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# Digital Twins within the Circular Economy: Literature Review and Concept Presentation

**Janine Mügge** *, **Anne Seegrün**, **Tessa-Katharina Hoyer**, **Theresa Riedelsheimer** and **Kai Lindow**

Fraunhofer Institute for Production Systems and Design Technology IPK, 10587 Berlin, Germany; kai.lindow@ipk.fraunhofer.de (K.L.)
* Correspondence: janine.muegge@ipk.fraunhofer.de; Tel.: +49-30-39006-299

**Abstract:** Digital twins offer a promising approach to sustainable value creation by providing specific life cycle data and enabling the monitoring and implementation of circular economy strategies throughout the product's life cycle. By analyzing product, component, and material data, as well as process data, it is possible to create transparency throughout a product's life cycle, build a data-driven product ecosystem, and establish new business and value creation models, from SMEs to large enterprises. This paper identifies application scenarios, their technological readiness level, and the challenges of digital twins for the circular economy in the manufacturing industry based on a systematic literature review. Gaps such as ensuring a continuous flow of information and taking into account the different levels of digitalization of companies are identified. As a main result, a holistic concept for the scoping of a digital twin for the circular economy is presented. One specific use case for end-of-life decision-making is elaborated upon. It is shown that the circular economy can be supported by digital twin data, especially for the optimal decision on end-of-life vehicles.

**Keywords:** digital twin; circular economy; sustainability

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## 1. Introduction

In recent years, the imperative of sustainability has garnered increasing attention and now stands as an indispensable objective in European but also global political agendas. With the European Green Deal and the United Nations (UN) Sustainable Development Goals, the vision of a greenhouse gas-neutral and resource-efficient economy has been established in politics [1]. One approach to supporting politics in the field of more resource-efficient value creation is to move from a linear to a circular economy (CE). CE pursues the goal of acting in a resource-conserving manner by, among other steps, extending a product's lifetime and keeping components and materials in the cycle [2]. However, the exchange of information is a major challenge due to the involvement of a large number of stakeholders and heterogeneous information systems, which complicates coordination and transparency. Effective information exchange is thus crucial to ensuring the success and efficiency of a CE. This ensures that all relevant stakeholders throughout the product and material cycle receive the necessary information to align their decisions with the CE principles. While the exchange of information usually works quite well up to the start of a product's use, the transfer of information is interrupted from the moment the product is handed over to the end user. Information regarding the product, its components, and its materials is often not transmitted. In addition, data on usage behavior, maintenance and repair work, and forecasts about the end of the product's service life are often missing. However, repair service providers, remanufacturers, or dismantlers require information about the condition of the product to conduct repairs or decide whether a component is suitable for reuse [3].

Digital technologies such as the digital twin (DT) can contribute to a data-driven implementation of CE by processing relevant information about individual assets for relevant stakeholders at the right time throughout the product lifecycle (PCL). The concept of a DT for CE is a promising approach for establishing a data-driven ecosystem that enables new business and value creation models, from SMEs to large enterprises [3,4]. Currently, this topic is being explored in several international research projects, such as the German project Catena-X [5] or RECLAIM [6].

However, there is no overarching analysis of the actual potential and readiness of DTs for CE. In this paper, the potential and current sustainability-oriented application scenarios of DTs for CE throughout the PLC are identified from a holistic perspective and evaluated in terms of their technology readiness level (TRL). In particular, considerations of its environmental sustainability are analyzed. To evaluate the state of the art of DTs for CE in the manufacturing industry, a systematic literature review (SLR) was conducted. Within the SLR, the following research questions (RQ) are addressed:

- RQ 1: What are the challenges of DTs for CE in the manufacturing industry?
- RQ 2: What are the application scenarios of DTs for CE in the manufacturing industry?
- RQ 3: In which phases of the PLC are DTs for CE primarily used?
- RQ 4: What is the TRL of DT applications?
- RQ 5: How can stakeholders be supported with the right data and information at the end of a vehicle's life to enable better decision-making?

To answer these RQs, an SLR was conducted first, and based on the results, a concept for a DT for CE was ascertained. This concept was further elaborated through the example of the end-of-life (EoL) decision support use case.

## 2. Methods and Approaches

To address the RQs, an in-depth understanding of the status of DTs for CE is initially established by conducting a SLR using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method [7].

To identify relevant results, the following search term was defined in the Scopus and Web of Science databases, which are two of the leading multiple databases for scientific research:

- Scopus: TITLE-ABS-KEY ("digital twin*" AND "circular*");
- Web of Science: TITLE-ABS-KEY ("digital twin*" AND "circular*").

A total of 260 papers were initially identified through the database search in Scopus and Web of Science, with 79 duplicates (as of the last database search in January 2024). The selection process is detailed in Figure 1. In the first step, the papers were categorized based on RQ 1, focusing on their industry relevance. Publications that lacked a focus on the manufacturing industry (reason 1), were not available in German or English (reason 2), or did not specifically address DT for CE (reason 3) were excluded. Subsequently, the remaining 49 abstracts underwent a thorough evaluation for their relevance as part of the full-text analysis. After a thorough examination of the full texts, an additional 18 publications lacking specific references to DT for CE were excluded. Consequently, 31 publications met the criteria for detailed analysis.

Based on the SLR, challenges and use cases for a DT for CE are identified. The application scenarios are grouped into clusters based on their similarity and summarized into use cases accordingly [8]. These are finally located as application scenarios in a conceptual model design for a DT for CE throughout the PLC. Building on this, a specific use case for decision support in EoL treatment is further elaborated and described in detail.

The findings from the literature search outlining the potential and application areas of DT for CE throughout the entire PLC are presented in the subsequent chapter.

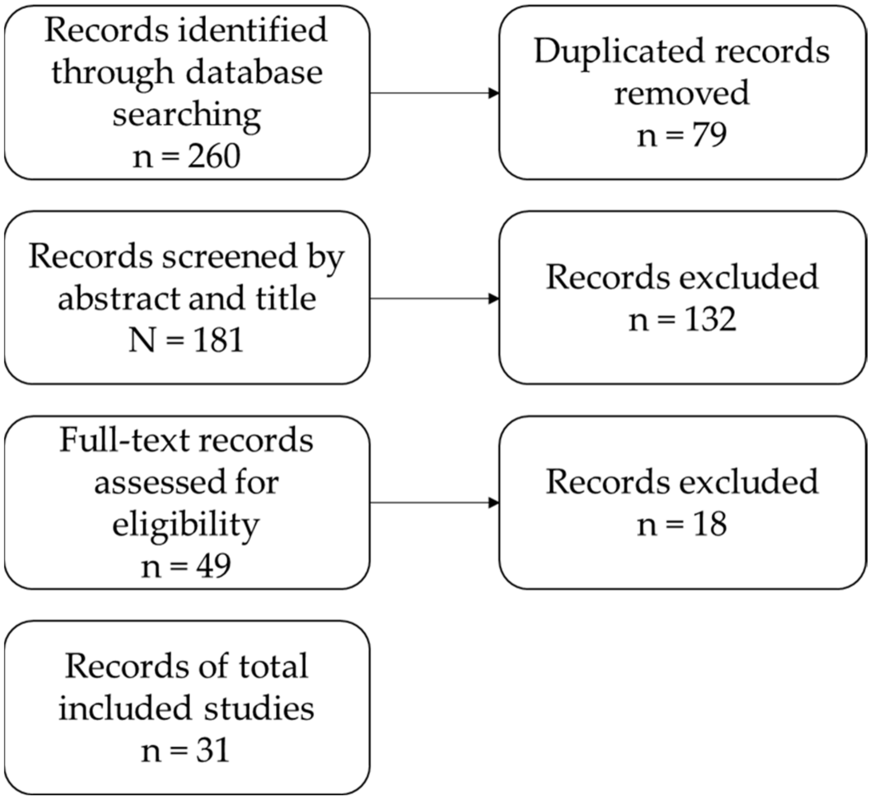



**Figure 1.** Selection process for the systematic literature review.

## 3. Literature Overview

The publication dates of the 31 relevant publications are depicted in Figure 2. The earliest paper emerged in 2018, and a continuous upsurge in publications has been observed since 2020. More than half of these publications surfaced within the last two years. The literature review highlights that the overall number of papers addressing the topic of DT for CE in manufacturing remains relatively low. In contrast, there are 26,840 papers solely addressing the term 'digital twin*' while 'circular*' yields 914,426 papers. However, the rising number of publications in the context of DT for CE, particularly in the last two years, signifies a growing interest and relevance in this topic, emphasizing its continuous development and highlighting that this research area is still in its formative stages.

In order to answer RQ 1–3, a detailed analysis of the full papers was conducted. Concerning RQ 2, the papers were sorted through the PLC to determine the primary phase of DT application, where its data and insights contribute to value addition. Therefore, the PLC is divided into three main stages: beginning-of-life (BoL), middle-of-life (MoL), and end-of-life (EoL). BoL encompasses product planning, development, and production; MoL includes distribution, utilization, and service; and EoL involves activities such as reuse, remanufacture, recycling, and recovery [9].

To address RQ 3, the TRL of the published research was evaluated using the following classification [10]:

- TRL 1: Basic principles observed (e.g., SLR, survey);
- TRL 2: Technology concept formulated (e.g., conceptual framework);
- TRL 3: Experimental proof of concept (e.g., validated conceptual framework);
- TRL 4: Technology validated in the lab;
- TRL 5: Technology validated in a relevant environment.

Furthermore, the publications were analyzed and clustered based on Potting et al.'s framework of nine R-strategies. Hence, the following classification is used [11]:

- Smarter product use and manufacture
  - R0 Refuse: Make the product redundant by abandoning its functions or by offering the same function with a radically different product;
  - R1 Rethink: Make product use more intensive;
  - R2 Reduce: Increase efficiency in product manufacture or use by consuming fewer natural resources and materials;
- Extend the lifespan of the product and its parts
  - R3 Reuse: Reuse by another consumer of a discarded product;
  - R4 Repair: Repair and maintenance of defective products;
  - R5 Refurbish: Restore an old product and bring it up to date;
  - R6 Remanufacture: Use parts of a discarded product or its parts in a new product with the same function;
  - R7 Repurpose: Use discarded products or their parts in a new product with a different function;
- Useful application of materials
  - R8 Recycle: Process materials to obtain the same or lower;
  - R9 Recover: Incineration of materials with energy recovery.

The results of the full-text analysis are shown in Tables 1 and 2. Table 1 lists the 31 publications from the literature research as well as the paper ID, the source, the year of publication, the first author, the title, and a short summary. Table 2 describes, besides the paper ID, the source, and the use cases described in the papers, and clusters them according to their PLC, TRL, and the mentioned R-strategies. The PLC refers to the phase in which the DT is applied. The classification "no specific R-strategy" in the column of R-strategies means that the respective papers do not mention a specific R-strategy but only describe the benefits of a DT for CE in general terms.

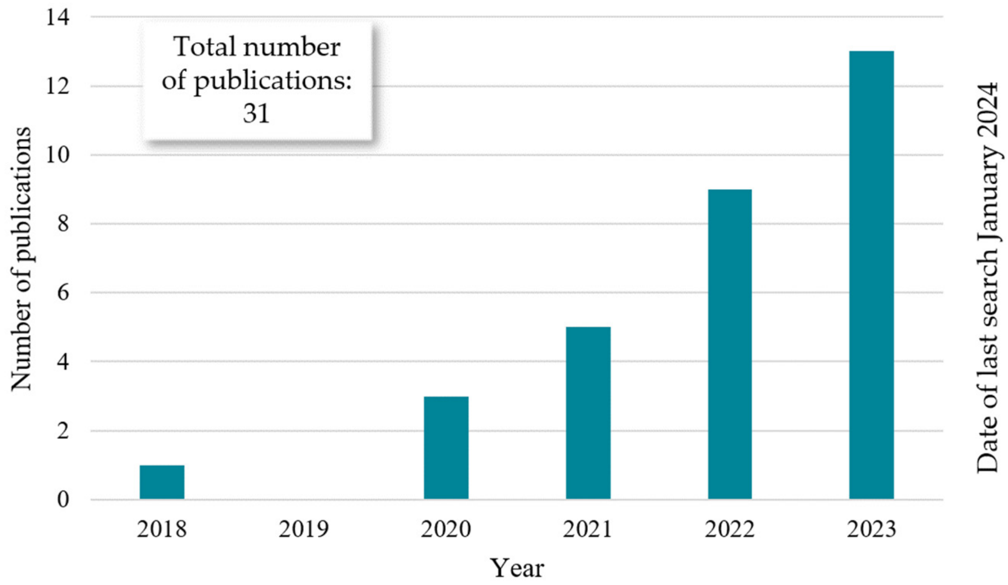



**Figure 2.** Distribution of publications over time.

**Table 1.** Relevant publications of the literature research.

| Paper ID | Reference | Year | First Author | Title | Short Summary | PLC | TRL | R-Strategy |
|---|---|---|---|---|---|---|---|---|
| 1 | [3] | 2021 | Preut, A. | Digital Twins for the Circular Economy | This article presents the potential contributions of DTs to the circularity of products and the management of circular supply chains. It includes applications for DTs for CE and a stakeholder analysis. | All | TRL 2 | Rethink, reuse, repair, refurbish, remanufacture, recycle |
| 2 | [12] | 2021 | Kalaboukas, K. | Implementation of Cognitive Digital Twins in Connected and Agile Supply Networks—An Operational Model | In this paper, the concept of cognitive DTs and how they can be deployed in connected and agile supply chains is elaborated. | BoL, EoL | TRL 2 | Rethink, recycle |
| 3 | [13] | 2022 | Ertz, M. | How transitioning to Industry 4.0 promotes circular product lifetimes | This paper explains how to use the DT as a service as an architecture reference model for Industry 4.0 to improve product design, access, maintenance, redistribution, and recovery. | All | TRL 2 | Rethink, reuse, repair, remanufacture, recycle |
| 4 | [14] | 2022 | Xu, L. | Digital Twins Approach for Sustainable Industry | This paper addresses the application scenarios of a DT throughout the entire PLC in order to realize a sustainable industry. | All | TRL 1 | Rethink, repair, remanufacture, recycle |
| 5 | [15] | 2020 | Rocca, R. | Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case | The aim of this paper is to present a laboratory application case showing how I4.0-based technologies such as DT can support CE practices by virtually testing a waste from electrical and electronic equipment disassembly plant configuration through a set of dedicated simulation tools. | MoL, EoL | TRL 3 | Reuse, repair, refurbish, recycle, recover |
| 6 | [16] | 2022 | Alves, L. | Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review | This article provides an overview of current approaches to traceability in the textile and garment value chains and examines a number of technologies, such as DT, that are essential to promoting CE in this value chain. | EoL | TRL 2 | Reuse, recycle, recover |
| 7 | [17] | 2023 | Mangers, J. | Digital twin of end-of-life process-chains for a circular economy adapted product design—A case study on PET bottles | This research presents a method to collect, process, and apply EoL process data to provide the BoL with important EoL knowledge through a CE-adapted product design assessment. | BoL, EoL | TRL 3 | Rethink, recycle |
| 8 | [18] | 2022 | Mulhall, D. | The Product Circularity Data Sheet—A Standardized Digital Fingerprint for Circular Economy Data about Products | This article describes the development of a circularity dataset for the exchange of standardized data throughout the entire supply cycle. The DT can collect the required data and map it digitally. | MoL, EoL | TRL 3 | Reuse, repair, remanufacture, recycle |

**Table 1.** *Cont.*

| Paper ID | Reference | Year | First Author | Title | Short Summary | PLC | TRL | R-Strategy |
|---|---|---|---|---|---|---|---|---|
| 9 | [19] | 2021 | Lawrenz, S. | Implementing the Circular Economy by Tracing the Sustainable Impact | This paper describes the use case of the DT in life cycle management. Therefore, the DT contains static as well as dynamic operational, status, and process data that can be used to drive sustainability. | MoL, EoL | TRL 2 | Reuse, repair, recycle |
| 10 | [20] | 2023 | Kerin, M. | Optimising remanufacturing decision-making using the bees algorithm in product digital twins | This article captures the design and demonstration of a DT model that optimizes remanufacturing planning using data from different instances in a product's life cycle. | EoL | TRL 3 | Remanufacture |
| 11 | [21] | 2022 | Carlsson, R. | Long-Lived Sustainable Products through Digital Innovation | This paper presents the "LAST" concept, which is intended to have the following product characteristics: long service life, accessible service and spare parts, sustainable materials, a long life cycle, as well as transparent information. The DT stores the relevant information and makes it available to users. | BoL, MoL | TRL 2 | Rethink, repair |
| 12 | [22] | 2022 | Islam, M.T. | Recycling Perspectives of Circular Business Models: A Review | This review article addresses the EoL, in particular the recycling process, and identifies the use of digital solutions such as the DT. | EoL | TRL 2 | Remanufacture, recycle |
| 13 | [23] | 2022 | Blomqvist, E. | Decentralized digital twins of circular value networks-A position paper | This paper presents a solution to the challenges of creating new ecosystems. An open, decentralized platform is developed that enables data exchange and uses a DT to represent circular flows. | All | TRL 2 | No specific R-strategy |
| 14 | [24] | 2022 | Bhullar, G. | Directive Drive System of Systems Approach to Visualise Data Chasms | This paper discusses how a "directive-driven" model incorporating a vendor-neutral approach can create interoperable systems that can visualize entire ecosystems beyond the standard DT concepts and bridge the chasms between operating domains of supply chains that provide products and services from raw materials to consumer goods. | All | TRL 2 | No specific R-strategy |
| 15 | [25] | 2021 | Pehlken, A. | No more flat tires: Overcoming data defects to achieve supply chain resilience | The paper explores potential information technologies such as DT and blockchain to avoid the data gaps in the supply chain so that the recycling loop for natural rubber from scrap tires can be completed regardless of the challenges posed by company secrets. | EoL | TRL 3 | Recycle |

**Table 1.** *Cont.*

| Paper ID | Reference | Year | First Author | Title | Short Summary | PLC | TRL | R-Strategy |
|---|---|---|---|---|---|---|---|---|
| 16 | [6] | 2020 | Zacharaki, A. | RECLAIM: Toward a New Era of Refurbishment and Remanufacturing of Industrial Equipment | This paper presents a new idea on refurbishment and remanufacturing based on big data analytics, machine learning, predictive analytics, and optimization models using deep learning techniques and DT models with the aim of enabling the stakeholders to make informed decisions about whether to remanufacture, upgrade, or repair heavy machinery that is toward its EoL. | EoL | TRL 3 | Refurbish, remanufacture |
| 17 | [26] | 2020 | Navas, M.A. | Disruptive Maintenance Engineering 4.0. | This paper presents a new disruptive maintenance model based on new technologies. Leveraging the DT, maintenance technicians can assess the real-time status, behavior, variables, alarms, etc., of systems through an authentic digital representation, eliminating the necessity for physical access to the system. | MoL | TRL 2 | Repair |
| 18 | [27] | 2020 | Pehlken, A. | Urban Mining: Applying Digital Twins for Sustainable Product Cascade Use | This paper presents the use case "RAUPE", which is a decision support system used at the EoL to decide whether components can be reused. | All | TRL 4 | Rethink, reuse, repair, recycle |
| 19 | [28] | 2018 | Isaksson, O. | Digitalisation, sustainability and servitisation: Consequences on product development capabilities in manufacturing firms | This paper builds on a conceptual literature review to identify relevant information about the three trends (digitalization, sustainability, and servitization) regarding their impact on design and societal development. This includes, for example, how sustainability issues can be implemented in the long term through digital solutions such as DTs. | MoL | TRL 1 | Repair |
| 20 | [29] | 2022 | Gebhardt, M. | Industry 4.0 technologies as enablers of collaboration in circular supply chains: a systematic literature review | This paper explores the intersection of CE, supply chain collaboration, and Industry 4.0. In this context, the DT is investigated as an enabler. | MoL, EoL | TRL 2 | Reuse, repair, remanufacture, recycle |
| 21 | [30] | 2023 | Rakesh, C. | Towards a Circular Economy: Challenges and Opportunities for Recycling and Re-manufacturing of Materials and Components | This paper explores the challenges and opportunities associated with recycling and remanufacturing materials and components within the context of a CE. DTs can help to overcome the challenges of dismantling, remanufacturing, and reassembly and improve the cost, quality, and feasibility of remanufacturing. | EoL | TRL 1 | Remanufacture, recycle |

**Table 1.** *Cont.*

| Paper ID | Reference | Year | First Author | Title | Short Summary | PLC | TRL | R-Strategy |
|---|---|---|---|---|---|---|---|---|
| 22 | [31] | 2023 | Turner, C. | Manufacturing in the Age of Human-Centric and Sustainable Industry 5.0: Application to Holonic, Flexible, Reconfigurable and Smart Manufacturing Systems | This paper presents a contribution by providing an assessment of the major manufacturing types in the context of Industry 5.0, highlighting the gaps in the current research, and providing a sustainable and human-centric agenda supported by life cycle assessment using modern production methodologies. DT dashboards help to present the results of historical and current data from the life cycle assessment. | BoL | TRL 2 | Rethink, reduce |
| 23 | [32] | 2023 | Ke, C. | An Intelligent Redesign Method for Used Products Based on Digital Twin | In order to improve the efficiency of design and obtain the optimal design scheme, an intelligent redesign method for used products based on the DT is proposed in this paper. The DT technology can connect the physical world with the virtual world and use the virtual model to simulate the redesign process, which is conducive to the dynamic adjustment and optimization of the redesign scheme. | EoL | TRL 4 | Remanufacture |
| 24 | [33] | 2023 | Mügge, J. | Empowering End-of-Life Vehicle Decision Making with Cross-Company Data Exchange and Data Sovereignty via Catena-X | This paper presents a decision support system based on DT data for a CE solution as a software application. The decision support system provides important information about the exact composition and condition of the vehicle, its components, and its materials. Thus, it helps to improve efficiency, sustainability, and the implementation of the CE. | EoL | TRL 4 | Reuse |
| 25 | [34] | 2023 | Mügge, J. | End-of-life decision support to enable circular economy in the automotive industry based on digital twin data | The paper presents the concept of a DT for a decision support system that includes a central decision logic that also includes the relevant KPIs and a survey for evaluating the decision logic utilized with a chosen dismantling company. | EoL | TRL 2 | Reuse |

**Table 1.** *Cont.*

| Paper ID | Reference | Year | First Author | Title | Short Summary | PLC | TRL | R-Strategy |
|---|---|---|---|---|---|---|---|---|
| 26 | [35] | 2023 | van Capelleveen, G. | The anatomy of a passport for the circular economy: a conceptual definition, vision and structured literature review | The paper deals with the importance of various variants of passports that are suggested to enhance the traceability of products and their components and accelerate the integration of the CE philosophy into supply chain management. This work serves as a basis to better specify the general holistic requirements and architectures for these passports that may be developed collaboratively by multiple supply chain stakeholders. | EoL | TRL 2 | Repair, reuse, recycle, recover |
| 27 | [36] | 2023 | Paramatmuni, C.; | Extending the capability of component digital threads using material passports | This article presents an overview of the nature of DTs for manufacturing based on the length scale of material property definitions employed in the respective computational framework and the type of material purchase specification system implemented in the industry. Then, the possible structure, significance, and challenges of realizing material passports that enable predictive maintenance and CE are discussed. | EoL | TRL 3 | Repair, reuse, recycle |
| 28 | [37] | 2023 | Seegrün, A. | Sustainable product lifecycle management with Digital Twins: A systematic literature review | This paper identifies current application scenarios focused on sustainability in the manufacturing industry using DTs and outlines the findings of a SLR. | All | TRL 1 | Rethink, reduce, repair, reuse, remanufacture, recycle |
| 29 | [38] | 2023 | Davila R, M.F. | Sustainability Digital Twin: a tool for the manufacturing industry | Two real-life case studies from the big component production industry located in northern Germany are discussed in this paper. They cover the use of DTs in manufacturing given their potential to contribute to solutions for the current environmental and digitalization challenges. | BoL | TRL 3 | Rethink, reduce |
| 30 | [39] | 2023 | Baalbergen, E.H. | Unleashing the potentials of digital twinning in the production of composite aircraft components | This paper discusses the potential of DTs in innovative production processes in the aircraft industry and describes first-hand results and experiences in developing and using DTs in the production of composite aircraft components, illustrated by concrete example applications. | BoL | TRL 3 | Rethink, reduce |
| 31 | [40] | 2023 | Kalaboukas, K. | Governance framework for autonomous and cognitive digital twins in agile supply chains | This paper emphasizes the concept of supply chain DTs and proposes a holistic governance approach integrating three different views: (1) business and sustainability; (2) data governance; and (3) cognition (AI) models of governance. | BoL | TRL 4 | Rethink |

**Table 2.** Results of the literature analysis.

| Paper ID | Reference | PLC | TRL | R-Strategy |
|---|---|---|---|---|
| 1 | [3] | All | TRL 2 | Rethink, reuse, repair, refurbish, remanufacture, recycle |
| 2 | [12] | BoL, EoL | TRL 2 | Rethink, recycle |
| 3 | [13] | All | TRL 2 | Rethink, reuse, repair, remanufacture, recycle |
| 4 | [14] | All | TRL 1 | Rethink, repair, remanufacture, recycle |
| 5 | [15] | MoL, EoL | TRL 3 | Reuse, repair, refurbish, recycle, recover |
| 6 | [16] | EoL | TRL 2 | Reuse, recycle, recover |
| 7 | [17] | BoL, EoL | TRL 3 | Rethink, recycle |
| 8 | [18] | MoL, EoL | TRL 3 | Reuse, repair, remanufacture, recycle |
| 9 | [19] | MoL, EoL | TRL 2 | Reuse, repair, recycle |
| 10 | [20] | EoL | TRL 3 | Remanufacture |
| 11 | [21] | BoL, MoL | TRL 2 | Rethink, repair |
| 12 | [22] | EoL | TRL 2 | Remanufacture, recycle |
| 13 | [23] | All | TRL 2 | No specific R-strategy |
| 14 | [24] | All | TRL 2 | No specific R-strategy |
| 15 | [25] | EoL | TRL 3 | Recycle |
| 16 | [6] | EoL | TRL 3 | Refurbish, remanufacture |
| 17 | [26] | MoL | TRL 2 | Repair |
| 18 | [27] | All | TRL 4 | Rethink, reuse, repair, recycle |
| 19 | [28] | MoL | TRL 1 | Repair |
| 20 | [29] | MoL, EoL | TRL 2 | Reuse, repair, remanufacture, recycle |
| 21 | [30] | EoL | TRL 1 | Remanufacture, recycle |
| 22 | [31] | BoL | TRL 2 | Rethink, reduce |
| 23 | [32] | EoL | TRL 4 | Remanufacture |
| 24 | [33] | EoL | TRL 4 | Reuse |
| 25 | [34] | EoL | TRL 2 | Reuse |
| 26 | [35] | EoL | TRL 2 | Repair, reuse, recycle, recover |
| 27 | [36] | EoL | TRL 3 | Repair, reuse, recycle |
| 28 | [37] | All | TRL 1 | Rethink, reduce, repair, reuse, remanufacture, recycle |
| 29 | [38] | BoL | TRL 3 | Rethink, reduce |
| 30 | [39] | BoL | TRL 3 | Rethink, reduce |
| 31 | [40] | BoL | TRL 4 | Rethink |

Figure 3 shows the distribution of the TRL of the publications. Most papers indicate a TRL of 2 (14) and 3 (9). Four publications have a TRL of 1, and another four have a TRL of 4, which are described in more detail below.

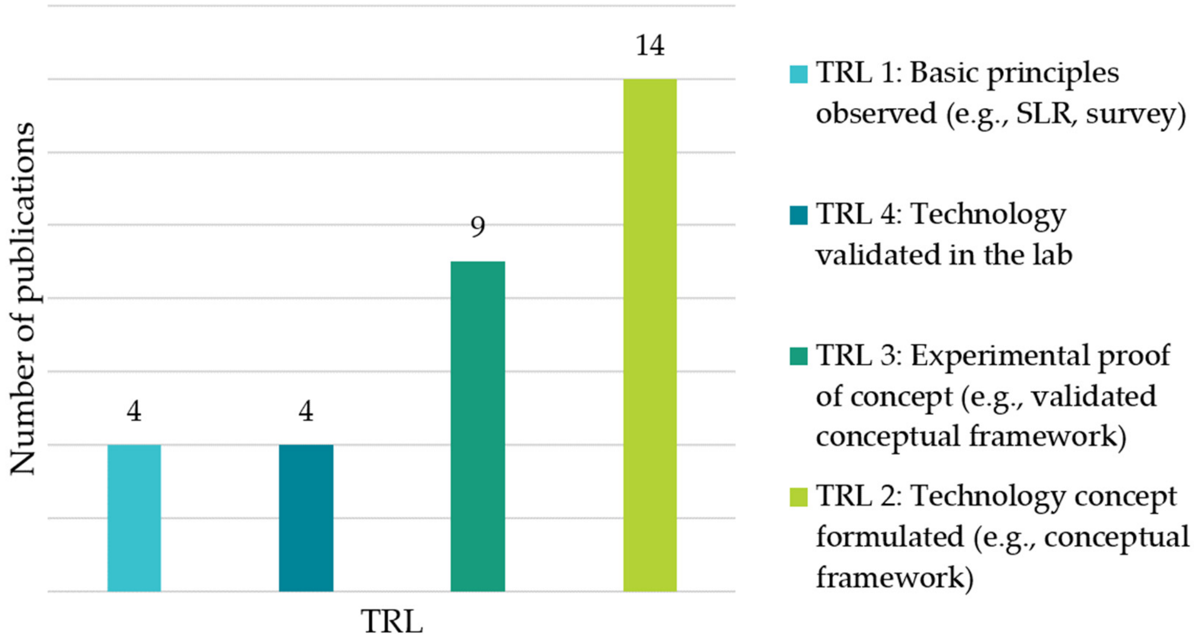



**Figure 3.** Distribution of publications with regard to the technology readiness level.

Pehlken and Baumann describe in their publication the case study "RAUPE", a decision support tool for the reuse of used car parts and their lifetime extension. The web application "RAUPE" was able to demonstrate a reduction in $CO_2$ emissions in the automotive industry through the reuse of components [27]. Ke et al. address the application of a redesign process for remanufacturing products based on DT in their paper. This includes the development of a repair scheme for remanufacturing and an innovative design scheme. The DT is used to analyze and summarize the necessary data of the PLC and to use the data to predict and optimize the remanufacturing process. Based on this, the remanufacturing process is simulated in order to check its feasibility. As part of a case study, the authors examine the redesign process of a commercial vehicle coupling. The results show that the remanufacturing process can be improved through the simulation process and the use of product-related data through the PLC [32]. Mügge et al. developed an EoL decision support system to enable CE, called the circularity cockpit. The software is designed to provide relevant data about a vehicle along the PLC to support dismantlers at the EoL in deciding whether an EoL vehicle offers the potential for selling used components. The application was validated as part of a customer feedback study [33]. Kalaboukas et al. utilize DT within the refrigerator supply chain to promote the selection of sustainable suppliers. For each potential supplier, inputs and outputs are modeled, and their system behavior is considered throughout the entire supply chain. This can lead to more efficient decisions regarding sustainability in the BoL [40]. Three of the four publications relate to the automotive industry and describe applications at the EoL that relate to returning components to the cycle by providing relevant information along the entire PLC.

None of the publications achieved a TRL of 5 or higher. These findings suggest that the overall TRL within the literature remains low. The majority of papers discuss the DT for CE at a conceptual level, while only a few provide validation. Consequently, although the potential applicability of DT for CE is outlined in these publications, it remains largely unexplored. Presently, there is insufficient evidence supporting the potential, validation, and implementation of DT for CE.

Figure 4 shows the distribution of publications along the PLC. The majority of DTs for CE applications are in the EoL (43%), followed by the MoL (22%).

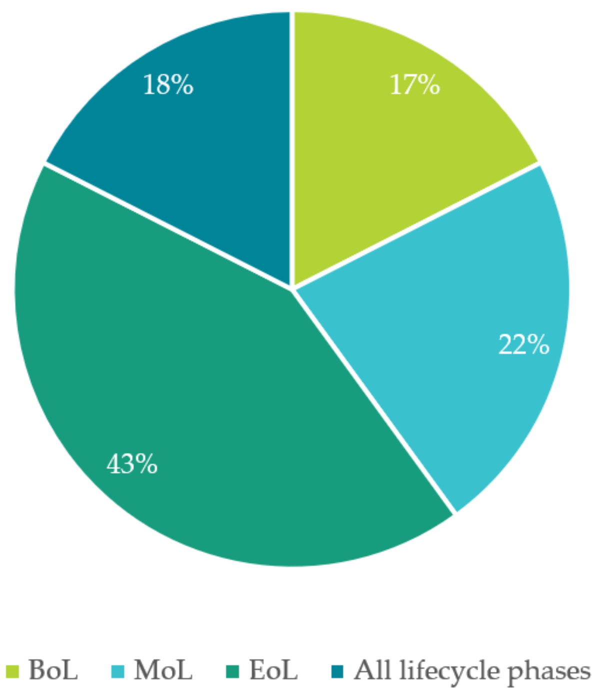



**Figure 4.** Distribution of publications along the product life cycle.

Table 3 shows the distribution of publications along the PLC, considering multiple responses. The EoL use case alone is described in 11 publications, which corresponds to a third of all publications. In addition, there are four publications that describe the EoL use case in conjunction with MoL and two in conjunction with BoL. Seven publications refer to the usability of DTs along the entire PLC and are not limited to specific R-strategies. The combination of BoL and MoL is only addressed in one publication.

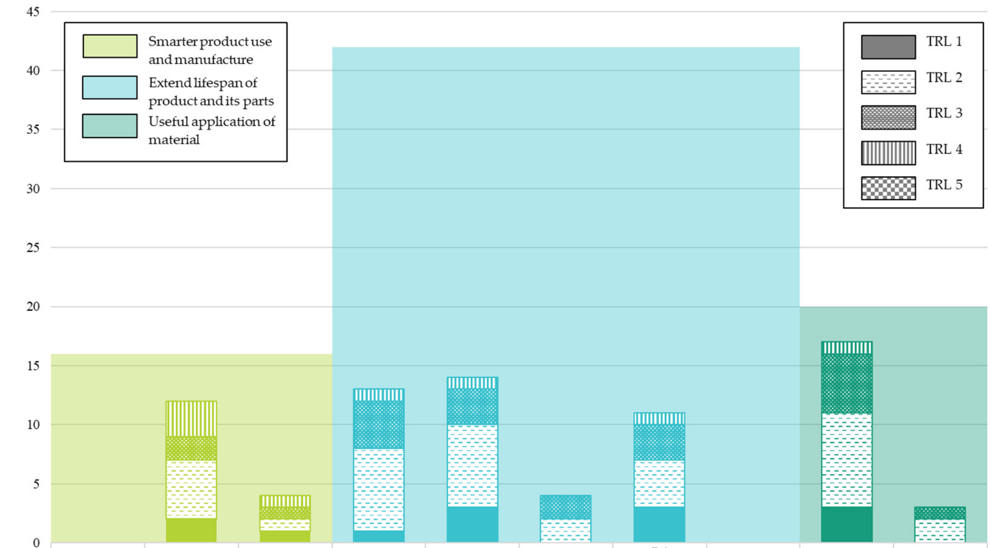
**Table 3.** Distribution of publications along PLC considering multiple mentions.

| PLC Phase | Number of Publications |
| --- | --- |
| Only BoL | 4 |
| BoL and MoL | 1 |
| MoL | 2 |
| MoL & EoL | 4 |
| EoL | 11 |
| BoL and EoL | 2 |
| All | 7 |

Figure 5 clusters the publications based on their TRL and their corresponding R-strategy, utilizing the framework proposed by Potting et al. [11].

Most papers address multiple strategies, leading to a cumulative count that exceeds the number of analyzed papers. Out of the 31 publications assessed, extending the life of products and their components is mentioned 42 times (Figure 5, light green). Additionally, the term "useful application of materials" is referred to 20 times (Figure 5, blue) and the term "smarter product use and manufacturing" 16 times (Figure 5, dark green). Specifically, the primary focus is on R-strategies such as recycling (17 mentions), repair (14), reuse (13), rethink (12), and remanufacturing (12).

A publication attains a TRL of 4, incorporating the R-strategies of rethink, reuse, repair, and recycle. The R-strategies of refuse and refurbishment are not explicitly mentioned in the context of DTs and CE. The R-strategies reduce and recover exhibit a low TRL of 1–2. Most of the other R-strategies predominantly have a TRL of 2, but there are also publications rated with TRLs of 1, 3, and 4.




| | R0 Refuse | R1 Rethink | R3 Reduce | R4 Reuse | R5 Repair | R5 Refurbish | R6 Remanufacture | R7 Repurpose | R8 Recycle | R9 Recover |
|---|---|---|---|---|---|---|---|---|---|---|
| | Smarter product use and manufacture | | | Extend lifespan of product and its parts | | | | | Useful application of material | |
| Gesamt | 16 | 16 | 16 | 42 | 42 | 42 | 42 | 42 | 20 | 20 |
| TRL 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TRL 4 | 0 | 3 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| TRL 3 | 0 | 2 | 1 | 4 | 3 | 2 | 3 | 0 | 5 | 1 |
| TRL 2 | 0 | 5 | 1 | 7 | 7 | 2 | 4 | 0 | 8 | 2 |
| TRL 1 | 0 | 2 | 1 | 1 | 3 | 0 | 3 | 0 | 3 | 0 |

**Figure 5.** Distribution of the publications according to technology readiness level and R-strategy.

## 4. Concept Presentation

To evaluate the state of the art of DTs for CE in the manufacturing industry, the current situation and challenges in circular product development are analyzed to identify potential applications for DTs for CE.

### *4.1. Current Challenges of the Circular Economy*

The literature review reveals a lack of collaboration and data exchange among stakeholders throughout the supply chain—particularly in the context of sustainability and CE [3,14–17,19–21,23,24,27,29]. While information exchange is part of collaborative engineering at the outset of the PLC, there's a breakdown in the flow of information once the product reaches the end user. Limited exchange of existing information occurs [3,27]. Additionally, the PLC involves numerous stakeholders with diverse requirements, standards, and communication interfaces for their data [3,21]. Furthermore, the majority of manufacturers worldwide consist of micro- and medium-sized enterprises, which means there is a risk of having many different data sets in different formats [21]. The level of digitization across companies in the value chain also varies significantly [3]. Consequently, due to inadequate product knowledge and increasing product complexity, crucial information required for EoL treatment is often absent at the EoL stage [3,27]. This absence hampers the possibility of returning products, components, and materials to the cycle [3,27]. In addition, expertise in designing circular products is often limited, which means that EoL treatment is not sufficiently considered at the BoL [3].

In summary, the following research gaps are identified:

- Ensuring continuous information flow during end-user usage;
- Ensure data exchange with a high number of diverse stakeholders and corresponding IT systems;
- Enabling the integration of SMEs;
- Establishment of a solution considering different digitalization states in the participating companies;
- Ensuring information provisioning in the EoL stage;
- Facilitating circular material flow after the traditional EoL stage;

- Design products for circularity;
- Use of life cycle data to realize circular product design.

### 4.2. Application Scenarios of Digital Twins for the Circular Economy

A DT for CE is intended to remedy this situation by acting as an enabler for CE, creating the necessary transparency throughout the PLC, and ensuring a closed loop at the product, component material, process, and information level. DTs support continuous data collection, analysis, and evaluation, providing this information to various stakeholders throughout the entire PLC [3,14–17,19–21,23,24,27,29,33–35,37]. As a result, new business models and services are emerging [3]. The following sections present the results of the literature review regarding the focused life cycle phase of DT applications.

#### 4.2.1. Digital Twins for Circular Economy for the Beginning-of-Life Stage

The analyzed research highlights the potential for optimizing product design at the outset of product development using information spanning the entire PLC. BoL encompasses product planning, development, and production.

This data from DTs throughout the PLC allows for deriving conclusions about design requirements related to longevity and user behavior (Feedback to Design) [3,13,19,21,29,37]. By considering EoL treatment as well as regional EoL conditions, the product design can be optimized for better reuse, remanufacturing, or recycling (Design for Reuse, Remanufacture, Recycling) [12,17,26,27,39,40]. By finding, analyzing, and evaluating new product configurations, products can be designed for a longer product life [13,14,17,27]. Overall, environmental impact can be monitored and reduced through enhanced product design methodologies (Design for Environment) [13,27,37]. In addition, product design decisions can be supported in terms of sustainability by considering the concept of ecological design, which involves material selection and compatibility. This includes analyzing and monitoring material inputs and outputs, real-time tracking of waste, emissions, and discharges, as well as assessing circular potential and achievements. Through these measures, greenhouse gas emissions can be quantified [37]. Additionally, DT for CE can predict specific indicators, such as recycling rates [22,29] or future $CO_2$ emissions [31,37]. This information can be visualized in a DT dashboard, which can be used to make important decisions regarding life cycle assessments at BoL [31]. Sustainability can also be influenced by the choice of suppliers and transport routes [38,40]. In addition, the sustainability of the manufacturing process can be improved by monitoring the status of the system and energy consumption [38,39]. Moreover, unnecessary downtime can be avoided, and the production system can be maintained in line with requirements [39]. The publications also highlight the growing number of regulations that must be considered in product development (design for compliance) [17,21]. Most of these regulations aim to extend the service life of products, increase reparability, limit hazardous substances, and ensure compliance with mandatory energy efficiency requirements [17].

In summary, there are the following DT application focuses during the BoL, which are illustrated in Table 4.

#### 4.2.2. Digital Twins for Circular Economy for the Middle-of-Life Stage

MoL includes distribution, utilization, and service. During product use, some publications suggest that a DT for CE can support longer product use by analyzing the product's condition data depending on user behavior and informing about necessary maintenance and service. DTs for CE can provide information about the product condition as well as technical features for maintenance [3,6,12–15,21,22,26,28,29,37]. Consequently, this capability enables the concurrent reduction of fuel consumption while enhancing driving safety and comfort, particularly in the automotive industry. Moreover, insights gleaned from product utilization offer valuable guidance for the development of future product iterations [37].

**Table 4.** DT application focus during BoL.

| DT Application Focus | References |
|---|---|
| Feedback on design | [3,13,19,21,29,37] |
| Design for reusing, remanufacturing, and recycling | [12,17,26,27,39,40] |
| Design for a longer product life | [13,14,17,27] |
| Design for the environment | [13,27,37] |
| Quantify GHG with real-time assessment | [37] |
| Prediction of indicators: recycling rates | [21,28] |
| Prediction of indicators: $CO_2$ emissions | [31,37] |
| DT dashboard to support decision making | [31] |
| Analyze the choice of suppliers and transport routes | [38,40] |
| Monitoring manufacturing processes | [38,39] |
| In-situ optimization in manufacturing | [39] |
| Design for compliance | [17,21] |

Furthermore, DTs can facilitate the tracking and management of products that are no longer in use. This collected data on condition and location can forecast returns, aiding in the establishment of logistical and technical structures for return systems and the provision of spare parts [3,27]. Within the sharing economy, insights into product usage enable customized billing for customers, while location information enables a demand-oriented allocation of shared products within specific areas [3].

Table 5 summarizes the application scenarios of a DT in the MoL.

**Table 5.** DT application focus during MoL.

| DT Application Focus | References |
|---|---|
| Longer product use by analyzing condition data, user behavior, and predictive maintenance | [3,6,12–15,19,21,22,26,28,29,37] |
| Provision of details on maintenance and product condition | [3,6,12–15,21,22,26,28,29,37] |
| Improves automotive efficiency, safety, and comfort | [37] |
| Feedback on design | [37] |
| Forecasting returns and setting up take-back systems and spare parts provision | [3,27] |
| Sharing economy: customized billing and location-based allocation | [3] |

#### 4.2.3. Digital Twins for Circular Economy for the End-of-Life Stage

EoL involves activities such as reuse, remanufacture, recycling, and recovery. The relevant research states that at the EoL, the DT for CE can support EoL decision-making for the most appropriate strategy of reusing or remanufacturing parts or recycling materials by providing the necessary information about the current condition of the product as well as its history. For example, this information may include the remaining expected life of products, components, and materials [3,6,12–20,22,24,25,27,29,30,32–34,36,37]. Under optimal conditions, such as when the DT contains relevant information typically acquired through time-consuming manual inspections, the manual inspection process for asset conditions can be significantly expedited or even bypassed entirely [3]. Other tasks of DTs in this stage include reducing product complexity by providing information and improving the efficiency of disassembly processes, as well as supporting the virtual disassembly of products [14,15,30,32,33,35,37]. Furthermore, information on dismantling and recycling directives can be provided [35].

Table 6 outlines the application scenarios of a DT in the EoL.

**Table 6.** DT application focus during EoL.

| DT Application Focus | References |
|---|---|
| Decision support for circular strategies | [3,6,12–22,24,25,27,29,30,32–34,36,37] |
| Provision of relevant EoL information, such as the remaining expected life of products and components, information on product condition, and history | [3,6,12–20,22,24,25,27,29,30,32–34,36,37] |
| Acceleration of the inspection process | [3] |
| Improving the efficiency of disassembly processes and supporting the virtual disassembly of the product | [14,15,30,32,33,35,37]. |
| Provision of dismantling and recycling directives | [3,27] |

### *4.3. Concept of a Digital Twin for Circular Economy*

Building upon the SLR and the identified application scenarios of a DT for CE, a conceptual framework was developed to encompass the entire PLC. This framework draws from the original definition proposed by Stark and Damerau [41] while integrating the works of Riedelsheimer et al. [42] and Seegrün et al. [43], transitioning from life cycle assessment to CE. It aligns with the definition of CE established by the Ellen MacArthur Foundation [2,11] and incorporates the nine R-strategies introduced by Potting [11].

The conceptual model is depicted in Figure 6.

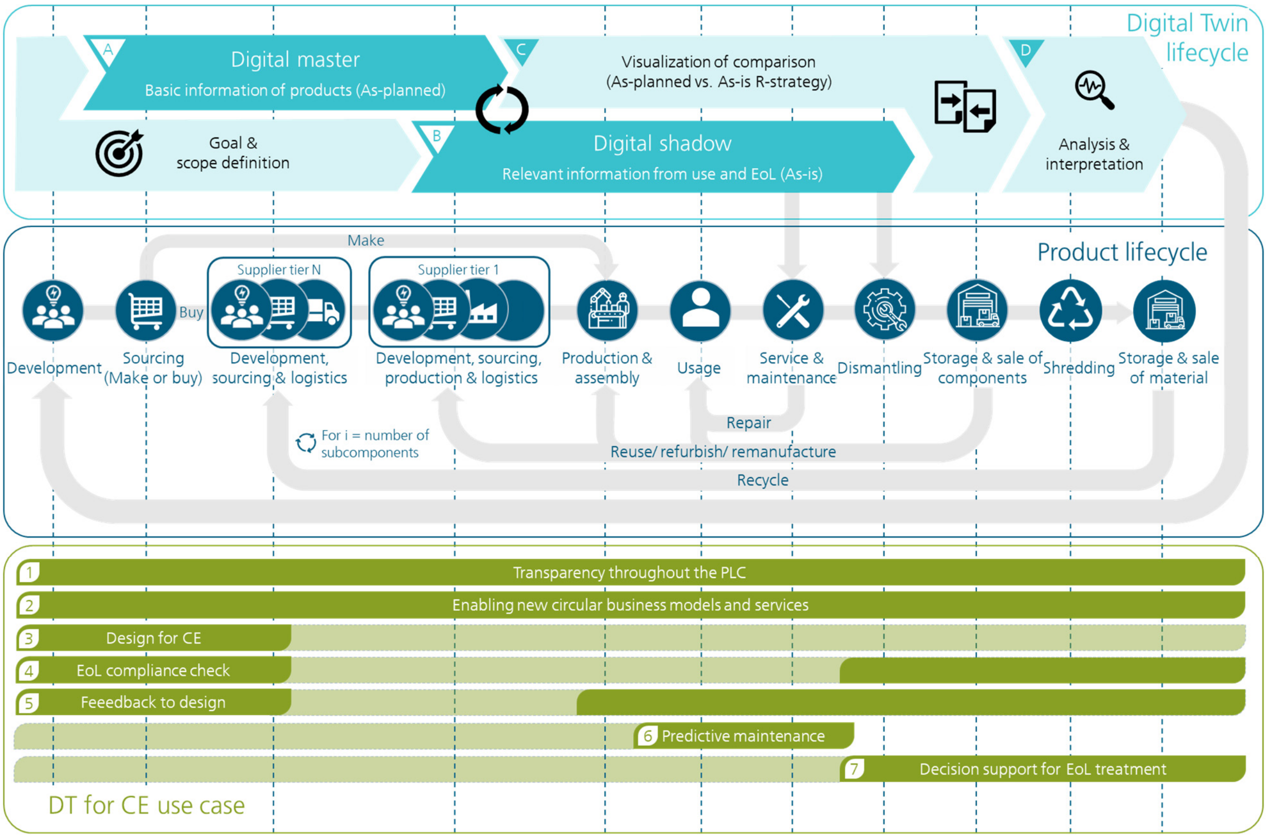



**Figure 6.** Concept of a digital twin for the circular economy and its use cases.

There are two main elements, i.e., the PLC, as depicted in the upper part of Figure 6, and the fundamental DT life cycle, which comprises the digital master, shadow, and DT core. The digital master encompasses all planning data for the product, including the intended product configuration (refer to Figure 6, A). The digital shadow, on the other hand, contains real-time data, such as service and maintenance records (see Figure 6, B). The intelligent linkage between the shadow and master models is responsible for generating the added value of the DT. It performs comparisons between planned and actual data, conducts simulations, and derives recommendations for the end user of the DT (refer to Figure 6, C and D).

Based on the SLR, application scenarios for a DT for CE were identified. These were grouped according to their similarity in the cluster analysis [8] and summarized into seven use cases:

1. Transparency throughout the PLC: DTs for CE enable transparency throughout the entire PLC by providing actual instance-specific data and information to stakeholders, such as the operator of the product.
2. Enabling new CE business models and services: The provided information can be semantically analyzed for different stakeholders and support decision-making. This results in new business models and services.
3. Design for CE: At the BoL, data from previous product generations stored in DTs can assist in comparing various product configurations in aspects like their circular design, such as longevity and recyclability.
4. EoL compliance check: At the BoL, adherence to legal regulations, including recyclability, must be ensured during the planning stages. Actual compliance can mostly be verified at the EoL. Any design characteristics found to be non-compliant at the EoL are then provided as feedback to the product development phase.
5. Feedback to Design: At the BoL, insights gained from the EoL evaluations, such as improving a product's circularity, its recyclability, longevity for extended use, or simplifying maintenance requirements, are integrated into the design process of new product generations.
6. Predictive maintenance: During the usage phase of an asset, the DT for CE can support the extension of a product's lifetime by analyzing the condition data of an individual asset, e.g., depending on the user behavior, and informing about necessary maintenance and repairs.
7. Decision support for EoL treatment: The use case 'Decision Support for EoL Treatment' involves capturing the history of an asset and evaluating its condition at the EoL. Instance-specific information is analyzed within the framework of the DT, leading to recommendations for the most suitable EoL strategy, considering both economic and environmental factors. Examples include calculating the expected remaining lifespan of components and estimating the energy consumption of refurbishment or recycling processes.

The use cases are shown in green in the concept below. The dark green phase represents the life cycle phase in which the use case mainly applies. The light green color indicates when data is obtained in the other PLC phases, such as in the use case decision support for EoL treatment, or when the decisions of the use case have an impact on other life cycle phases, such as in the use case design for CE.

For all use cases, it is assumed that the DT is updated by new events in the form of new artifacts of the PLC. For example, the condition of a product or its list of parts must be updated in order to provide the EoL with the relevant information about the current components for dismantlers.

Use Case—Decision Support for the End-of-Life Treatment

The analysis revealed that a DT for CE can be used across all phases of the PLC. Depending on the specific application area, DTs for CE pursue different objectives that align with the individual needs and challenges of various stakeholders. These objectives may occasionally conflict. For instance, sustainability aspects take precedence for a sustainability expert, while a business executive typically focuses on the economic position. Therefore, it is crucial to identify the relevant stakeholders at the outset of the process to comprehend and accommodate their specific requirements. This facilitates a targeted and tailored design of the DT for CE, allowing for the early identification and addressing of potential conflicts and inconsistencies.

The following section provides a detailed explanation of the EoL use case decision support for EoL treatment, no. 7, as visualized in Figure 7. The aim of this use case is to provide the dismantling company, which is responsible for the EoL treatment of products, with the necessary information regarding the PLC of products, their components, and materials. These details are generated using instance-specific DTs. Their role is to assist the disposer in making informed decisions concerning the EoL of a product, especially regarding the future path of individual components. This might involve evaluating whether a specific component can be reused or should be recycled.

The first step is to check whether a component can technically be reused due to regulatory requirements or its functionality. Regulatory requirements prohibit the reuse of certain safety-relevant components, such as airbags, or concerning materials such as lead, mercury, cadmium, or chromium [44]. Additionally, the dismantler is faced with the question of which CE strategy makes economic and ecological sense. Here, the current market prices for reusable components and the prices for secondary materials are taken into account, as well as the current demand. In order to take environmental aspects into consideration, factors such as the $CO_2$ footprint of remanufacturing and the logistical burden are included. For example, if a component has to be transported around the world for the remanufacturing process, this could be environmentally unfavorable.

In order to make these decisions, the dismantler needs product-specific, instance-specific, and process-specific information. This includes information on the use of operating materials, the spatial conditions, and the company's processes.

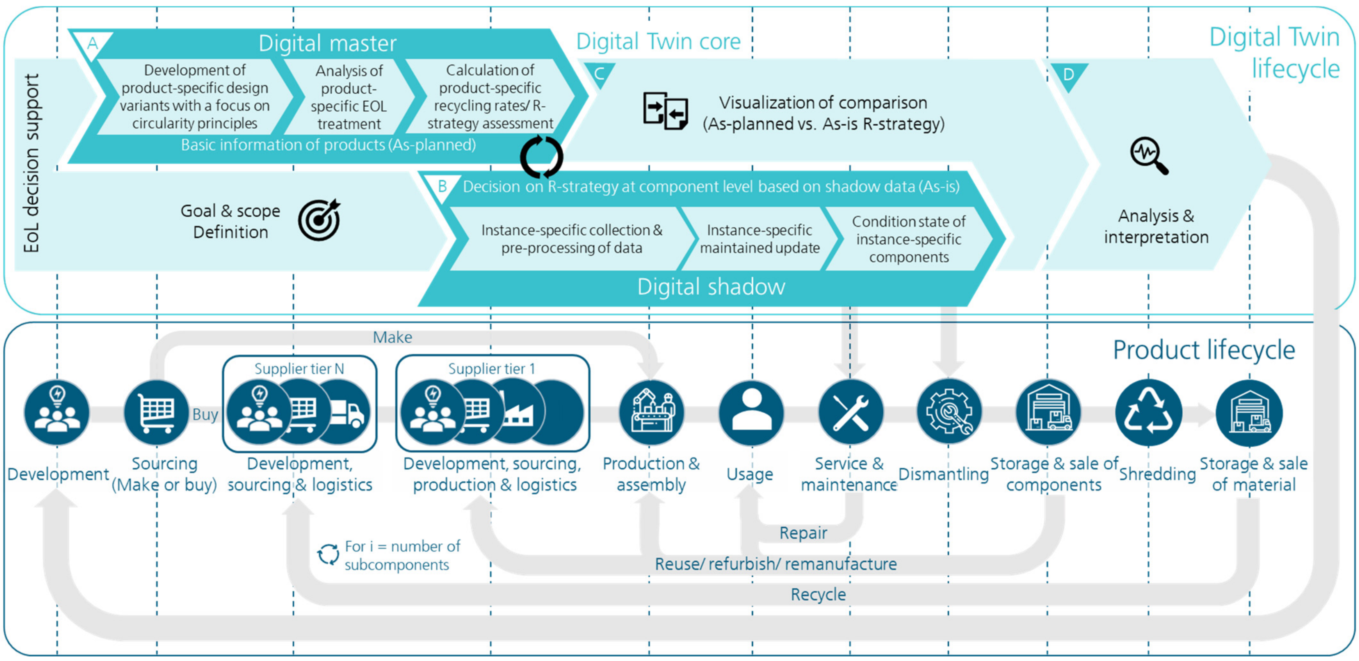



**Figure 7.** Use case: end-of-life decision support.

In the design phase of the product, various design variants are developed that are based on the principles of CE. Particularly, the planned EoL circular strategy for the product is supported. Additionally, at the start of the product's life cycle, the specific treatment procedure for the end of the product's life cycle can be considered. This enables early planning of calculations for recycling rates or evaluations of R-strategies. These details are fundamental product information (as planned) as part of the digital master (refer to A in Figure 7), which must be stored and referenced in the DT as type-specific data. At this stage, detailed inventory lists, expected lifespans, or planned circular strategies for each product, for instance, are available.

During the production and use phases, the product generates individual data, captured through a unique identifier in the digital shadow (see B in Figure 7). This includes activities such as component replacement or repairs in the workshop. Concurrently, the condition of these specific components can be recorded and updated by new events across various stages of the PLC.

The linking of master models and shadow data in the core of the DT enables access to comprehensive life cycle information, including data related to production, usage, and the end of the life cycle. As a result, these data are processed deliberately and transformed into valuable information.

By comparing planned lifespans and intended EoL circular strategies, along with ongoing assessments of the actual condition of specific components, decision-making regarding a technically feasible R-strategy is supported at the end of the PLC. For instance, if a component is designed for an average lifespan of 15 years and has already reached that age, it may not be necessary to undergo extensive energy- and resource-intensive remanufacturing. If the old product is still operational, it is more practical to consider placing it in reuse, where the energy and resource requirements are considerably lower than those associated with remanufacturing. Conversely, a nearly new component might be installed in a new product if the old product is no longer usable overall. Another scenario could involve safety-related components, such as a vehicle's airbag, which might not be allowed for reuse due to legal reasons.

The analysis and interpretation within the DT core (see D in Figure 7) can, therefore, be utilized to assist the disposer in making EoL decisions by providing relevant information from the entire PLC.

In order to successfully apply the use case, the data of a product as well as its components and materials must be continuously updated in DT throughout the PLC. This includes, in particular, data from product use, such as data on usage behavior and the numerous repairs and changes to a product throughout its life. In addition, the dismantler must be able to view all this information at the end of its life, preferably in the form of a software application.

## 5. Discussion

The results show that a DT for CE represents an overall promising approach for achieving resource-efficient value creation. Moreover, it enhances collaboration among stakeholders throughout the entire supply chain, a crucial aspect of value creation along the life cycle.

The findings derived from the literature review reveal the diversity of DTs in facilitating CE strategies throughout the entire PLC (RQ 1, RQ 2, and RQ 3). DTs, in the context of CE, support transparency along the PLC, offering insights on the assets in focus that can be accessed across diverse phases of the PLC and by various stakeholders. The extent of the requisite information depends on the objectives of the DT and the DT users. While a component manufacturer may find product-type-specific data sufficient, an EoL processor requires instance-specific information at both the product and component level in order to be able to make decisions about subsequent product or component usage. The conducted SLR showed a variety of applications in different phases. The data collected with DTs throughout a product's life cycle can be used for optimizing the design of future product generations in the BoL, the so-called process of feedback to design. Its applications range from optimizing product design for circularity and sustainability, considering EoL treatments during product development, and defining intended circular strategies at the EoL. Analyzing various product generations can lead to choosing sustainable, durable variants. Additionally, supplier selection in this phase can significantly impact a product's ecological footprint. In manufacturing, real-time energy data can be monitored, enabling sustainability optimizations.

Within the context of MoL, the DT for CE is employed to furnish necessary information for maintenance and repair. It also enables predictions regarding the time when a component reaches the end of its lifespan, facilitating the timely procurement of replacement parts. Furthermore, deploying a DT can optimize and reduce resource consumption and emissions during product usage.

At the EoL, DTs can aid in providing information about the product or its components for dismantling to identify and locate mandatory disassembly components, such as batteries, to estimate the technical feasibility as well as the economic and environmental effort and added value. Through comprehensive information like the remaining expected lifespan or individual component quality assessments, decisions can be made on the basis of or within the DT for the optimal circular strategy. Additionally, relevant disassembly and recycling information for individual components can be provided, visualizing a virtual disassembly process.

However, upon analysis of the literature and respective application scenarios, it becomes evident that the technological readiness remains relatively low, typically up to TRL 2 to 3 (RQ 3). While most publications outline technological concepts and some validate them through exemplary use cases, there's still a dearth of publications detailing industrial applications.

Due to societal, legal, and political demands for circular products involving increased usage of secondary materials and component reusability, it is reasonable to expect that the topic of DTs for CE will receive more attention, consequently leading to a rise in TRL. Companies will need to respond to this demand by implementing suitable technological solutions and facilitating information exchange throughout the PLC. The following open challenges and actions could be deduced:

- Creating incentives to enable data sharing [3];
- Considering privacy and data security when collecting, sharing, and using data [3,17,19,23];
- Developing a decentralized platform that enables secure and trusted collaboration [23];
- Defining access rights and roles [3,23];
- Semantically interpreting existing data [3,23].

## 6. Conclusions and Outlook

In this paper, an SLR was conducted using the PRISMA method to identify the actual potential and readiness of DTs for CE throughout the PLC. Moreover, 260 publications from the scientific databases Web of Science and Scopus were analyzed. As a result, 31 papers focused on specific use cases of DTs for CE were analyzed in detail. Based on the SLR, the TRL of the described use cases was evaluated (RQ 4), and the phases of the PLC in which DTs for CE are mainly used were examined. This involved a subdivision into the BoL, MoL, and EoL phases and the various R-strategies (RQ 3). Using the cluster method, seven use cases for DTs for CE through the PLC were identified (RQ 2). As one of the biggest challenges in the transition from a linear to a circular economy, the exchange of information and the existing lack of information from the time of product use were identified (RQ 1). The introduction of a DT for CE has shown that it has the potential to improve material and product circularity and conserve resources by enabling transparency throughout the PLC and providing relevant information to the relevant stakeholders at the right time.

As a result of the SLR, a concept for a DT for CE was developed, which includes the PLC, the DT with its elements digital master and digital shadow, as well as the seven application scenarios and their placement in the life cycle. In addition, the use case decision support for EoL treatment was described in more detail, and the data requirements and data providers were identified (RQ 5). This study enables companies to obtain a clear overview of potential application scenarios for DTs for CE. It also provides the basis for future research and implementation.

Currently, the focus of the study is on research purposes only, with industrial use cases not included. Another limitation is that not all use cases of DTs are published or declared as such. The industrial feasibility has also not been validated by application partners. In addition, current regulatory changes, the dynamic environment, and the introduction of a digital product passport will lead to changes.

In summary, from a research perspective, the business models need to be further developed and evaluated, as well as the data requirements and data providers identified for each use case, to assess and increase ecological maturity and added value. In order to assess the industrial relevance, it is recommended to conduct interviews with various representatives of the entire supply chain as a first step to validate the use cases. In addition, the application scenarios should be described in a software application. It is also possible to transfer the application potential of a DT for CE to other sectors, such as aerospace, rail, or machinery, as CE is cross-industry. Additionally, it would be interesting for further research to compare in which phases of the PLC data collection occur and in which phase this data is provided and utilized in the form of a use case.

The concept of DT for CE should be increasingly implemented within an industrial context, and the actual potential from a sustainability perspective should be assessed for several product types.

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