sustainability

MDPI

Article

Digital Twins for the Circular Economy

Anna Preut *, Jan-Philip Kopka and Uwe Clausen

Fraunhofer Institute for Material Flow and Logistics IML, 44227 Dortmund, Germany;
jan-philip.kopka@iml.fraunhofer.de (J.-P.K.); uwe.clausen@iml.fraunhofer.de (U.C.)
* Correspondence: anna.preut@iml.fraunhofer.de; Tel.: +49-231-9743-377

Abstract: Accurate information plays an important role for the circulation of materials and products. It influences the economically and ecologically successful execution of processes such as reconditioning and the corresponding supply chain management. Digitization concepts, such as digital twins, enable the relevant information to be made available to the right actor at the right time in a decentralized manner. It is assumed that digital twins will play an important role in the future and can contribute, among other things, to the successful implementation of circular economy strategies. However, there is no uniform definition of the term digital twin yet and the exploration and use of digital twins in the context of circular economy products and supply chains is still in its infancy. This article presents potential contributions of digital twins to the circularity of products and the management of circular supply chains. To this end, the derivation and validation of a definition for the term digital twin is described. A stakeholder analysis with a special focus on the processes of the individual stakeholders results in an overview of potentials and information requirements of circular supply chains for a digital twin. The paper concludes that circular supply chains can benefit from digital twins, but that there is still a need for research and development, particularly regarding product and use case-specific implementations of the concept.

Keywords: digital twin; circular economy; circular supply chain management; product life cycle; information management

Citation: Preut, A.; Kopka, J.-P.; Clausen, U. Digital Twins for the Circular Economy. *Sustainability* **2021**, *13*, 10467. https://doi.org/10.3390/su131810467

Academic Editors: Vinit Prida, Federico Adrodegari, Daniela Cristina Antelmi Pigosso and Gianmarco Bressanelli

Received: 4 August 2021
Accepted: 15 September 2021
Published: 20 September 2021

1. Introduction

Information plays an important role for decision making as well as the correct and efficient execution of processes. This also applies to decisions and processes in product and material cycles, as they accord to the goals and concept of the circular economy.

The manufacturer of a new product needs information regarding possible use cases of the respective product in order to analyse which requirements it should meet for this purpose. Repair service providers or refurbishers require, for example, information on the condition and disassembly details of a specific used product to be able to perform tests and repairs accordingly.

Information on the condition, and for example, the location of an individual product, also plays an important role in material flow management and logistics, not only in the circular economy. As a link between individual phases and actors, logistics and material flow management are essential for the implementation of material and product cycles. Unlike in the established linear economy system, take-back logistics, spare parts procurement and redistribution of reprocessed or reusable products and materials are central functional areas of logistics and material flow management in this context. Depending on the specific product, it is often impossible to predict when the use phase of a product will end due to a defect or a user decision and if or when a product will be sent for reprocessing, reuse or recycling. Return logistics, spare parts procurement and redistribution are therefore characterized by small, heterogeneous material flow quantities as well as poor predictability.

It is assumed that better cross-product lifecycle information management in supply chain networks can help to ensure that the circulation of materials and products can be successfully implemented economically and ecologically, despite special challenges such as heterogeneous, small material flows [1–6].

1.1. Characteristics of Today's Information Systems

Different characteristics of today's information systems make cross-product lifecycle information management difficult [1,7].

While the collection, acquisition and exchange of information works relatively well at the beginning of a product's life cycle (considered as product development and manufacturing phase), there is usually a break in information when a product is handed over to the end user. Existing information about the material and product is only passed on together with the product to a limited extent. With the beginning of the product's use phase, often no further information about the product is recorded and documented, and cannot be passed on accordingly [7,8].

A variety of actors with heterogeneous information systems is involved in a product life cycle, making it difficult to exchange existing information without suitable interfaces and transformation of information into exchangeable data formats [8].

In addition to technical heterogeneity, structural and semantic heterogeneity of the different information systems pose further challenges. Different structuring of the same facts (structural heterogeneity) and different interpretations of the same terms (semantic heterogeneity) as well as different knowledge backgrounds can lead to problems of understanding between the different actors [4,8–10].

Moreover, legal and organizational requirements for data protection and data security are to be considered when collecting, exchanging and using information. Without a perceivable individual advantage, stakeholders are often unwilling to share information with other stakeholders, irrespective of the technical, structural and semantic challenges mentioned above. As a result, information that has an impact on the successful circulation of materials and products is often not available [1,11–13].

1.2. Digitization Concepts, Digital Twin, Research Question

A significant development potential is still seen for digitization in the context of the circular economy [14]. Digitization concepts have the potential to enable better information management and more transparency regarding relevant information for the circulation of materials and products [1,3,4,12,14].

As an example of a corresponding digitization concept, this paper takes a closer look at the digital twin. A digital twin is a virtual representation of a physical product based on existing information about that product [15]. Established institutions and companies promote the digital twin as one of the most promising and significant information technologies of the upcoming years [16,17]. Interest in the digital twin has increased significantly over the past five to ten years, as for example the development of the number of publications per year on the topic shows, according to databases such as Google Scholar (Figure 1). The digital twin is assumed to have potential for various fields of application, including the circular economy. However, research and development in this area is still in its infancy [16,18]. This paper aims to answer the following research questions:

(1) Which information is relevant for different stakeholders in the circulation of products and materials?

(2) What is a digital twin, and how can it contribute to better information management for the circular economy?

Based on the systematic evaluation of 114 definitions and descriptions of the circular economy, Kirchherr et al. [19] define the term circular economy as follows:

> "A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city,

region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations".

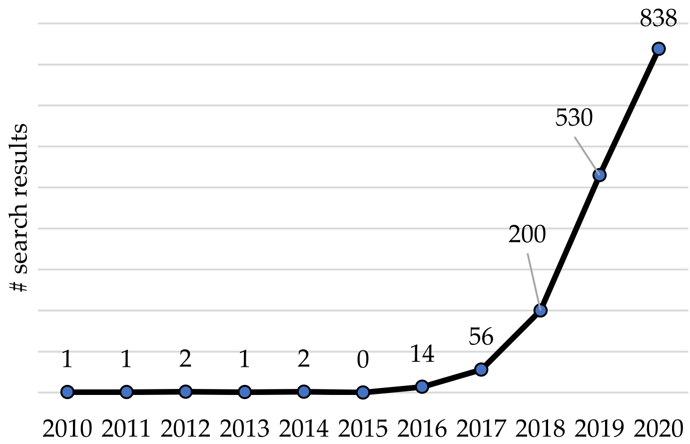

Figure 1. Number of Google Scholar search results for keyword "digital twin" in article title (any article language) 2021–2020 (last accessed 27 August 2021).

To answer the first research question, actors involved in product and material cycles of a circular economy and their respective processes are analysed. The second research question is answered by deriving and validating a definition of the term digital twin and conducting a comprehensive literature review. The methodological approach chosen for this purpose is described in more detail in Section 2. The results are summarized in Section 3 and critically discussed in Section 4. Concluding, Section 5 summarizes the key findings of this paper and presents further questions and research and development needs resulting from these findings.

2. Materials and Methods

The following two sections describe the methodological approach chosen and implemented to answer the two research questions.

2.1. Process and Stakeholder Analysis to Identify Information Requirements

To answer research question 1, a process and stakeholder analysis was conducted. As a starting point for this analysis, the circular economy systems diagram (Figure 2) of the Ellen MacArthur Foundation, a common illustration of the different biological and technical circulation options in the circular economy, was used. Only the technical circulation options were considered for the process and stakeholder analysis since the successful implementation of biological cycles depends more on the characteristics of the product and its materials than on the information management along its life cycle [20].

According to the respective circular economy processes and phases shown in the diagram, the general stakeholders of material and product cycles, which will be examined in more detail in Section 3.1, were derived as material/parts/product manufacturer, provider/distributor, user, sharing system provider, maintenance/repair service provider, re-user, refurbisher/remanufacturer, and recycler.

Literature research was conducted to find more detailed information on process flows and process related information requirements. Generic process flows for each of the identified stakeholders were mapped within a process flow diagram. Information needs of the different stakeholders that could be identified during the research on the individual process steps were summarized in tabular form. During the research, all results from reputable sources (known research institutions and companies) were considered. Accordingly, information from scientific publications and grey literature as well as from press releases and entries on the organizations' websites were included in the evaluation. The information determined by the research was supplemented in part by logical assumptions made by the authors.

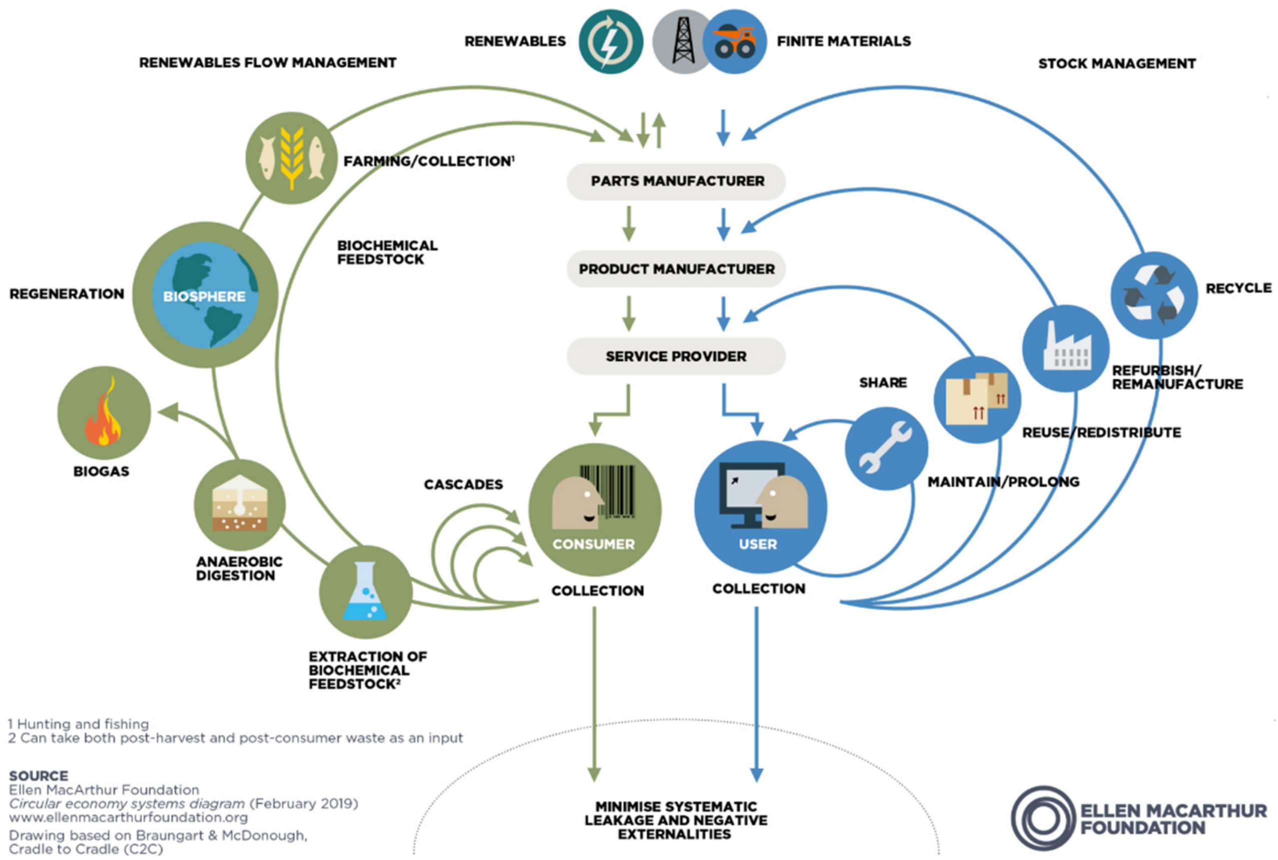

Figure 2. Circular economy system diagram [20].

2.2. Development and Validation of a Definition for the Term Digital Twin

Although the concept of the digital twin gained increasing attention over the past decade, there is no uniform definition for the term digital twin. Therefore, to address the question of what a digital twin is and how it can contribute to better information management within the circular economy, a definition for the term was established. Based on descriptions and definitions of the scientists Michael Grieves and John Vickers [15], who are widely regarded as the originators of the idea for the digital twin [15,21,22] the following working definition was set.

The digital twin is (1) a virtual collection of information. Based on this virtual information (2) a specific, planned or already existing product (3) is described from an atomic micro level to a general macro level. The digital twin contains all information about the respective product and its condition that is relevant for the management and control of the product life cycle. (4) It is a distributed, decentralized concept for managing product information (5) along the entire life cycle of the specific product. (6) It is based on a physical information link with the real product. (7) If possible, the information is transmitted in real time. (8) To enable an information link, the digital twin and its physical counterpart must be embedded in a suitable software and hardware environment.

The bracketed numbers mark eight key terms/characteristics (KCs) that the authors identified in joint discussion of the working definition. The identified KCs were used to compare the working definition with descriptions and definitions of a digital twin from other sources, and thereby validate the working definition. For the comparison digital twin descriptions and definitions in German and English language were searched. The search was conducted in Google Search and Google Scholar. Scientific publications as well as grey literature, additionally a selection of blog entries and dictionary entries on company websites were considered. The main selection criteria were that the sources described the understanding of the digital twin in certain detail in that they met basic reliability requirements in a quick check (e.g., official website of a company or research institution, check of the website's imprint). The search occurred in the period from April to September 2019. The timeliness/novelty of the publication was not given special consideration, and in certain cases, no clear publication date was given. The aim was not to include all relevant and available sources in the search and evaluation, but to find an arbitrary set number of at least ten sources for comparison. Eleven sources were found.

In order to validate the working definition, it was checked whether these eight characteristics were also included in the comparative descriptions and definitions of these eleven sources. The results of the comparison are documented in Table 1. The row totals show the matches of the respective comparative source with the working definition. The column totals display the sum of all comparative sources that match the respective key characteristic. The results of the comparison show that there are strong correlations between the working definition and the comparative descriptions and definitions.

Table 1. Documentation of the comparison of the working definition with other definitions and descriptions of the digital twin (KC, key characteristic; 1, KC occurs in the source; 0, KC does not occur in the source).

Source	KC 1	KC 2	KC 3	KC 4	KC 5	KC 6	KC 7	KC 8	∑
[23]	1	0	1	1	1	1	0	1	6
[21]	1	1	0	1	1	1	0	1	6
[24]	1	1	1	0	0	1	0	1	5
[25]	1	1	1	1	1	1	1	1	8
[26]	1	1	1	1	0	1	1	1	7
[27]	1	1	1	1	1	1	1	1	8
[28]	1	1	1	1	1	1	1	1	8
[29]	1	1	0	1	1	1	1	1	7
[30]	1	1	1	1	1	1	1	1	8
[31]	1	1	1	1	1	1	0	1	7
[32]	1	1	1	0	1	0	1	1	6
∑	11	10	9	9	9	10	7	11	

Based on the results, the working definition for the digital twin was considered validated.

Conclusions regarding the digital twin's potential for improving information management in the circular economy were drawn in the course of further literature research and by merging it with the information requirements identified in the stakeholder and process analysis.

3. Results

This section details the results of the research conducted and the research questions are answered.

3.1. Information Requirements Resulting from Process and Stakeholder Analysis

The following subsections present the results of the process and stakeholder analysis. For this purpose, generic process steps and the resulting information requirements for the circulation of products and materials are presented and illustrated for each stakeholder derived from the cycle diagram in accordance with the list in Section 2. We also discuss governmental and regulatory actors in Section 3.1.10. Although they are usually not directly represented in schematic visualisations such as the butterfly diagram referred to in this article, they play a crucial role in the becoming of the circular economy and benefit from information availability.

3.1.1. Material/Parts/Product Manufacturer

In the field of product manufacturing, a distinction can be made between the manufacturer of materials, parts, and products. Since the process and stakeholder analysis was performed at a general level and not related to a specific product, this distinction did not seem to add value. Therefore, the roles were equated in the context of the further analysis and will be referred to below only as manufacturer. When referring to a product, this description can also be equated with material or parts.

The manufacturer's task is to develop and manufacture a new product. It plays a central role in the circular economy, as decisions in development and manufacturing affect, for example, the longevity and reparability of the respective product [33]. The manufacturer's goal is to produce and sell a successful product. To achieve this, they must know the requirements of the market and customers as well as legal specifications. Maintenance and error reports, as well as sales, usage and complaint experiences of comparable products can be used in product development and manufacturing to continuously improve products, including regarding their suitability for the circular economy. Manufacturer processes and associated information requirements are summarized in Table 2.

Table 2. Manufacturer processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Product development Product manufacturing	Market and customer requirements, legal specifications, maintenance and error reports, usage and complaint reports of comparable products	Produce a successful product	User, experts, repair service provider, laws and legal guidelines

3.1.2. Provider/Distributor

The provider/distributor sells products to users. They require information on the features and functions of the products in order to be able to provide information and advice to customers in sales discussions. In the case of a purchase, the customer may need to be provided with information such as assembly, installation and operating instructions, safety instructions and information on return options and disposal along with the purchase of the product. Accordingly, the provider/distributor must have this information. The information required by the provider/distributor (Table 3) is widely similar to the information required by the user. However, purposes and involved processes differ due to the actors' different roles [34].

Table 3. Provider/distributor processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Sales Customer advisory	Technical and functional product information, assembly and installation instructions, operating and safety instructions, return and disposal options	Sell product, customer satisfaction	Manufacturer, product

3.1.3. User

To use the product, depending on type and nature of the product as well as the type of user himself, it may be necessary to install or assemble the product in some form after its receipt and before it can be used. For correct installation and use, the user needs installation and operating instructions in sufficient and understandable form. User instructions may include warnings and safety instructions, for example with information on hazardous ingredients, temperature ranges to be observed when storing and using the product, etc. [34].

In the product cycles of the circular economy, the user plays a key role. Through decisions and actions, such as the repair of a defective product or the correct selection and use of a possible take-back system, they contribute significantly to the success of the circular economy. Besides the availability of suitable take-back systems, this also requires the user to have the necessary information about which take-back points exist and which, e.g., depending on the product's condition or its location, is most suitable for the product [33]. (Table 4).

Table 4. User processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Installation/assembly Usage	Installation/assembly instructions, warnings, and safety instructions Instructions for use and maintenance	Problem free usage, obtain the intended use, maintenance	Manufacturer, provider, distributor
Return	Information on return and disposal points	Proper return and disposal of products no longer used	Manufacturer, provider, distributor

3.1.4. Sharing System Provider

The sharing system provider enables the shared use of a product by different users. As well as the provider/distributor, who sells products to users (see Section 3.1.2), they need to provide the users with information required to use the product safely and properly, e.g., installation and assembly instructions, operating and safety guidelines. They need information regarding the condition of a product in order to make sure, that the product is usable or if not to manage maintenance, repair and replacement of the product. Information on the location of an individual product can further be helpful to ensure and monitor a demand-based allocation of a large number of products of a sharing pool, e.g., to different areas or sharing stations. Information about the duration of use can, for example, enable usage-based accounting with the customer [35]. Mentioned processes and associated information requirements are summarized in Table 5.

Table 5. Sharing system provider processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Customer advisory Product provision Pool management (accounting, reallocation, maintenance . . .)	Technical and functional product information, assembly, and installation instructions, operating and safety instructions, return and disposal options, product location Information regarding product condition, usage time per user	Sell product, customer satisfaction, ensure product quality and safety	Manufacturer, provider/distributor, user, product

3.1.5. Maintenance/Repair Service Provider

Repair and maintenance processes occur during a product use phase and are intended to extend the use phase of the respective product. The processes are not associated with a change of ownership or user [36]. To repair or maintain a product, information regarding product condition (which parts need repair?) and technical product characteristics as well as for example assembly/disassembly instructions and safety information (how to perform the repair/maintenance process?) is needed. Repair and maintenance of a product can be performed by a user or a professional maintenance/repair service provider. Professional providers often request a description of the defect to be repaired for their repair orders [37–39]. Helpful condition information can also be a repair and maintenance history, which provides information about which type of maintenance and repair was performed by whom and when. Information regarding spare parts availability and sources are relevant if the maintenance and repair process includes the exchange of components.

The generic process steps and associated information requirements of maintenance/repair service providers are summarized in Table 6.

Table 6. Maintenance/repair service provider processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Maintenance/ repair	Product condition, disassembly/assembly instructions, warnings and safety instructions, instructions for maintenance, maintenance and repair history/documentation, spare parts availability and sources	Identify defect, repair and maintain a product	Manufacturer, user, product

3.1.6. Re-User

The re-user is comparable to the user (Section 3.1.3) with the difference that they reuse a used product without the product having to be checked, reprocessed, or modified in any way beforehand. They may receive the product from a relative, for example, or at a flea market or online marketplace. In comparison to the user (Section 3.1.2), the re-user owns and uses an already used product outside of a supporting business model or system such as a product-service-system. Additionally, there is no general practice regarding the amount or nature of information passed on to the re-user.

In order to use the product, they need the same information as the user of a new product. Additionally, information regarding traces of usage, defects and resulting function limitations as well as safety hazards would be desirable. That information is at least of interest when it comes to the purchase decision of a used product. Similar to the user of a new product (Section 3.1.7) they need information regarding the availability of take-back-systems at the end of the use phase to keep the product in cycle [34]. (Table 7)

Table 7. Re-user processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Installation/ assembly	Installation/assembly instructions, warnings and safety instructions	Problem free usage, obtain the intended use, maintenance	Manufacturer, provider, distributor, previous user
Usage	Instructions for use and maintenance, information regarding product condition (e.g., defects and resulting function limitations)		Previous user, product
Return	Information on return and disposal points	Proper return and disposal of products no longer used	Manufacturer, provider, distributor, take-back-system provider

3.1.7. Refurbisher/Remanufacturer

The refurbisher/remanufacturer can be the original manufacturer, a company contracted by the manufacturer or also a manufacturer-independent company. It processes used or defective products after the end of a use phase. To this end, the products are reconditioned such that they reach a certain quality level (e.g., functional or as good as new) [36,40]. The refurbishing/remanufacturing of a product includes the steps testing, disassembly, cleaning, replacement or repair of components, and finally the reassembly and final testing of the reconditioned product [41–44]. The purpose of the inspection is to record and document the condition of the products being reconditioned as they enter and leave the refurbishing/remanufacturing. Testing is performed with regard to function and safety [42,44]. Based on the quality of the information provided to the refurbisher/remanufacturer, they can be enabled to utilize technological advances such as augmented reality (AR) to their full potential and significantly streamline the refurbishment/remanufacturing process [45].

For proper testing of a product's condition and identification of defects, the refurbisher/remanufacturer needs information on technical product characteristics and intended product functions/usage. Disassembly and cleaning require information such as disassembly and safety instructions, e.g., notes on chemicals and items that should not be brought into contact with the product. To repair and replace components of the product, information to identify the single components and check spare parts availability, such as product/component ID or the product/spare part provider, are needed. Additionally, assembly instructions are necessary to reassemble the product at the end of the refurbishing/remanufacturing properly. Refurbisher/remanufacturer processes and information requirements are summarized in Table 8.

Table 8. Refurbisher/remanufacturer processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Testing	Technical and functional characteristics of the product	Identify product condition and causes of potential errors, procure needed spare parts, refurbish/remanufacture product	Manufacturer, provider/distributor, user, product
Disassembly and cleaning	Disassembly and cleaning instructions		
Replacement/repair of components	Product/component IDs, spare parts availability and sources		
Reassembly	Assembly instructions		

3.1.8. Recycler

The recycler recovers secondary materials for the production of new products from products that are no longer used and are disposed of instead. To do this, the products are often first broken down into their components by disassembly. The individual components are then sorted according to material type. Composite materials are separated and shredded using mechanical-physical processes. The separated materials are then sorted again to produce homogeneous quantities of as high a quality as possible. These are cleaned and processed by shaping processes into secondary material, e.g., in the form of blocks or granules [34,46–48].

Disassembly instructions and information on the material composition of individual components are helpful for disassembly and sorting of products (Table 9).

Table 9. Recycler processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Disassembly Sorting Cleaning Secondary Material production	Disassembly instruction, Material type and characteristics, critical ingredients	Prepare products and gain homogeneous material quantities/high quality secondary material	Manufacturer, user, product

3.1.9. Logistics Service Provider

The logistics service provider plays a central role within the product cycle, within the stakeholder-specific processes described above, but in particular, as a link between the processes of the different stakeholders. Logistics accompanies the product along the entire cycle, such as in the form of transports between the individual stakeholders, the procurement of spare parts or the distribution of products from a sharing provider. However, the processes of product return and spare parts management are to be considered thoroughly at this point. Reverse flows in the circular economy can be characterized by a high degree of heterogeneity, small scale and unpredictability, and thus place great requirements on the flexibility and adaptability of the logistics services [49].

For economic circulation of products and materials appropriate flows of input products to re-use, repair, refurbishing/remanufacturing and recycling processes are needed. In order to be reused, reconditioned or recycled, products must be captured by suitable take-back-systems and brought to the next, appropriate cycle actor [46,50]. To manage associated transport and storage processes and to match existing cycle capacities (e.g., regarding recycling and refurbishing locations) and products, information regarding the condition of a specific product and its location is needed besides processes such as transport, storage and handling of products within and between different cycle phases (Table 10).

Table 10. Logistics Service provider processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Transport, storage and handling of products	Information regarding product specifications and product condition (including location)	Manage the product to be with the right stakeholder at the right time, suitable transport, storage and handling of the product	All actors and processes involved in the product lifecycle, product

3.1.10. Governmental and Regulatory Actors

Governmental and regulatory actors are not represented within the butterfly diagram but unquestionably important to the circular economy and for the reason added as a stakeholder. Government actors can use laws, investment, research programs, and other incentives to promote a sustainable economy and punish harmful behaviour of the individual cycle actors [33].

To be able to monitor the implementation of legal requirements and guidelines, different information about the product life cycle can be interesting for them (Table 11). Generally, governmental and regulatory actors are believed to need access to a wide variety of data in order to fulfil tasks such as market surveillance [34]. With regard to the objectives associated with the waste pyramid, which plays a central role in the context of circular economy legislation, information on whether and to what extent a product is shared, reused, refurbished/remanufactured, recycled or landfilled, for example, could be of interest [6].

Table 11. Governmental and Regulatory processes and associated information requirements.

Process Steps	Required Information	Purpose	(Potential) Information Source
Monitor	Information regarding product specifications and product lifecycle	Enforce law	All actors and processes involved in the product lifecycle

3.2. How the Digital Twin Can Contribute to Improved Information Management in the Circular Economy

As described in Section 2.2, the digital twin is a virtual collection of information regarding a specific product and its entire lifecycle—from the design phase to end-of-life management, e.g., in terms of recycling. It enables visualization of design parameters and status data of a real product based on its data model. In case of changes in the state of the real product, its virtual image can be automatically updated through near-real-time transmission and evaluation of sensor data. The digital twin thus enables direct and vivid monitoring of its real counterpart. Information can be exchanged across different processes and actors and throughout the entire life cycle. Processes and product condition become more transparent and traceable [16,25].

The stakeholders described above can add relevant information to this information collection and extract the information they need for the successful and efficient implementation of their respective processes. Certain information requirements described in

Section 3.1 and summarized in Table 2 through Table 11. can be served directly by the digital twin of a single product. Other added values, e.g., the optimization of spare parts management and transportation planning, can result from the integration of the digital twin into higher-level information and management systems, such as procurement management, warehouse management and transportation management systems, or global enterprise resource planning systems. Potentials and benefits of the digital twin resulting from higher transparency and traceability are described in the following sections.

3.2.1. Improvement of Product Development and Manufacturing

The information collected during a product life cycle can be used for the development of new products, where it can lead to improvements in product design. From life cycle data of existing products, for example, conclusions can be drawn about design requirements regarding durability, cyclability and user behaviour for new products. In the production phase, the digital twin can contribute to faster processing of customized orders and the automation of processes [16,35,45,51–53].

3.2.2. Reduction of Incorrect Use and Thus Shortened Product Life or Waste of Resources

The data collected during the use and operation of products may be used to optimize the performance of products and to detect incorrect user behaviour. The information can be used, for example, in the context of sharing systems to control the correct use of products and to ensure the longest possible usability. The digital twin can help users to gain a better understanding of the functions and correct handling of a product. Based on the condition data of the digital twin, the user can also be informed about necessary maintenance and repairs that contribute to the longest possible usability of the product [35,51,53].

3.2.3. Enabling Information-Based, Decentralized Decision-Making for Product and Material Flow Management

The digital twin can be used to optimize the tracking and management of returns of products that are no longer in use. Based on the condition and location data the products can be better tracked and returns can be forecast. The information from the digital twin can thus be used to improve logistical and technical structures of return systems and overall product and material flow management within the circular economy. This makes small-scale and heterogeneous material flows more manageable. Based on detailed condition and defect information, decisions as to whether a product can or should be directly reused, refurbished/remanufactured or recycled at the end of a use phase can be made decentrally. This can, for example, reduce unnecessary transports between different stakeholders [54].

3.2.4. Better Conditions for Executing Recycling, Refurbishing, Remanufacturing, Repairs and Re-Use

Uncertainty about the exact condition of a product at the end of a use phase can be a barrier to resale to a private end user or a re-distributor [55]. The digital twin can increase transparency and trust between the different actors and facilitate the purchase decision. As part of the implementation of recycling, refurbishing, remanufacturing and repair, the digital twin can contribute to optimizing sorting, disassembly and inspection processes. In the optimum case, for example, the inspection process can be significantly shortened or even skipped, as the digital twin contains all the information that could be obtained through an inspection [16,54].

3.2.5. Enabling Circular Economy Business Models

Based on the increased transparency along the entire product lifecycle provided by the digital twin, new business models and services can be developed and offered [35,54]. Currently, the most widely used and discussed options for this are needs-based, predictive maintenance and repair services. However, other areas of application are also conceivable, e.g., in the context of sharing systems, for the optimal monitoring and distribution of a sharing provider’s products.

As the analysis of stakeholders and their processes in Section 3.1 underlines, the economically and ecologically successful implementation of product and material circulation is a joint task of all stakeholders involved. By increasing transparency and linking different sources of information, the digital twin can strengthen and improve trust and collaboration between the different stakeholders.

4. Discussion

Based on the results presented, it becomes obvious that information plays a central role in and for the successful implementation of the circular economy, as it does in all areas of our daily lives. It forms the basis for the successful execution of processes and the economic and sustainable management of dynamic, heterogeneous and small-scale product and material flows. The various stakeholders of product and material cycles have different information requirements. In most cases, the information required in each case is likely not to be found with just one other stakeholder but is distributed among many different stakeholders and information sources. The digital twin can contribute to better acquisition, consolidation, and provision of the relevant information at the relevant points in the cycle. It can thus contribute to more transparency and better collaboration between different cycle actors. By integrating it into higher-level information systems or the information systems of the individual stakeholders, many economic benefits, and new opportunities for the successful further transformation to the circular economy are conceivable.

The results can be seen as a first step on the path of further research into the potential of the digital twin and other cross-product lifecycle information management systems for the circular economy. The analysis of stakeholder processes and related information requirements was performed independent of the individual product using literature research and conclusions based on this research. It can be assumed that the information requirements of the individual actors differ to varying degrees in terms of content and level of detail depending on the type and nature of a product. For certain products, the consideration of certain actors considered in the cycle management of the respective product is probably not relevant at all, since the products are not eligible for refurbishing or recycling per se, for example. A product-specific analysis is therefore required for more precise statements regarding the requirements and potential of the digital twin.

The information requirements presented do not automatically equate to missing information. Particularly in closed product loops, in which the manufacturer of a product carries out its refurbishing/remanufacturing, for example, it is expected that the availability of information regarding the product is fundamentally higher than in an open loop, in which a manufacturer-independent actor carries out reconditioning or recycling.

For further research and implementation as well as resulting more concrete statements on the potential of digital twins in the context of the circular economy, more research standardization is needed in different areas. The challenges for today’s information management described in the introduction, such as a variety of heterogeneous information systems and a lack of trust and cooperativeness between different stakeholder, also complicate the development and implementation of a digital twin. Questions of data protection and data security must be clarified, as must the ability to integrate a digital twin into the processes and heterogeneous information systems of different stakeholders. The definition of roles and associated access rights to the digital twin as well as standardization might help here.

The realisation of a digital twin requires additional IT infrastructure and processes. It causes corresponding resource consumption during implementation and use, e.g., through the construction of hardware for data storage and exchange. By analysing and comparing the resources required for the implementation and use of digital twins and the resources that can be saved by using digital twins, the potentials of the digital twin for the circular economy must be made quantifiable—both in economic and ecological terms. It is likely that the results of cost analyses and cost–benefit considerations for digital twins of different product types will differ greatly (e.g., inexpensive, short-lived product vs. high-quality, long-lived product), since, for example, the product-specific reuse and recycling options and the correlating economic and ecological benefits will differ. Additionally, the prerequisites for the development and implementation of a digital product twin depend on other factors such as the product design, and if applicable, the product's existing IT connections.

5. Summary/Conclusions

In this paper, we described the challenges and importance of information in material flow management with special focus on the processes and stakeholders of the circular economy. In this context, we introduced the digital twin as a digitization concept to enable relevant product-information being available to the right stakeholder at the right time. We approached a definition of the term digital twin, and based on the Ellen MacArthur foundation's circular economy/butterfly diagram (Figure 2), described the typical stakeholders and their respective processes in material and product cycles of the circular economy. In particular, information requirements in individual process steps of the different stakeholders were considered.

The type and variety of information requirements presented show that the digital twin has the potential to contribute to better circulation of materials and products. However, from a sustainability perspective, as discussed in Section 4, it is necessary to further examine how great the potential is to improve material and product circulation by using a digital twin and thus to preserve natural resources. The authors assume that a valid answer to this question can only be found in the practical implementation and performance testing of the digital twin in a specific material or product cycle. It is expected that the potential and the useful level of information detail of a digital twin will differ greatly depending on the type of product. Therefore, further research is particularly relevant regarding this aspect of digital twins since they are presented as potential solutions to sustainability-related challenges such as the circular economy transition.

Author Contributions: Conceptualization, A.P., J.-P.K.; Investigation, A.P.; Methodology, A.P., J.-P.K.; Writing—original draft, A.P., J.-P.K.; Writing—review and editing, A.P., J.-P.K., U.C.; supervision, U.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported as Fraunhofer Cluster of Excellence Circular Plastics Economy CCPE.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Berg, H.; Wilts, H. Digital platforms as market places for the circular economy—requirements and challenges. In *Nachhaltigkeits Management Forum | Sustainability Management Forum*; Springer: Berlin/Heidelberg, Germany, 2018; Volume 27, pp. 1–9.
2. González-Sánchez, R.; Settembre-Blundo, D.; Ferrari, A.M.; García-Muiña, F.E. Main Dimensions in the Building of the Circular Supply Chain: A Literature Review. *Sustainability* **2020**, *12*, 2459. [CrossRef]
3. Pagoropoulos, A.; Pigosso, D.C.A.; McAloone, T.C. The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Procedia CIRP* **2017**, *64*, 19–24. [CrossRef]
4. Sillanpää, M.; Ncibi, C. *The Circular Economy: Case Studies about the Transition from the Linear Economy*; Elsevier Science: Amsterdam, The Netherlands, 2019; ISBN 9780128152683.
5. Rudolph, C. Geschäftsmodell Circular Economy: Gegenwart und Zukunft der (erweiterten) Kreislaufwirtschaft. In *CSR und Geschäftsmodelle*; Bungard, P., Ed.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 123–137, ISBN 978-3-662-52881-5.
6. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels. 2020. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF (accessed on 30 March 2021).
7. Weetman, C. *A Circular Economy Handbook for Business and Supply Chains: Repair, Remake, Redesign, Rethink*; Kogan Page Publishers: London, UK, 2016; ISBN 9780749476762.
8. Bleiholder, J.; Schmid, J. Datenintegration und Deduplizierung. In *Daten-und Informationsqualität*; Hildebrand, K., Gebauer, M., Hinrichs, H., Mielke, M., Eds.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2018; pp. 121–140, ISBN 978-3-658-21993-2.

9. Piro, A.; Gebauer, M. Definition von Datenarten zur konsistenten Kommunikation im Unternehmen. In *Daten-und Informationsqualität*; Hildebrand, K., Gebauer, M., Hinrichs, H., Mielke, M., Eds.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2018; pp. 141–153, ISBN 978-3-658-21993-2.
10. Bruhn, M. Integrierte Kommunikation. In *Unternehmenskommunikation*; Meckel, M., Schmid, B.F., Eds.; Gabler: Wiesbaden, Germany, 2008; pp. 513–556, ISBN 978-3-8349-0973-2.
11. Al-Rakhami, M.S.; Al-Mashari, M. A Blockchain-Based Trust Model for the Internet of Things Supply Chain Management. *Sensors* **2021**, *21*, 1759. [CrossRef] [PubMed]
12. Yang, S.; Aravind Raghavendra, M.R.; Kaminski, J.; Pepin, H. Opportunities for Industry 4.0 to Support Remanufacturing. *Appl. Sci.* **2018**, *8*, 1177. [CrossRef]
13. Schwinn, K. Informationsmanagementprozesse im Unternehmen. In *Daten-und Informationsqualität*; Hildebrand, K., Gebauer, M., Hinrichs, H., Mielke, M., Eds.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2018; pp. 253–268. ISBN 978-3-658-21993-2.
14. Henzelmann, T.; Büchele, R.; Andrae, P.; Wiedemann, A.; Bundesministerium für Umwelt. Naturschutz und nukleare Sicherheit. In *GreenTech Made in Germany 2018: Umwelttechnik-Atlas für Deutschland*; Bundesministerium für Umwelt: Berlin, Germany, 2018.
15. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems New Findings and Approaches. In *Transdisciplinary Perspectives on Complex Systems New Findings and Approaches*; Kahlen, F.-J., Flumerfelt, S., Alves, A., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 85–113, ISBN 978-3-319-38754-3.
16. Tao, F.; Zhang, M.; Nee, A.Y.C. *Digital Twin Driven Smart Manufacturing*; Academic Press: Cambridge, MA, USA, 2019; ISBN 9780128176306.
17. Gartner, Inc. *Gartner 2018 Hype Cycle for IT in GCC Identifies Six Technologies That Will Reach Mainstream Adoption in Five to 10 Years*; Gartner, Inc.: Stamford, CT, USA, 2018.
18. Voell, C.; Chatterjee, P.; Rauch, A.; Golovatchev, J. How Digital Twins Enable the Next Level of PLM—A Guide for the Concept and the Implementation in the Internet of Everything Era. In *Product Lifecycle Management to Support Industry 4.0*; Chiabert, P., Bouras, A., Noël, F., Ríos, J., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 238–249, ISBN 978-3-030-01613-5.
19. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
20. Ellen MAcArthur Foundation. Infographic. Circular Economy Systems Diagram. Available online: https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic (accessed on 26 June 2020).
21. Macchi, M.; Roda, I.; Negri, E.; Fumagalli, L. Exploring the role of Digital Twin for Asset Lifecycle Management. *IFAC-PapersOnLine* **2018**, *51*, 790–795. [CrossRef]
22. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine* **2018**, *51*, 1016–1022. [CrossRef]
23. Anderl, R.; Haag, S.; Schützer, K.; Zancul, E. Digital twin technology—An approach for Industrie 4.0 vertical and horizontal lifecycle integration. *Inf. Technol.* **2018**, *60*, 125–132. [CrossRef]
24. Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik. Smarte Fabrik 4.0—Digitaler Zwilling, Berlin. 2017. Available online: https://www.ipk.fraunho-fer.de/con-tent/dam/ipk/IPK_Hauptseite/dokumente/themenblaetter/vpe-themenblatt-digitaler-zwilling.pdf (accessed on 20 August 2019).
25. Kuhn, T. Digitaler Zwilling. *Informatik-Spektrum* **2017**, *40*, 440–444. [CrossRef]
26. Schwede, C. *Das entscheidet mein digitaler Zwilling*; Fraunhofer-Institut für Materialfluss und Logistik: Dortmund, Germany, 2017.
27. Stuecka, R. Digitaler Zwilling in der Produktion: Von der digitalen Planung bis zum physischen Produkt und zurück. Available online: https://www.ibm.com/de-de/blogs/think/2017/04/21/digital-twin/ (accessed on 26 July 2021).
28. Grösser, S. Digitaler Zwilling. Available online: https://wirtschaftslexikon.gabler.de/definition/digitaler-zwilling-54371/version-277410 (accessed on 13 April 2019).
29. Institute for Information Management in Engineering. Beyond the Digital Twin-Making Analytics Come Alive. In *visIT: Industrial IoT—Digital Twin*; Beyerer, J., Ed.; Institute for Information Management in Engineering: Karlsruhe, Germany, 2018; pp. 4–5.
30. Usländer, T. Engineering of Digital Twins. Available online: https://www.iosb.fraunhofer.de/servlet/is/81767/ (accessed on 23 July 2019).
31. Talkhestani, B.A.; Jazdi, N.; Schloegl, W.; Weyrich, M. Consistency check to synchronize the Digital Twin of manufacturing automation based on anchor points. *Procedia CIRP* **2018**, *72*, 159–164. [CrossRef]
32. Defense Acquisition University. Digital Twin. Available online: https://www.dau.mil/glossary/Pages/Glossary.aspx#!both|D|27349 (accessed on 13 April 2019).
33. Fennemann, V.; Hohaus, C.; Kopka, J.-P. Moving in Circles: Logistics as Key Enabler for a Circular Economy. 2018. Available online: http://publica.fraunhofer.de/dokumente/N-502288.html (accessed on 30 March 2021).
34. Adisorn, T.; Tholen, L.; Götz, T. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. *Energies* **2021**, *14*, 2289. [CrossRef]
35. 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]
36. Walther, G. *Nachhaltige Wertschöpfungsnetzwerke: Überbetriebliche Planung und Steuerung von Stoffströmen entlang des Produktlebenszyklus*; Springer: Berlin/Heidelberg, Germany, 2010; ISBN 9783834922281.

37. Bosch. Ihr Online-Reparaturauftrag. Available online: https://repair.bosch-diy.com/de/de/onlinerepair/diy/desktop/get/repair (accessed on 26 March 2021).
38. Acer. Online-Service für Kunden. Available online: http://customercare.acer-euro.com/customerselfservice/CaseBooking.aspx?CID=DE&LID=GER&OP=1 (accessed on 26 March 2021).
39. Saturn. Reparaturauftag Erstellen. Available online: https://hilfe.saturn.de/app/answers/detail/a_id/4784/~{}/reparaturauftrag-erstellen (accessed on 26 March 2021).
40. British Standards Institution (BSI). *Design for Manufacture, Assembly, Disassembly and End-of-Life Processing (MADE)—Terms and Definitions*; Beuth Verlag GmbH: Berlin, Germany, 2009; (BS 8887-2:2009-04-30).
41. Deutsches Institut für Normung DIN. *Fertigungsverfahren Zerlegen- Einordnung, Unterteilung, Begriffe*; Beuth Verlag GmbH: Berlin, Germany, 2003; (DIN 8591:2003-09).
42. Verein Deutscher Ingenieure VDI. *Recycling of Electrical and Electronical Equipment-Re-use*; Verein Deutscher Ingenieure VDI: Harzgerode, Germany, 2014; (Guideline 2343).
43. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Deutsches Ressourceneffizienzprogramm II: Programm zur Nachhaltigen Nutzung und zum Schutz der Natürlichen Ressourcen. 2016. Available online: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/progress_ii_broschuere_bf.pdf (accessed on 26 March 2021).
44. Ulrike Lange. Kurzanalyse Nr. 18: Ressourceneffizienz Durch Remanufacturing-Industrielle Aufarbeitung von Altteilen. 2017. Available online: https://www.ressource-deutschland.de/fileadmin/user_upload/downloads/kurzanalysen/VDI_ZRE_Kurzanalyse_18_Remanufacturing_bf.pdf (accessed on 26 March 2021).
45. Subramoniam, R.; Sundin, E.; Subramoniam, S.; Huisingh, D. Riding the Digital Product Life Cycle Waves towards a Circular Economy. *Sustainability* **2021**, *13*, 8960. [CrossRef]
46. Hagelüken, C. Bedeutung des EU Kreislaufwirtschaftspakets für das Metallrecycling. *Chem. Ing. Tech.* **2017**, *89*, 17–28. [CrossRef]
47. Förstner, U.; Köster, S. *Umweltschutztechnik, 9. Auflage*; Springer Vieweg: Berlin, Germany, 2018; ISBN 978-3-662-55163-9.
48. Martens, H. Recyclingtechnik. In *Handbuch Konstruktionswerkstoffe: Auswahl, Eigenschaften, Anwendung*; Moeller, E., Ed.; Hanser Publications: München, Germany, 2014; pp. 881–910, ISBN 978-3-446-43590-2.
49. The Circular Economy 100 (CE100) Programme. Waste Not, Want Not: Capturing the Value of the Circular Economy through Reverse Logistics. 2016. Available online: https://www.dpdhl.com/en/trends-in-logistics/studies/circular_economy.html (accessed on 8 September 2021).
50. Verein Deutscher Ingenieure VDI. *Recycling of Electrical and Electronical Equipment-Logistics*; Verein Deutscher Ingenieure VDI: Harzgerode, Germany, 2010; (Guideline 2343).
51. Antikainen, M.; Uusitalo, T.; Kivikytö-Reponen, P. Digitalisation as an Enabler of Circular Economy. *Procedia CIRP* **2018**, *73*, 45–49. [CrossRef]
52. Huber, D.; Kaiser, T. Wie das Internet der Dinge neue Geschäftsmodelle ermöglicht. In *Industrie 4.0*; Reinheimer, S., Ed.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2017; pp. 17–27, ISBN 978-3-658-18164-2.
53. MacArthur, E.; Waughray, D. *Intelligent Assets: Unlocking the Circular Economy Potential*; Ellen MacArthur Foundation: Cowes, UK, 2016.
54. DHL. Digital Twins in Logistics: A DHL Perspective on The Impact of Digital Twins on The Logistics Industry. 2020. Available online: https://dpdhlcsiace.secure.force.com/DHLPageCampaignRegistration?FormId=39 (accessed on 12 September 2021).
55. Tunn, V.S.C.; van den Hende, E.A.; Bocken, N.M.P.; Schoormans, J.P.L. Digitalised product-service systems: Effects on consumers' attitudes and experiences. *Resour. Conserv. Recycl.* **2020**, *162*, 105045. [CrossRef]