DIGITALIZATION MEETS CIRCULAR ECONOMY

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This paper examines the role of digitalization in the implementation of the circular economy (CE). It shows that the circular economy can be seen as a tool for sustainability and that digitalization is a key driver for its implementation. The links between the circular economy and digitalization are shown and the concept of the digital circular economy is presented based on a narrative literature analysis. The Smart CE framework and the Digital Function for Circular Economy (DF4CE) framework are presented. The DF4CE framework links digital functions to the 10 R strategies of the circular economy. It derives seven mechanisms for how digital functions can improve the circular economy, including recycling, reuse and reduction. The paper emphasizes that further empirical research and practical guidelines are needed for the further development of the digital circular economy.

Keywords:
circular economy,
digitalization,
sustainability,
smart CE framework,
DF4CE framework

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1 Introduction and Motivation

Driven by global challenges such as climate change and resource scarcity, sustainability has become a critical megatrend that aims to balance current and future environmental, social, and economic needs, often guided by the UN Sustainable Development Goals (SDGs). (*THE 17 GOALS | Sustainable Development*, n.d.)The circular economy is a specific approach that supports this goal. It's a transformative model that replaces the linear "take-make-dispose" system by focusing on minimizing waste and maximizing resource use through closed loops, keeping materials in circulation longer. The circular economy aims to reduce environmental impact, increase resource efficiency and promote sustainable economic growth without depleting finite resources, thereby supporting ecological balance and social equity. In fact, the circular economy is seen as a tool for achieving the SDGs as stated, e.g., in the EU circular economy objectives. (Rodríguez-Antón et al., 2022) Essentially, the circular economy serves as a critical tool for achieving broader sustainability goals, including the SDGs, by conserving resources and protecting the environment for future generations. While sustainability is the goal, circular economy is an important means to achieve it, complementing other approaches such as energy efficiency.

Digitalization, a key megatrend, is the use of digital technologies to improve or transform activities. More broadly, digital transformation involves fundamental changes in organizational culture, business models, and value creation. Crucially, this transformation can strategically advance sustainability and circular economy goals, making digitalization a key driver of the circular economy. The importance of digitization to support the implementation of the circular economy has been clearly addressed by several academic authors and many other organizations, such as the World Economic Forum (WEF) or the OECD. (e.g. (Barteková & Börkey, 2022; (Jensen, 2022) Kristoffersen et al., 2020; Neligan et al., 2023) Thus, businesses will "create new opportunities for innovation, differentiation, synergies and jobs."(Jensen, 2022) For example, (Neligan et al., 2023) show that in the manufacturing sector, companies with a strong digital focus are more likely to adopt new business models that promote resource efficiency; other examples include the textile and the agricultural industries. (Heim & Hopper, 2022)(Farace & Tarabella, 2024).

The term "Digitainability" links the megatrends of sustainability and digitalization, emphasizing often-overlooked synergies. (Lichtenthaler, 2021) Scarce existing literature focuses on strategic perspectives, proposing frameworks like the Digitainability Assessment Framework (DAF) or conceptual models for integration. (Gupta & Rhyner, 2022)

As the concept of circular economy can be understood as a tool for sustainability, it can be assumed that applying digitalization to the circular economy would result in much more concrete and practical instructions for action. Therefore, in this paper, we would like to address the following research question: How can digitalization, e.g., through tools like the digital product passport, support the implementation and effectiveness of circular economy strategies?

To provide a broad overview of current knowledge, we use a narrative literature review. This method synthesizes research to provide a comprehensive, interpretive summary of a topic. Unlike systematic reviews with strict methodologies, narrative reviews are more flexible and subjective, incorporating different studies and perspectives. (Paré et al., 2015, p. 185 pp; Tate et al., 2015) However, narrative reviews face challenges such as subjectivity and bias in study selection and interpretation. Their less transparent and reproducible methods can hinder verification and lead to incompleteness. They often lack critical appraisal of study quality, which limits the generalizability of conclusions and makes them less suitable for making definitive recommendations than systematic reviews. Comprehensive analysis of complex, multidisciplinary topics is also inherently difficult for any literature review.

The paper is organized as follows: After the introduction, we will elaborate on the concept of circular economy as well as the corresponding implementation strategies, thus setting the stage for the discussion of the role of digitalization in the implementation of the circular economy. Then the role of digital technologies as drivers of the circular economy will be elaborated, followed by the presentation of the digital circular economy. Some conclusions will be drawn.

2 Circular Economy

In the following we first introduce the circular economy concept in more detail before presenting implementation strategies for the circular economy.

2.1 The Circular Economy Concept

The long-dominant linear economy operates on a "take-make-dispose" principle: extract raw materials, make products, and discard them as waste. While this model drives growth, it depletes finite resources and generates significant pollution. (Luban et al., 2025)

In stark contrast, the circular economy represents a paradigm shift, advocating a "close the loop" system. The concept was first developed in the 1970s. (Stahel, 2016) While definitions vary, Kirchherr et al. provide an in-depth discussion of the various understandings and conceptualization of the term. According to the authors the circular economy is an economic model that uses innovative business strategies to replace the "end-of-life" concept. It focuses on minimizing waste and promoting the reuse, recycling and recovery of materials throughout production, distribution and consumption. This model works at the micro (products, businesses, consumers), meso (eco-industrial parks) and macro (cities, regions, nations) levels. Its overarching goal is sustainable development, which aims to improve environmental quality, achieve economic prosperity, and ensure social equity for present and future generations. (Kirchherr et al., 2017, p. 224)

The circular economy challenges the linear model by prioritizing minimal waste and maximum resource use. It aims to eliminate waste and pollution, keep products/materials in circulation through reuse, repair and remanufacturing, and regenerate natural systems. This requires a shift from over-consumption to responsible resource management through reduction, reuse and recycling. The goal is a regenerative system that minimizes environmental impact while promoting long-term economic prosperity - a critical step toward a sustainable and resilient future.

The circular economy aims to decouple economic value from resource consumption, ultimately reducing material flows and their environmental impacts, including greenhouse gas emissions. Prioritizing resource prevention and minimizing the use of raw materials is therefore key, surpassing recycling in importance. (Hofer et al., 2025)

The transition from linear ("take-make-consume-discard") to circular models represents a significant shift in resource management and production, driven by environmental degradation, resource depletion, and sustainability requirements. The circular economy offers a regenerative model that focuses on resource efficiency, waste reduction, and closed-loop systems. (Dabija & Năstase, 2024) Some of the key drivers of the transition include: (Dabija & Năstase, 2024; Dennison et al., 2024; Supanut et al., 2024)

- Environmental concerns: The depletion of natural resources and the environmental impact of industrial activities have necessitated a shift to sustainable practices. The circular economy provides a framework for reducing waste, emissions, and resource extraction.
- Resource scarcity: The finite nature of natural resources has prompted industries to explore ways to extend the life cycle of materials and products. Circular economy principles such as reuse, recycling, and remanufacturing address this challenge by promoting resource conservation.
- Economic opportunities: The circular economy offers opportunities for innovation, cost savings and competitive advantage. Businesses can create new revenue streams through product-as-a-service models, sharing platforms, and resource recovery.

2.2 Implementation Strategies for the Circular Economy

Concepts such as sustainability, digitalization and circular economy are all rather high-level and offer few concrete instructions for action. Therefore, the concepts need to be concretized and operationalized. One of the most frequently mentioned concepts in the scholarly literature and among practitioners are the so-called "R-strategies". (Hänggi et al., 2025)

The 'R-strategies', also known as circular strategies, are a fundamental operationalization of the circular economy. They provide a practical framework for businesses and policymakers to transition from a linear "take-make-dispose" model to a circular one. They form a central framework of the circular economy that aims to keep products and materials in a continuous cycle, minimize the consumption of natural resources and reduce waste production.

Although there are different numbers of these so-called R-strategies, in the literature most authors refer to Potting et al. who propose 10 different R-strategies. (Potting et al., 2017). Based on an extensive review of the literature, Kirchherr et al. also identified these 10 R strategies. (Kirchherr et al., 2017) So the number of "R's" can vary, but the underlying principle remains the same: to create a closed-loop system. Since the 10 R's are well described in the literature, we will only briefly summarize them below.

To provide a clear flow of the 10 R-strategies, imagine a descending ladder, where each step represents a strategy, with the most desirable at the top and the least at the bottom. Here's a flow text description: At the top of this hierarchy are strategies that aim to make consumption and production more sustainable from the outset. These include Avoiding non-essential products (**Refuse**), Rethinking the efficiency of use (**Rethink**), and reducing the use of resources (**Reduce**). These approaches aim to reduce the need for new products and resources from the outset. The next stage involves strategies to extend the life of products and components. These include **Reuse**, **Repair**, **Refurbish**, **Remanufacture** and **Repurpose** of products. These measures help keep products in use longer and reduce the need for new products. The final stage is recycling (**Recycle**) and recovering energy from waste (**Recover**).

However, not all 10 strategies are implemented to the same extent.

While considerable practical and scholarly attention has been focused on understanding circular consumer practices, including reuse, recycling, and repair, the comprehensive research conducted by (Zimmermann et al., 2024) reveals a notable deficiency in examining the importance of consumer behavior with respect to other central R-strategies, particularly refuse, rethink, and reduce (strategies closely related to consumer attitudes and mindful consumption) and refurbish and remanufacture (strategies that involve the reintegration of a product at the end of its life cycle to be used again in its original capacity). In their research, the authors also analyzed the barriers to further adoption of circular R strategies. In their recent book (Podleisek et al., 2025) present several case studies of successful circular market offerings, with details on each retention option.

These approaches are designed to make effective use of materials that can no longer be used in their original state. Although strategies such as reuse, recycling, and repair are at the bottom of the hierarchy, they play an essential role in the transition to a circular economy by ensuring that waste products and materials are used as much as possible and returned to the production cycle.

Based on an also extensive study of real-world cases as well as a literature review (Hofer et al., 2025) ropose a different framework. The so-called "Value Hill" concept is used to illustrate the product life cycle (PLC) in both a linear and a circular context. In the linear value hill, the focus is on maximizing short-term profits, with little attention paid to the long-term sustainability of the product and the resources used. The authors differentiate the pre-use, use, and post-use phase. In the circular value hill, value is also added in the pre-use phase, and the highest value is reached in the use phase. However, if the product declines in the post-use phase, the Rs aim to slow down or close this cycle and capture the added value of the product beyond its use phase by retaining all or part of the resources already used.

3 Digital Technologies as Drivers of the Circular Economy

Digitization is the process of converting analog information into a digital format. Essentially, it's taking something physical or analog and turning it into digital data. Digitalization is about using digitized information to improve or enable existing processes. It's about using digital technologies to make processes more efficient. Digital transformation is about fundamentally changing the way an organization operates by integrating digital technologies across all areas of the business. It's about creating new business models, cultures and customer experiences. Relevant digital concepts and technologies include the Internet of Things (IoT), smart factory, cyber-physical systems (CPS), big data analytics, cloud computing, artificial intelligence (AI), distributed ledger technology (DLT) and blockchain, digital twin, digital product passport (DPP), digital platforms, and digital data spaces. Digital technologies have the potential to serve as central facilitators of the circular economy by closely monitoring the path of products, components, and materials, while making the resulting data accessible for improved resource management and informed decision-making at various stages of the industrial life cycle. (Hariyani et al., 2024; Kristoffersen et al., 2020)

Data plays a pivotal role in digital transformation by serving as the foundation upon which organizations can build more efficient, innovative, and competitive operations. Integrating data into business processes enables better decision-making, improved customer experiences, and streamlined operations. This transformation is driven by the ability to collect, analyze, and leverage vast amounts of data to gain insights and drive strategic initiatives. At its core, data is the raw material that fuels digital transformation. It provides the insights, intelligence, and direction needed to drive meaningful change.

In this context, based on a comprehensive literature study Kristoffersen et al. come up with the "Smart CE framework". (Kristoffersen et al., 2020) The framework consists of three main components: data transformation layers, resource optimization capabilities, and an intermediate layer that connects these components and consists of data flow processes, as shown in Figure 1. The various components were brought together using a hierarchical structure as the primary organizing principle, where each successive level is dependent on its predecessors. Specifically, regarding the data transformation level, resources must be connected via an Internet of Things (IoT) sensor to facilitate the generation of data. This data can then be transformed into information by integrating it with additional data sources and providing contextual relevance, culminating in the achievement of wisdom.

Similarly, in terms of resource optimization capabilities, diagnostic analytics provides insight into the underlying causes of events while building on descriptive analytics that elucidate the actual events. Similarly, data flow processes initially collect and integrate data to increase the effectiveness of data analytics.

In their paper Berg & Wilts state that implementing circularity is primarily an information problem. Numerous elements play a significant role in generating information asymmetries and market opacities that support a "take-make-dispose" of the linear economy paradigm. (Berg & Wilts, 2018) Examples are, among others, lack of information about used products and secondary materials, lack of data regarding product and material compositions, lack of data standards affect the comparability of environmental costs. (Staab et al., 2022) Both, Staab et al. as well as Berg & Wilts argue that when it comes to implementing the circular economy, digital data platforms can offer several benefits.

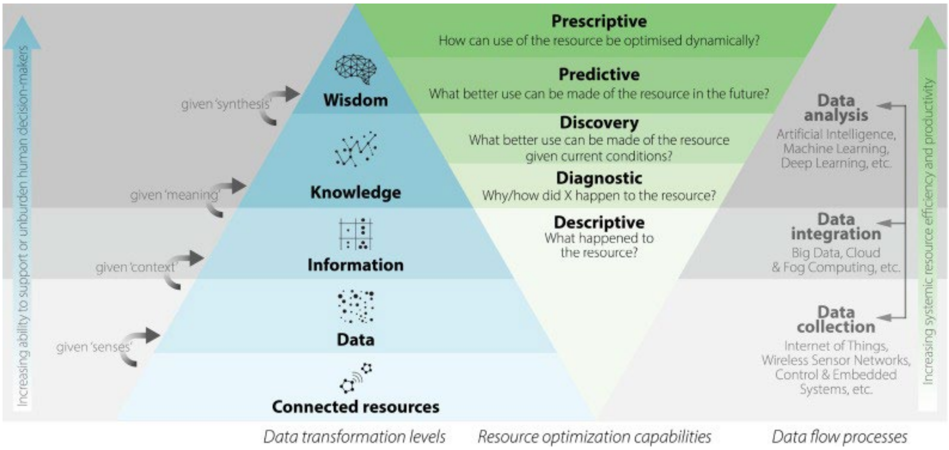

Figure 1: Smart Circular Economy Framework
Source: (Kristoffersen et al., 2020)

Data platforms play a critical role in advancing circular economy strategies by enabling the efficient sharing, management, and use of data across multiple sectors. These platforms support the transition to a circular economy by promoting sustainable practices such as reducing, reusing and recycling resources. They achieve this by providing a structured environment for data sharing and collaboration between stakeholders, thereby improving decision-making processes and fostering innovation. To this end, information-sharing platforms have been developed to facilitate the exchange of information such as the location of actors, the resources to be shared, and the costs of operating in such a network. In their recent research Möller et al. give an in-depth introduction and overview of data spaces and data space-enabled data ecosystems. (Möller et al., 2024)

In some cases, data sharing is now necessary to comply with regulations. In their recent paper Ströher et al. elaborate the case of adoption of automated data sharing for "carbon accounting" within and beyond organizations' boundaries is imperative to comply with existing and upcoming regulations, to maintain competitiveness, and to foster sustainable practices for mitigating climate change. (Ströher et al., 2025)

However, real-world data platform implementation faces several challenges, ranging from jointly agreed data models to organizational orchestration mechanisms. (Acerbi et al., 2022; Blackburn et al., 2023)

Thus, data platforms are systems that collect, manage, and analyze data from various sources. They shall act as a central repository for storing data, making it easily accessible for users and applications. "Digital Product Passports" (DPPs) as a structured collection of product data throughout its entire lifecycle, rely on data platforms for their storage, management, and accessibility. DPPs use a unique identifier and electronic access to share product data, making them essential components of modern data platforms. DPPs are seen as concrete measure to implement circular economy strategies. (Plociennik et al., 2022; Ramesohl et al., 2022; Zhang & Seuring, 2024)

However, the implementation of Digital Product Passports (DPPs) in the context of the circular economy faces several challenges and barriers. These barriers are mainly related to technological, organizational and environmental factors that hinder the effective adoption and use of DPPs. Despite their potential to improve transparency, traceability and sustainability throughout the product life cycle, these challenges need to be addressed to fully realize the benefits of DPPs in promoting a circular economy. In line with the extensive research conducted by Chaudhuri et al., four primary barriers are identified: the need to formulate and articulate the business case for adopting DPPs; the increased demand for data; the establishment of data standards and ensuring interoperability between systems; the level of implementation effort required; and the need to ensure data security and integrity. (Chaudhuri et al., 2024)

In another study, the authors, while focusing on the building sector, identified challenges such as the lack of standardization of data templates and difficulties in collecting and tracking the data needed to create and maintain DPPs. Standardization would facilitate the implementation of passports, but aligning existing approaches and identifying overlaps remains a current challenge. (Honic et al., 2024) In addition to standardization and complex data management, Abedi et al. identified reluctance to share information between partners as a major obstacle to the adoption of DPPs in the circular economy. (Abedi et al., 2024)

In their recent work, Heeß et al. develop design principles that provide insight into how a Digital Product Passport should be designed to address the challenges and ensure the willingness of stakeholders to share their data, using the case of the low carbon hydrogen market. (Heeß et al., 2024)

A data-driven circular economy requires access to data throughout the product lifecycle. This requires breaking down data silos, facilitating data sharing across stakeholder boundaries, and fostering a culture of collaboration for collective benefit. Digitalization and data availability are key enablers, and a concrete measure to achieve this is the implementation of data platforms and digital product passports (DPPs).

4 The Digital Circular Economy

If we accept that digitalization plays a crucial role in the implementation of the circular economy, then the question arises as to how digital technologies or the digital functions identified by Kristofferson et al., for example - data collection, integration and analysis - can be applied specifically in the context of circular economy strategies. (Kristoffersen et al., 2020) In their study, the authors use examples from the literature to illustrate the relationship between digital technologies that support circular strategies in operational processes.

Based on an extensive study Liu et al. develop a framework of digital technologies for the circular economy. (Liu et al., 2022) To our knowledge, this is the only comprehensive study to explore the concept of the digital circular economy in detail.

In the framework the authors link digital functions to the 10 circular economy strategies (10 R) based on their study of the literature. In the study, the authors provide details on each feature, including examples drawn from the literature. The intersections of the x-axis (circular economy strategy) and the y-axis (digital functions) form different combinations of using a specific digital function to enhance a specific circular economy strategy. Using the relevant details from the study, the framework clarifies which digital technologies can be used to support which circular economy strategy.

Furthermore, the authors come up with seven so-called 'mechanisms'. These mechanisms were derived by mapping the digital functions discussed in the papers examined to the corresponding circular strategies. The results of this mapping are presented in the "Digital Function for Circular Economy" (DF4CE) framework (Figure 2). The size of the circles in represents the number of mentions during the analysis and thus the frequency of discussion in previous studies. A higher frequency indicates a more comprehensive understanding of the implementation of digital functions for circular strategies. Thus, the seven derived mechanisms describe how digital functions can contribute to improving the circular economy.

It is evident that within the field of literature, these digital functionalities are predominantly employed for the purpose of ***reduce***, succeeded by ***rethink***, and subsequently, ***recycle***. Again, the study provides several examples of the respective intersections based on the literature analysis. Furthermore, the authors claim that the seize of the circle can be interpreted as the respective maturity level of each specific digital function for each specific circular economy strategy. While this sounds understandable, one should be careful not to equate the number of use cases identified with the maturity of the solutions.

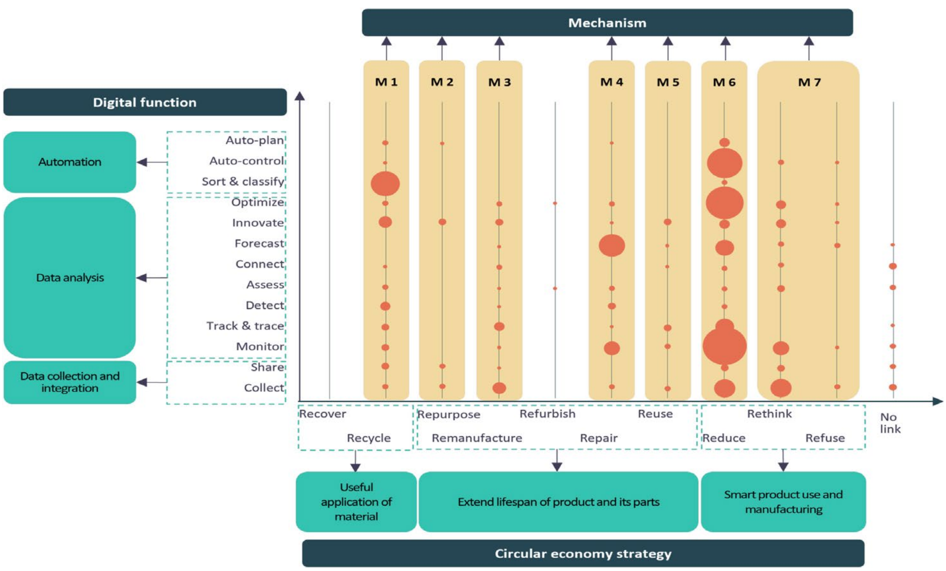

Figure 2: Structure of conceptual framework
Source: (Liu et al., 2022)

The research by Liu et al. certainly contributes to the theoretical understanding of how digitalization can support the implementation of circular economy strategies. Moreover, the paper provides some practical insights based on the examples identified in the literature. However, despite its valuable contribution to the field on the relationship between digital technologies and circular economy strategies, further research is needed to derive real-world guidelines to support the further development of the digital circular economy.

5 Conclusions

The aim of this research was to provide a comprehensive overview of existing knowledge on the relationship between how digitalization can support the implementation of the circular economy, based on a narrative literature review. It was found that the topic as such is quite complex. Not only are the concepts of digitalization and circular economy as such complex, but as a third dimension we also must consider the respective industry contexts.

However, this approach has several shortcomings. First, the methodological approach does not systematically cover the existing knowledge in the field. This would require a systematic literature review. Second, although some relevant findings could be developed, they are still insufficient. On the one hand, because of the non-systematic literature review, and on the other hand, from a practical point of view, the results need further investigation and further research.

From a practical point of view, it would be necessary not only to learn how to implement the R strategies in a specific business and industry context, but also to enable companies to prioritize the possible actions regarding solving existing challenges and/or deriving corresponding benefits. Therefore, a qualitative analysis such as the framework presented can only serve as a starting point. A quantitative assessment would be a necessary next step. Also, as the examples mentioned in Liu et al. are based on the analyzed literature, an analysis of real cases in different industries and thus empirical research would also be an important contribution. (Liu et al., 2022)

Another avenue for future research will be the role of integrated data platforms and DPPs in their respective contexts, as several challenges may arise, such as how to motivate actors in a given ecosystem to share data on a common platform. In addition, the issue of data security and privacy becomes relevant and important when collecting and sharing data.

Additional barriers and challenges to the adoption of digital technologies for circular economy implementation that should be further explored are identified in the research by Hariyani et al.: Costs of implementation, complexity and integration issues, data protection and security concerns, interoperability and standardization, risk management, resistance to change and cultural barriers, data quality and reliability, ethical and social implications, regulatory and political framework conditions, technological developments. (Hariyani et al., 2024) In addition, the authors, as well as Liu et al., based on their review of the literature, mention several future avenues of research in the area discussed in this paper. (Liu et al., 2022)

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