassembly	Design for disassembly allows rapid product disassembly, improves reparability, and reduces consumable input and waste output	Close the loop	The virtual disassembly method based on a 3D software platform can guide the product disassembly process
Design for quality	Achieving high-quality product design helps improve product quality to meet customer needs	Extend product lifespan	Digital prototyping technology can be used to improve product function
Design for supply chain management	Designs that consider supply chain-related factors can help improve product efficiency and reduce instability in the supply chain	Use fewer materials and resources	Blockchain and Internet of things technologies can be used to establish a product supply chain traceability system
Design for lifecycle	Considering the product lifecycle in the design helps assess overall resources consumed and pollution generated in the product lifecycle	Use fewer materials and resources	Virtual manufacturing systems based on digital twin technology consider all important factors at each stage of the product lifecycle
Design for the environment	Considering environmental impacts in product design helps achieve sustainability goals	Close the loop	Additive manufacturing technology can significantly reduce raw materials, waste, transport, and energy inputs in the production and delivery processes

4.2. Product Use

From a high-level abstraction perspective, we can observe consumers dealing with PSSs by interacting with physical products to request and enjoy services, as shown in Figure 4. In PSS, the "service" part acts as an invisible intermediary between customers and products. Part of the PSS plays the role of the product's user interface, allowing consumers to request services and then receive and use them. At the back end of the PSS, the embedded sensors in the product communicate with the cloud-based product support environment, which collects sensor data to build and maintain the product's digital twin. Data analysis can be used to extract essential usage data and update product status. We can then simulate the product in its current state to determine whether maintenance or software updates are required [80]. Figure 4 schematizes the mode of PSS operation. If customers want to find a new app, they can navigate through the phone's user interface to find the app store icon, launch it, and then browse the retrieved apps. At the back end of the PSS, a large-scale cloud-based system is necessary to collect, catalog, archive, validate, and retrieve various apps.

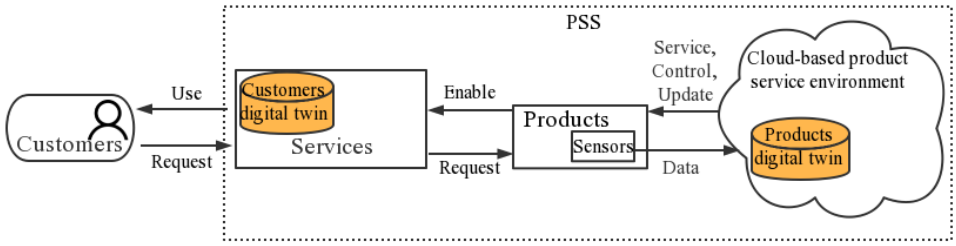

Figure 4. Product-service systems (PSS) internal interaction process.

In Figure 4, we focused on the operation of the PSS. The back-end cloud-based product supporting the environment should be considered. Digital twin is the representation of a product and the environment's sensor data flow, which keeps the product continuously updated. Certain control and decision-making processes must be present in the system to update product status, analyze data, and simulate product status. To adapt over time and improve its performance and the performance of PSS, we should have an intelligent support system with specific monitoring and execution capabilities.

PSSs should be able to understand consumers to provide better and sharper services. In other words, PSSs should have a digital twin of a customer and use that data representation as the basis for data analysis and simulation. Figure 5 schematizes the digital twin of customers and products contained in the "Services" section and the cloud-based product service environment. The smart PSS of the future is expected to have an updated and analytically capable digital twin for the product and consumer. Sensor data support control, analysis, and decision-making activities, enabling the PSS to respond and adapt to consumer needs and the environment where the product is used. In addition, the PSS has the ability to learn as the system operates.

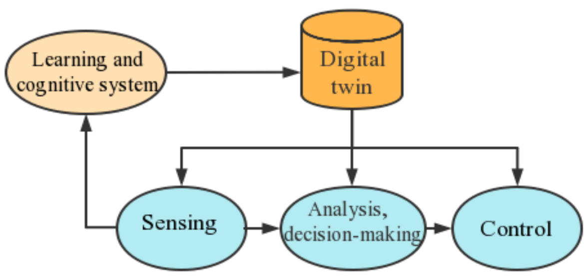

Figure 5. Digital twin of consumers and products in smart product-service systems.

PSSs can enable the collaborative consumption of products and services and help make CE a reality. The continuous development of the digital twin has become a driving force for the improvement of PSSs. DTs help manufacturers capture operational data on products that customers are actually using to deliver advanced services, such as operational status monitoring and preventive maintenance. In addition, manufacturing enterprises can engage customers in the whole end-to-end process of product service, from R&D and design to operation, to provide purpose-targeted services.

4.3. Product Recovery

Under the linear economy model, consumers discard products at their EoL as waste, which not only pollutes the environment, but also wastes resources that can otherwise be restreamed or recycled for use in remanufacturing instead of consuming valuable raw materials. The CE can support the closed-loop recycling of products or materials through the improvement of the reverse supply chain [81] and progress in smart technology. The development of Internet technology and e-commerce platforms has led to the emergence of several Internet-based recycling platforms. The platforms are based on the O2O (combined online and offline) e-commerce model, which can track user information, monetary information, and logistics information, to manage the reverse recycling chain and generate statistical information. Internet-based recycling platforms combine new technologies, such as the IoT and big data, to build a complete recycling ecosystem. A smart waste collection system based on IoT, including radiofrequency identification tags, near-field communication sensors, and global positioning system (GPS) sensors, can obtain real-time data on the status of smart recycling bins and on the users involved in recycling to optimize the recycling process [82]. The recycling platforms consist of a mobile phone–based application through which users can locate the nearest or most suitable smart recycling bin and are rewarded with money or points for participating in recycling [83].

AI technologies used in waste recycling systems can identify the types of recyclable products and materials through image recognition technology and analyze user behavior data [84]. Machine learning-based optimization techniques are already being used in IoT-based smart waste collection systems. These methods help analyze incoming waste materials, the size of the waste bins, and the type of waste collection vehicles necessary. For instance, Gupta et al. [85] obtained data from sensors installed on bins and used machine-learning algorithms to sort recyclable materials by type, such as plastic, metal, or glass, and dispatch the recyclable products and materials to a recycling plant.

Internet technology, combined with mobile apps, establishes direct contact between consumers and manufacturers or recyclers to prevent a large number of recyclable products and materials from becoming solid wastes and provides conditions needed for reverse logistics. IoT technology allows companies to track products throughout their lifecycle, enabling CE strategies, such as reuse, remanufacturing, recycling, and product sharing. Using IoT, cloud computing, big data analytics, and AI technology, smart waste bins solve not only the problem of product recycling, but also the problem of urban waste management.

5. Application and Discussion

This research determined that DTs, such as IoT, cloud computing, big data, and AI, act as facilitators for CE business models and enable the transition to a CE. In the initial stage of the product lifecycle, that is, the design stage, DTs help realize the circular design of the product, such as detachable and recyclable components, to achieve the third CE performance objective, that is, to close the loop. In addition, product design to increase lifespan helps achieve the second CE performance objective, that is, to slow down resource flows. In the middle stage of product lifecycle, that is, the use stage, the application of DTs makes the product "smart"; thus, value is no longer generated from the design and production stage but from the use stage [86,87]. IoT technology can monitor and track product activities, collect usage data, and combine with cloud computing, big data analytics, and AI to provide technical support for product use, guide users on optimizing the process of product use, extend product lifetime, and accomplish the CE second performance objective, which is to slow down resource consumption. Based on the usage data, the product design can be improved to satisfy the CE first performance objective, enhance the efficiency of raw materials, and reduce the flow of resources. DTs can also facilitate preventive or predictive maintenance; thus, products can maintain an increased service life. At the end stage of product lifecycle, the loop can be closed by streaming the product into a second life or by efficient recycling through efficient reverse logistics systems. However, CE activities in this final stage of the product life are closely related to the design in the initial stage of the product life [37,87]. Increasing the investment in DTs in the product design stage is necessary to create conditions for the product to close the loop in the end stage.

The effects of various DTs as drivers of CE performance objectives are as follows. IoT technology can be used to monitor and track product activity, optimize production processes and supply chains, meet customer needs with less raw materials, and improve resource efficiency, whereas user data captured by IoT can be mobilized to maintain or upgrade products and provide customers with high-quality services. Cloud technology provides customers with convenient and timely access to maintenance services, increasing service demands and extending product lifetimes. Cloud technology provides companies with the opportunity to access large amounts of data in the supply chain, which increases the company's understanding of real-time operations and results in a highly cost-effective and reliable supply chain. The cloud establishes and maintains the digital twin of products by collecting sensor data, simulating physical objects in real time, providing insight into problems that may arise in the process, and making recommendations for product improvements; thus, the need for expensive physical testing is eliminated, and the production costs are reduced. Big data technology, which is widely used at all stages of the product lifecycle, can improve product design to facilitate EoL recycling, and provides preventive and predictive maintenance. AI technology enables companies to accurately predict the waste generated and optimize demand for products, thus improving supply chain management and reducing unnecessary warehousing and potential shortages, thereby reducing costs. Additive manufacturing combines mechanical manufacturing technology with digital information technology to produce customized products and save materials without increasing costs.

In the following sub-section, the significant role of DTs in facilitating CE business model innovation is further clarified and discussed using a bike-sharing platform as an example of a real-world AB-PSSs. The findings from the example have been used to support the conceptual framework.

Reflections on a Bike-Sharing Platform as an Example of AB-PSSs

The growth of Internet technology has driven the growth of the sharing economy and the resulting peer-to-peer sharing of resources, such as car sharing, power bank sharing, and home appliance sharing [88–90]. Digitization facilitates the emergence of new circular AB-PSSs, where users complete transactions via online platforms and social media that use IoT products [47,91]. Digital infrastructure also facilitates continuous data exchange between service providers and the devices used by users, enabling pay-per-use device services [92].

Circular business models, such as AB-PSS, have been enabled by DTs [93]. A growing number of mobility AB-PSS initiates the implementation of bicycle-sharing systems by consumers [1,94]. In recent years, shared bicycle systems have flourished in smart cities, and the majority of them have been successful. As a typical example, an intelligent transportation system can effectively improve transportation mobility and safety while also reducing environmental impacts. Since 2016, the shared bicycle system has begun to grow rapidly in China, drastically altering citizens' travel habits. The bicycle-sharing service is based on a time-sharing rental model by companies, which provides citizens with many public bicycles at public places, such as bus and subway stations, commercial and residential areas, and university campuses. To illustrate the effect of DTs on CE, we thus proposed to study the case of bicycle-sharing service.

Bike sharing is an AB-PSS that allows consumers to pay for the use of a shared bike. This business model can reduce the negative impacts of overbuying by reducing the total number of products required, increasing the use frequency of products, and extending the product lifecycle through maintenance and upgrades [93]. An IoT-based smart lock is installed on the shared bicycle, and functions, such as positioning, unlocking, returning, and paying, are all managed through a smartphone app. Therefore, this AB-PSS relies on DTs and the user's smartphone.

Companies evolving in use-oriented business management systems are usually responsible for product costs over the whole product lifecycle costs [95], which is an incentive for them to design their products for a CE. A network capable of performing on-site support, such as transport, repair, maintenance, upgrade, and collection, can maintain the normal operation of the system and extend the lifespan of the shared bicycles. When bicycles become technologically obsolete, they are collected and replaced. Old bicycles are repaired, updated, and cleaned before they are returned to the system.

The entire system underpinning bike sharing can be regarded as the process of data collection, analysis, processing, and operational feedback. IoT technology is key and foundational to interconnecting mobile phones, bicycles, and the cloud. A mobile app can be used by the clients to search for nearby bicycles and carry out unlocking, fee calculation, and mobile payment. The bicycle terminal can collect travel data and transmit the GPS information and status of the electronic lock to the cloud through the subscriber identity module card. The cloud controls the entire system, collects information, and issues commands to control the bicycle terminal. This workflow is shown in Figure 6.

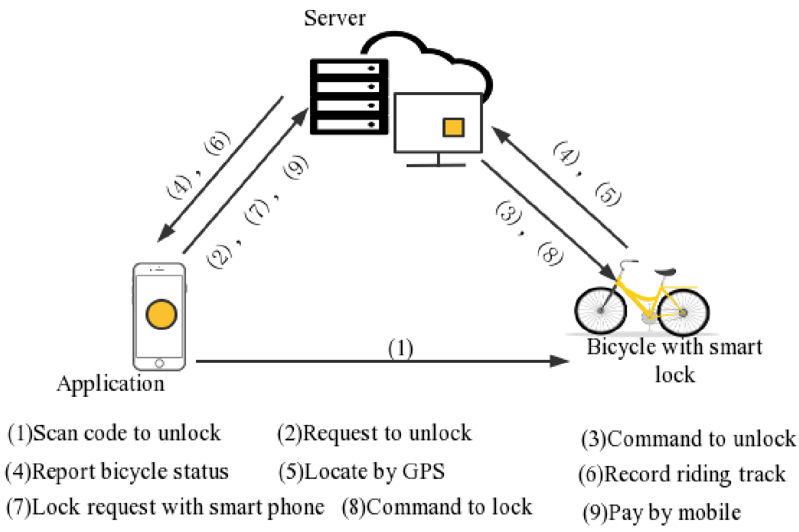

Figure 6. Internet of things workflow in bicycle sharing.

AI technology supports intelligent scheduling, balancing supply and demand, and accurately predicting shared bicycle parking areas and peak and valley parking periods. Therefore, AI helps provide rational recommendations on parking spots and no random parking. If the vehicle is not in the specified parking area, it cannot be locked by phone for settlement. The cloud platform mainly operates in data storage and management and is the hub of the entire bike-sharing operation. After the user scans the QR code on the bike, the command requesting the unlocking is uploaded to the cloud system to unlock the bicycle; at the same time, the real-time status and location of the shared bicycle are also uploaded to the cloud, thereby achieving the function of synchronous billing. The cloud platform can help handle user recharge and payment services and, by establishing a user credit system, implement civilized use and proper parking [96].

DTs are currently developing at a rapid pace, and the impending 5G technology delivers low communication time delays and highly accurate locations for bike-sharing platforms. This feature enables the realization of improved location-based services, such as an electronic fence and cycling path records. In addition, with sensor and technology developments, more sensors are embedded in the shared bicycle, resulting in increased data collection about cycling. With some data mining methods, these data can be transformed into highly intuitive and understandable forms for decision makers to accept, thus making the city run increasingly efficiently [95].

DTs-driven products for AB-PSS adhere to the recycling design strategy listed in Section 4.1, making the design easy to maintain, upgrade, disassemble, and recycle. As illustrated in Figure 7, the IoT, cloud platforms, and AI provide the technical foundation for developing AB-PSS. The IoT is mainly used for networking the peer-to-peer sharing of resources and collecting data. Smart shared products have sensors and communication modules that can sense the surrounding environment and communicate with the IoT platform to serve shared product networking. The cloud platform provides data storage and management for shared products, including condition data, distribution of shared products, and demand data. AI is mainly used for big data analysis and feedback to provide technical support for smart operations. Using big data to analyze when and where shared products are commonly used can help rationally plan the deployment of the products and improve resource utilization.

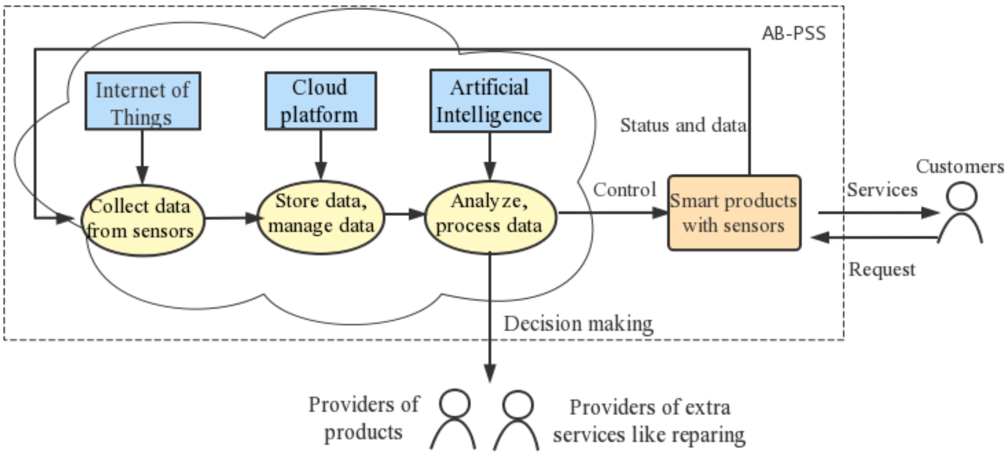

Figure 7. Key digital technologies' workflows in an access-based product-service system (AB-PSS).

AB-PSS extends the product lifecycle by shifting responsibility for repairs and maintenance to suppliers. The information collected by the IoT provides better technical support for on-site maintenance technicians. For example, it analyzes maintenance and fault management data to discover which parts fail most frequently, which can improve the design or quality of the parts. In addition, the big data on users can be analyzed to provide effective preventive and predictive bicycle maintenance [48,87,97]. At the end of the lifecycle, the IoT technology can capture the real-time location and status of the bicycle through GPS, and the appropriate collection activities and recycling conditions can then be organized. In summary, in the case of shared bicycles, DTs enable improvements in CE. DTs combined with the AB-PSS business model can improve resource efficiency, extend product life, and close the loop on resource flows.

6. Conclusions

Based on our analysis of the extant literature, we proposed a conceptual framework in which DTs, such as the Internet, IoT, cloud computing, big data, and AI, play important roles in each stage of the product lifecycle (i.e., design, use, and EoL). By working on the three performance objectives of CE—increasing resource efficiency, extending product lifespan, and closing the loop—we argued that DTs potentially enables radical improvements to the CE model, provided that the environmental and economic costs of DTs are assessed and balanced with benefits. New technologies and innovations provided by Industry 4.0 have been used for various circular product designs, such as design for long life, design for lease or service, design for reuse in manufacturing, and design for material recycling. In addition, non-materialization design should also be considered as a way to reduce the amount of material required while the core functionality is continuously delivered. From the beginning of the product lifecycle, we considered slowing down the resource flow of products, and by entering the closed-loop cycle, new PSS business models have emerged to satisfy customer needs for personalized, experiential, and other professional services. PSSs are divided into three categories according to the degree of service and ownership transfer of product in the transaction process: product-oriented PSSs, usage-oriented PSSs, and result-oriented PSSs. This paper abstractly analyzed the consumer–service–product interaction process in the PSS business model that provides professional services to consumers through the Internet, IoT, cloud platforms, and digital twin technology. When the product reaches EoL, the loop through reuse, remanufacturing, and recycling should be closed. DTs are conducive to the improvement of the management of reverse supply chains and to the reduction of transportation flows. With the help of the Internet, IoT, cloud computing, big data analytics, and AI, Internet-based recycling platforms and smart recycling bins have established direct and effective connections for consumers, recyclers, and manufacturers.

DTs can support both CE and PSSs to enable circular business models that support our theoretical framework. In recent years, many popular AB-PSSs based on smartphone apps, such as the bike-sharing system studied here as an example of DTs driving the transition toward a CE, have been developed. The development of the Internet and the IoT provided the foundations for the use of shared bicycles based on an AB-PSS. The IoT technology ensures bike data collection and networking. The information collected through the IoT helps provide better technical support for on-site maintenance technicians, thereby extending the service life of the bicycles. The positioning technology provided by the IoT enables reverse recycling activities, such as refurbishment and remanufacturing of bicycles, to close the loop. The cloud platform offers data storage and management for shared bicycles, and AI provides technical support for smart operations through big data analysis. To achieve the transition from a linear economy to CE, we must integrate DTs across all stages of the product lifecycle and operate a transition from a traditional "product-centric" focus to a "service-centric" focus on solutions and product services to achieve whole lifecycle management.

The applied methodology and setup of the study entail some limitations that provide avenues for future research. We deliberately employed the bike-sharing model of mobility AB-PSS as an example to discuss DTs in CE. Additional applications should be provided in the future to assess how digitalization can support the transition toward a CE. Moreover, the sustainability potential of DTs in products can be assessed during their development, as the required sensors and server infrastructures cause negative impacts on the environment that may outweigh their positive effects [98].

The selected case discussed here is based on an AB-PSS, and the research field is somewhat narrow; however, future research can investigate other PSSs. We also suggested studying the degree and scope of DTs, supporting the transition to CE by conducting empirical research using a wide range of data from enterprises across industries. The range of DTs included in Industry 4.0 is vast, and new information technologies are constantly emerging. The fields of CE and Industry 4.0, for example, eco-industrial parks or regional-scale CE, have many under-researched topics [99,100]. The realization of CE through Industry 4.0 requires continuous monitoring and control of the entire lifecycle [84]. The research presented in this paper is preliminary but provides a reference framework for further empirical research.

Author Contributions: Methodology, T.S., M.R. and Z.S.E.; Validation, B.Y., M.R., M.S. and G.B.; Formal analysis, Y.H., T.S., B.Y., M.R., Z.S.E., M.S., G.B., K.B.-D. and G.L.; Investigation, Y.H., T.S., B.Y., M.S., K.B.-D. and G.L.; Writing—original draft, Y.H.; Writing—review & editing, T.S., B.Y., M.R., M.S., G.B., K.B.-D. and G.L.; Visualization, Z.S.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was supported by the Henan Institute of Science and Technology in China, CentraleSupelec of the University of Paris-Saclay in France, Sumy National Agrarian University in Ukraine, and the University of Turin in Italy. In addition, we would like to thank the anonymous reviewers whose comments have greatly improved this manuscript.

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

Abbreviations

DTs	digital technologies;
CE	circular economy;
AB-PSS	access-based product-service system;
IoT	Internet of things;
CPS	cyber-physical systems;
AI	artificial intelligence;
GPS	global positioning system.

References

1. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E.J. The circular economy–a new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
2. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32. [CrossRef]
3. Ellen MacArthur Foundation. *Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition*; EMF: Cowes, UK, 2013; Volume 1.
4. Ellen MacArthur Foundation. *Artificial Intelligence and the Circular Economy*; EMF: Cowes, UK, 2019.
5. Irani, Z.; Sharif, A.M. Food security across the enterprise: A puzzle, problem or mess for a circular economy? *J. Enterp. Inf. Manag.* **2018**, *31*, 2–9. [CrossRef]
6. Rajput, S.; Singh, S.P. Connecting circular economy and industry 4.0. *Int. J. Inf. Manag.* **2019**, *49*, 98–113. [CrossRef]
7. 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]
8. 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]
9. Rosa, P.; Sassanelli, C.; Urbinati, A.; Chiaroni, D.; Terzi, S. Assessing relations between circular economy and industry 4.0: A systematic literature review. *Int. J. Prod. Res.* **2020**, *58*, 1662–1687. [CrossRef]
10. Pham, T.T.; Kuo, T.-C.; Tseng, M.-L.; Tan, R.R.; Tan, K.; Ika, D.S.; Lin, C.J. Industry 4.0 to accelerate the circular economy: A case study of electric scooter sharing. *Sustainability* **2019**, *11*, 6661. [CrossRef]
11. Dev, N.K.; Shankar, R.; Qaiser, F.H. Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resour. Conserv. Recycl.* **2020**, *153*, 104583. [CrossRef]
12. Yadav, G.; Luthra, S.; Jakhar, S.K.; Mangla, S.K.; Rai, D.P. A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case. *J. Clean. Prod.* **2020**, *254*, 120112. [CrossRef]
13. Pieroni, M.P.; McAloone, T.C.; Pigosso, D.C. Business model innovation for circular economy and sustainability: A review of approaches. *J. Clean. Prod.* **2019**, *215*, 198–216. [CrossRef]
14. 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]
15. Guzzo, D.; Trevisan, A.H.; Echeveste, M.; Costa, J.M.H. Circular innovation framework: Verifying conceptual to practical decisions in sustainability-oriented product-service system cases. *Sustainability* **2019**, *11*, 3248. [CrossRef]

16. 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]
17. 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]
18. Grafström, J.; Aasma, S. Breaking circular economy barriers. *J. Clean. Prod.* **2021**, *292*, 126002. [CrossRef]
19. Abdul-Hamid, A.-Q.; Ali, M.H.; Tseng, M.-L.; Lan, S.; Kumar, M. Impeding challenges on industry 4.0 in circular economy: Palm oil industry in Malaysia. *Comput. Oper. Res.* **2020**, *123*, 105052. [CrossRef]
20. 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]
21. Alcayaga, A.; Hansen, E.G. Smart products as enabler for circular business models: The case of B2B textile washing services. In Proceedings of the 3rd PLATE 2019 Conference, Berlin, Germany, 18–20 September 2019; pp. 18–20.
22. Bocken, N.M.; Mugge, R.; Bom, C.A.; Lemstra, H.J. Pay-per-use business models as a driver for sustainable consumption: Evidence from the case of HOMIE. *J. Clean. Prod.* **2018**, *198*, 498–510. [CrossRef]
23. 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]
24. Flaherty, T.; Domegan, C.; Anand, M. The use of digital technologies in social marketing: A systematic review. *J. Soc. Mark.* **2021**, *11*, 378–405. [CrossRef]
25. Mushi, G.E.; Di Marzo Serugendo, G.; Burgi, P.Y. Digital technology and services for sustainable agriculture in Tanzania: A literature review. *Sustainability* **2022**, *14*, 2415. [CrossRef]
26. Pirola, F.; Boucher, X.; Wiesner, S.; Pezzotta, G. Digital technologies in product-service systems: A literature review and a research agenda. *Comput. Ind.* **2020**, *123*, 103301. [CrossRef]
27. Liberati, A.; Altman, D.G.; Tetzlaff, J.; Mulrow, C.; Gøtzsche, P.C.; Ioannidis, J.P.A.; Clarke, M.; Devereaux, P.J.J.; Kleijnen, J.; Moher, D. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *J. Clin. Epidemiol.* **2009**, *62*, e1–e34. [CrossRef] [PubMed]
28. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *10*, 89. [CrossRef]
29. Ellen MacArthur Foundation. What Is a Circular Economy? 2013. Available online: https://www.ellenmacarthurfoundation.org/circular-economy/infographic (accessed on 14 April 2021).
30. Franco, M.A. Circular economy at the micro level: A dynamic view of incumbents' struggles and challenges in the textile industry. *J. Clean. Prod.* **2017**, *168*, 833–845. [CrossRef]
31. Geng, Y.; Doberstein, B. Developing the circular economy in China: Challenges and opportunities for achieving 'leapfrog development'. *Int. J. Sustain. Dev. World Ecol.* **2008**, *15*, 231–239. [CrossRef]
32. Murray, A.; Skene, K.; Haynes, K. The circular economy: An interdisciplinary exploration of the concept and application in a global context. *J. Bus. Ethics* **2017**, *140*, 369–380. [CrossRef]
33. Bilitewski, B. The circular economy and its risks. *J. Waste Manag.* **2012**, *1*, 1–2. [CrossRef]
34. Spring, M.; Araujo, L. Product biographies in servitization and the circular economy. *Ind. Mark. Manag.* **2017**, *60*, 126–137. [CrossRef]
35. Go, T.F.; Wahab, D.A.; Hishamuddin, H. Multiple generation life-cycles for product sustainability: The way forward. *J. Clean. Prod.* **2015**, *95*, 16–29. [CrossRef]
36. Mont, O. Innovative approaches to optimising design and use of durable consumer goods. *Int. J. Prod. Dev.* **2008**, *6*, 227. [CrossRef]
37. Bakker, C.; Wang, F.; Huisman, J.; Den Hollander, M. Products that go round: Exploring product life extension through design. *J. Clean. Prod.* **2014**, *69*, 10–16. [CrossRef]
38. Nobre, G.C.; Tavares, E. Scientific literature analysis on big data and internet of things applications on circular economy: A bibliometric study. *Scientometrics* **2017**, *111*, 463–492. [CrossRef]
39. Van Loon, P.; Van Wassenhove, L.N. Assessing the economic and environmental impact of remanufacturing: A decision support tool for OEM suppliers. *Int. J. Prod. Res.* **2018**, *56*, 1662–1674. [CrossRef]
40. Teece, D.J. Business models, business strategy and innovation. *Long Range Plan.* **2010**, *43*, 172–194. [CrossRef]
41. Richard, W.; Peter, B. Go Downstream: The New Profit Imperative in Manufacturing. *Harv. Bus. Rev.* **1999**, *77*, 41.
42. Michelini, R.; Razzoli, R. Product-service for environmental safeguard: A metrics to sustainability. *Resour. Conserv. Recycl.* **2004**, *42*, 83–98. [CrossRef]
43. Bocken, N.M.; De Pauw, I.; Bakker, C.; Van Der Grinten, B. Product design and business model strategies for a circular economy. *J. Ind. Prod. Eng.* **2016**, *33*, 308–320. [CrossRef]
44. Dimache, A.; Roche, T. A decision methodology to support servitisation of manufacturing. *Int. J. Oper. Prod. Manag.* **2013**, *33*, 1435–1457. [CrossRef]
45. Tukker, A. Eight types of product–service system: Eight ways to sustainability? Experiences from SusProNet. *Bus. Strategy Environ.* **2004**, *13*, 246–260. [CrossRef]

46. Morlet, A.; Blériot, J.; Opsomer, R.; Linder, M.; Henggeler, A.; Bluhm, A.; Carrera, A. *Intelligent Assets: Unlocking the Circular Economy Potential*; Ellen MacArthur Foundation: Cowes, UK, 2016.
47. Valencia, A.; Mugge, R.; Schoormans, J.; Schifferstein, H. The design of smart product-service systems (PSSs): An exploration of design characteristics. *Int. J. Des.* **2015**, *9*, 13–28.
48. Baines, T.; Lightfoot, H.W. Servitization of the manufacturing firm: Exploring the operations practices and technologies that deliver advanced services. *Int. J. Oper. Prod. Manag.* **2014**, *34*, 2–35. [CrossRef]
49. Reim, W.; Parida, V.; Örtqvist, D. Product–Service Systems (PSS) business models and tactics–a systematic literature review. *J. Clean. Prod.* **2015**, *97*, 61–75. [CrossRef]
50. Kujala, S.; Artto, K.; Aaltonen, P.; Turkulainen, V. Business models in project-based firms–Towards a typology of solution-specific business models. *Int. J. Proj. Manag.* **2010**, *28*, 96–106. [CrossRef]
51. Adrodegari, F.; Saccani, N. Business models for the service transformation of industrial firms. *Serv. Ind. J.* **2017**, *37*, 57–83. [CrossRef]
52. Trevisan, A.H.; Zacharias, I.S.; Liu, Q.; Yang, M.; Mascarenhas, J. Circular economy and digital technologies: A review of the current research streams. *Proc. Des. Soc.* **2021**, *1*, 621–630. [CrossRef]
53. Rajput, S.; Singh, S.P. Industry 4.0 Model for circular economy and cleaner production. *J. Clean. Prod.* **2020**, *277*, 123853. [CrossRef]
54. Rüßmann, M.; Lorenz, M.; Gerbert, P.; Waldner, M.; Justus, J.; Engel, P.; Harnisch, M. *Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries*; Boston Consulting Group: Boston, MA, USA, 2015; pp. 54–89.
55. Bag, S.; Gupta, S.; Kumar, S. Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. *Int. J. Prod. Econ.* **2021**, *231*, 107844. [CrossRef]
56. Paton, S.; Ates, A.; Sminia, H.; Smith, M. Making sense of high value manufacturing: Relating policy and theory. *Prod. Plan. Control* **2021**, 1–12. [CrossRef]
57. Li, L. China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0". *Technol. Forecast. Soc. Change* **2018**, *135*, 66–74. [CrossRef]
58. Lee, J.; Davari, H.; Singh, J.; Pandhare, V. Industrial Artificial Intelligence for industry 4.0-based manufacturing systems. *Manuf. Lett.* **2018**, *18*, 20–23. [CrossRef]
59. Liu, M.; Ma, J.; Lin, L.; Ge, M.; Wang, Q.; Liu, C. Intelligent assembly system for mechanical products and key technology based on internet of things. *J. Intell. Manuf.* **2017**, *28*, 271–299. [CrossRef]
60. Dubey, R.; Gunasekaran, A.; Papadopoulos, T.; Childe, S.J.; Shibin, K.; Wamba, S.F. Sustainable supply chain management: Framework and further research directions. *J. Clean. Prod.* **2017**, *142*, 1119–1130. [CrossRef]
61. Agrawal, R.; Wankhede, V.A.; Kumar, A.; Luthra, S.; Huisingh, D. Progress and trends in integrating Industry 4.0 within Circular Economy: A comprehensive literature review and future research propositions. *Bus. Strategy Environ.* **2022**, *31*, 559–579. [CrossRef]
62. Abdul-Hamid, A.Q.; Ali, M.H.; Osman, L.H.; Tseng, M.L.; Lim, M.K. Industry 4.0 quasi-effect between circular economy and sustainability: Palm oil industry. *Int. J. Prod. Econ.* **2022**, *253*, 108616. [CrossRef]
63. Çetin, S.; Gruis, V.; Straub, A. Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. *Resour. Conserv. Recycl.* **2022**, *15*, 200110. [CrossRef]
64. Kalogiannidis, S.; Kalfas, D.; Chatzitheodoridis, F.; Kontsas, S. The Impact of Digitalization in Supporting the Performance of Circular Economy: A Case Study of Greece. *J. Risk Financ. Manag.* **2022**, *15*, 349. [CrossRef]
65. Ahmed, A.A.; Nazzal, M.A.; Darras, B.M. Cyber-physical systems as an enabler of circular economy to achieve sustainable development goals: A comprehensive review. *Int. J. Precis. Eng. Manuf. -Green Technol.* **2022**, *9*, 955–975. [CrossRef]
66. 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. Change* **2022**, *177*, 121508. [CrossRef]
67. Rakhshan, K.; Morel, J.C.; Daneshkhah, A. Predicting the technical reusability of load-bearing building components: A probabilistic approach towards developing a Circular Economy framework. *J. Build. Eng.* **2021**, *42*, 102791. [CrossRef]
68. Uribe-Toril, J.; Ruiz-Real, J.L.; Galindo Durán, A.C.; Torres Arriaza, J.A.; de Pablo Valenciano, J. The Circular Economy and retail: Using Deep Learning to predict business survival. *Environ. Sci. Eur.* **2022**, *34*, 2. [CrossRef]
69. Arranz, C.F.; Sena, V.; Kwong, C. Institutional pressures as drivers of circular economy in firms: A machine learning approach. *J. Clean. Prod.* **2022**, *355*, 131738. [CrossRef]
70. de Sousa Jabbour, A.B.L.; Jabbour, C.J.C.; Choi, T.M.; Latan, H. 'Better together': Evidence on the joint adoption of circular economy and industry 4.0 technologies. *Int. J. Prod. Econ.* **2022**, *252*, 108581. [CrossRef]
71. Kurniawan, T.A.; Othman, M.H.D.; Hwang, G.H.; Gikas, P. Unlocking digital technologies for waste recycling in industry 4.0 era: A transformation towards a digitalization-based circular economy in Indonesia. *J. Clean. Prod.* **2022**, *357*, 131911. [CrossRef]
72. Delpla, V.; Kenné, J.P.; Hof, L.A. Circular manufacturing 4.0: Towards internet of things embedded closed-loop supply chains. *Int. J. Adv. Manuf. Technol.* **2022**, *118*, 3241–3264. [CrossRef]
73. Rusch, M.; Schöggl, J.P.; Baumgartner, R.J. Application of digital technologies for sustainable product management in a circular economy: A review. *Bus. Strategy Environ.* **2021**, 1–16. [CrossRef]
74. Talla, A.; McIlwaine, S. Industry 4.0 and the circular economy: Using design-stage digital technology to reduce construction waste. *Smart Sustain. Built Environ.* 2022; *ahead-of-print*. [CrossRef]

75. Shevchenko, T.; Danko, Y. Circular Data Framework throughout the Whole Value Chain from Mining to Manufacturing, from Refurbishing to Recycling. In *Role of Circular Economy in Resource Sustainability*; Springer Nature: Cham, Switzerland, 2022; Volume VII, pp. 7–16. [CrossRef]
76. Patyal, V.S.; Sarma, P.; Modgil, S.; Nag, T.; Dennehy, D. Mapping the links between industry 4.0, circular economy and sustainability: A systematic literature review. *J. Adv. Manuf. Technol.* **2022**, *35*, 1–35. [CrossRef]
77. Medkova, K.; Fifield, B. *Circular Design—Design for Circular Economy*; Lahti Cleantech Annual Review; Lahti University of Applied Sciences: Lahti, Finland, 2016; p. 32.
78. Krstić, M.; Agnusdei, G.P.; Miglietta, P.P.; Tadić, S.; Roso, V. Applicability of Industry 4.0 Technologies in the Reverse Logistics: A Circular Economy Approach Based on Comprehensive Distance Based Ranking (COBRA) Method. *Sustainability* **2022**, *14*, 5632. [CrossRef]
79. Neligan, A.; Baumgartner, R.J.; Geissdoerfer, M.; Schöggl, J.P. Circular disruption: Digitalisation as a driver of circular economy business models. *Bus. Strategy Environ.* **2022**. [CrossRef]
80. Rosen, D.W. Thoughts on design for intelligent manufacturing. *Engineering* **2019**, *5*, 609–614. [CrossRef]
81. Shevchenko, T.; Saidani, M.; Danko, Y.; Golysheva, I.; Chovancová, J.; Vavrek, R. Towards a smart E-waste system utilizing supply chain participants and interactive online maps. *Recycling* **2021**, *6*, 8. [CrossRef]
82. Han, Y.; Shevchenko, T.; Qu, D. Smart E-waste Management in China: A Review. In *Congress on Intelligent Systems*; Springer: Singapore, 2022; pp. 515–533. [CrossRef]
83. Kang, K.D.; Kang, H.; Ilankoon, I.; Chong, C.Y. Electronic waste collection systems using Internet of Things (IoT): Household electronic waste management in Malaysia. *J. Clean. Prod.* **2020**, *252*, 119801. [CrossRef]
84. Fayomi, G.U.; Mini, S.E.; Chisom, C.M.; Fayomi, O.S.I.; Udoye, N.E.; Agboola, O.; Oomole, D. Smart Waste Management for Smart City: Impact on Industrialization. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *655*, 012040. Available online: https://iopscience.iop.org/issue/1755-1315/655/1 (accessed on 27 March 2021). [CrossRef]
85. Gupta, P.K.; Shree, V.; Hiremath, L.; Rajendran, S. The use of modern technology in smart waste management and recycling: Artificial intelligence and machine learning. In *Recent Advances in Computational Intelligence*; Springer: Cham, Switzerland, 2019; pp. 173–188.
86. Lenka, S.; Parida, V.; Wincent, J. Digitalization capabilities as enablers of value co-creation in servitizing firms. *Psychol. Mark.* **2017**, *34*, 92–100. [CrossRef]
87. Porter, M.E.; Heppelmann, J.E. How smart, connected products are transforming competition. *Harv. Bus. Rev.* **2014**, *92*, 64–88.
88. Curtis, S.K.; Lehner, M. Defining the sharing economy for sustainability. *Sustainability* **2019**, *11*, 567. [CrossRef]
89. Pouri, M.J.; Hilty, L.M. Digitally enabled sharing and the circular economy: Towards a framework for sustainability assessment. In *Advances and New Trends in Environmental Informatics*; Springer: Cham, Switzerland, 2020; pp. 105–116.
90. Esfandabadi, Z.S.; Diana, M.; Zanetti, M.C. Carsharing services in sustainable urban transport: An inclusive science map of the field. *J. Clean. Prod.* **2022**, *357*, 131981. [CrossRef]
91. Belk, R. Sharing versus pseudo-sharing in Web 2.0. *Anthropologist* **2014**, *18*, 7–23. [CrossRef]
92. Bocken, N.; Ingemarsdotter, E.; Gonzalez, D. Designing sustainable business models: Exploring IoT-enabled strategies to drive sustainable consumption. In *Sustainable Business Models*; Springer: Cham, Switzerland, 2019; pp. 61–88.
93. Tunn, V.; Van den Hende, E.; Bocken, N.; Schoormans, J. Digitalised product-service systems: Effects on consumers' attitudes and experiences. *Resour. Conserv. Recycl.* **2020**, *162*, 105045. [CrossRef]
94. Fishman, E. Bikeshare: A review of recent literature. *Transp. Rev.* **2016**, *36*, 92–113. [CrossRef]
95. Adrodegari, F.; Saccani, N.; Kowalkowski, C.; Vilo, J. PSS business model conceptualization and application. *Prod. Plan. Control* **2017**, *28*, 1251–1263. [CrossRef]
96. Shen, S.; Wei, Z.Q.; Sun, L.J.; Su, Y.Q.; Wang, R.C.; Jiang, H.M. The shared bicycle and its network—Internet of shared bicycle (IOSB): A review and survey. *Sensors* **2018**, *18*, 2581. [CrossRef] [PubMed]
97. Kim, H.; Cluzel, F.; Leroy, Y.; Yannou, B.; Yannou-Le Bris, G. Research perspectives in ecodesign. *Des. Sci.* **2020**, *6*, e7. [CrossRef]
98. Rymaszewska, A.; Helo, P.; Gunasekaran, A. IoT powered servitization of manufacturing–an exploratory case study. *Int. J. Prod. Econ.* **2017**, *192*, 92–105. [CrossRef]
99. Bouillass, G.; Saidani, M.; Lameh, J.; Yannou, B. Digital technologies to advance circular economy at territorial level: Challenges and solutions. In Proceedings of the IEEE 28th ICE/ITMC & 31st IAMOT Joint Conference, Nancy, France, 19–23 June 2022; Available online: https://ice-iamot-2022-conference.org/ (accessed on 27 July 2022).
100. Hein, A.M.; Jankovic, M.; Feng, W.; Farel, R.; Yune, J.H.; Yannou, B. Stakeholder power in industrial symbioses: A stakeholder value network approach. *J. Clean. Prod.* **2017**, *148*, 923–933. [CrossRef]