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REVIEW OF DIGITAL TECHNOLOGIES FOR THE CIRCULAR ECONOMY AND THE ROLE OF SIMULATION

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ABSTRACT

The Circular Economy (CE) is essential for achieving sustainability, with digital technologies serving as key enablers for its adoption. However, many businesses lack knowledge about these technologies and their applications. This paper conducts a structured literature review (SLR) to identify the digital technologies proposed in recent literature for CE, their functions, and current real-world use cases. Special attention is given to simulation, which is considered a valuable digital technology for advancing CE. The analysis identifies the digital technologies Artificial Intelligence, the Internet of Things, Blockchain, simulation, cyber-physical systems, data analytics, Digital Twins, robotics, and Extended Reality. They are used for waste sorting and production automation, disassembly assistance, demand analysis, data traceability, energy and resource monitoring, environmental impact assessment, product design improvement, condition monitoring, predictive maintenance, process improvement, product design assessment, and immersive training. We discuss the findings in detail and suggest paths for further research.

1 INTRODUCTION

The United Nations proposed 17 Sustainable Development Goals (SDGs) in 2015, aiming to achieve greater sustainability by 2030 (United Nations 2015). Businesses should adapt their practices to align with Circular Economy (CE) principles, as CE is considered essential for achieving the SDGs and reaching net-zero emissions (Govindan 2023). Among the enablers of CE adoption are digital technologies (Sharma et al. 2023). There is no uniform definition for digital technologies. Appelfeller and Feldmann (2023) define digital technologies as technical components, concepts, and methods for the digital transformation of businesses that involve hardware, software, and/or connectivity, with functionalities based on digital data. These technologies enhance competitiveness and can contribute significantly to business value (Appelfeller and Feldmann 2023).

However, studies indicate that businesses often lack knowledge of digital technologies and their applications (Appelfeller and Feldmann 2023), which hinders CE implementation and the transition toward sustainability. This paper addresses this knowledge gap by summarizing which digital technologies are proposed in recent literature and outlines their functions and use cases for CE. The goal is to support businesses in identifying suitable technologies to accelerate their sustainability transitions. A particular emphasis is placed on simulation, an established digital technology in domains related to sustainability, which has also been proposed as a key enabler of CE (Charnley et al. 2019). Thus, special attention is payed to the current role and applications of simulation. In doing so, this paper also contributes to the simulation research community by contextualizing its relevance within CE. The following research questions (RQs) guide this work:

- **RQ1**: What digital technologies are proposed for CE?
- **RQ2**: What functions do these technologies serve within the context of CE, and what are their reported use cases?
- **RQ3**: What is the current role of simulation in facilitating CE practices?

This paper is structured as follows: Section 2 introduces CE and simulation, including an overview of related publications. Section 3 outlines the steps of the structured literature review (SLR), which serves as the research method to answer the RQs. Section 4 summarizes the findings, while Section 5 discusses them. The paper concludes and offers an outlook in Section 6.

2 CIRCULAR ECONOMY AND SIMULATION

CE is a key factor in achieving sustainability (Geissdoerfer et al. 2017). Sustainability seeks to achieve a balance between economic growth, social fairness, and environmental resilience, catering to the needs of both current and future generations (Geissdoerfer et al. 2017). Boulding (1966) first introduced the concept of CE, arguing that finite resources must be recovered and reused to address scarcity. Since then, the importance of CE in both research and industry has increased (Frishammar and Parida 2019).

Nowadays, CE is defined as an economic system centered around business models that shift away from the 'end-of-life' concept, focusing instead on reducing, reusing, recycling, and recovering materials to achieve sustainable development for the benefit of both present and future generations (Kirchherr et al. 2017). In this context, CE aims to minimize emissions, resource input, waste, and energy inefficiencies by slowing down, constricting, and closing material and energy cycles (Geissdoerfer et al. 2017). A framework that structures strategies to accomplish this is the 9R-framework by Potting et al. (2017), which consists of the ten approaches: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover to increase circularity. These strategies are ranked in order of impact, where Refuse significantly enhances circularity while Recover has the least effect. Using this framework as a guideline, the end-of-life concept can be replaced by business models targeted at sustainable development (Kirchherr et al. 2017). Consequently, CE can help to tackle environmental, social, and economic challenges (Schroeder et al. 2019).

Related work on digital technologies for CE includes Schöggl et al. (2023) who examine the implementation stages of four digital technologies for the CE. Rusch et al. (2023) review applications of four digital technologies for the CE using sustainability-related terms and automated coding. Sánchez-García et al. (2024) identify opportunities and challenges, focusing on two digital technologies.

Simulation is one digital technology that holds significant potential for advancing CE goals. It is employed to examine systems with experimental models to gain valuable insights (VDI 2014). Simulation is widely applied across domains related to CE, such as sustainability (Moon 2017). Within the scope of CE itself, Charnley et al. (2019) highlight how simulation supports data-driven approaches in the context of CE. Furthermore, La Torre et al. (2021) emphasize the importance of simulation as an educational tool for promoting awareness and understanding of CE principles, which are important in driving systemic changes towards the implementation of CE. Recent advancements in simulation applications have expanded its utility to specialized areas within CE, such as small medical devices, as demonstrated by Shoaib et al. (2024). Additionally, simulation can be integrated with other emerging digital technologies relevant to CE, including Digital Twins (DTs) and immersive platforms like the Metaverse (Kunert et al. 2024), further broadening its scope and impact. To the authors' knowledge, no review focusing specifically on simulation within the context of CE has been discussed in the literature to date.

3 RESEARCH METHOD

In order to answer the RQs, our research design is structured with a five-step approach, adopting the methods of vom Brocke et al. (2009) for SLRs in information systems. It consists of establishing a suitable review scope, conceptualizing the topic, conducting the literature search, analyzing and synthesizing the literature, and outlining the research agenda. This approach enhances the legitimacy of our work and helps us achieve our objective of summarizing prior knowledge, as it ensures methodological rigor, reproducibility, transparency, and traceability (Paré et al. 2016).

First, we limited the review scope to representative peer-reviewed English conference papers and journal articles on digital technologies for CE to synthesize proposed technologies and their applications.

Second, we explored different terminologies used in the literature to conceptualize the topic. We identified that the key term "method" should be included as a conceptual synonym for technology-related approaches, ensuring a more comprehensive literature synthesis.

In step three, the actual literature search, we searched the databases Scopus and IEEE Xplore using the search string: "circular economy" AND ("technolog*" OR "method"). We limited the search to publications from 2023 and 2024, as a recent state of the art is most relevant to our topic. We only included the 50 most cited works from each year and each database, making our approach representative but not exhaustive (Cooper 1988). From these 200 papers, only ones with a citation count of at least two were included. This led to 50 papers from each 2023 and 2024 from Scopus with a citation count of at least two, eight papers from IEEE Xplore from 2023, and ten papers from 2024 from IEEE Xplore.

In step four, during the analysis and synthesis, duplicates and inaccessible papers were removed, resulting in 113 publications. Next, abstracts were checked for relevancy to our topic, which resulted in 73 papers. After a full paper check for relevancy and quality criteria, like sound argumentation and an established research methodology (Levy and Ellis 2006), a final number of 50 publications remained. We then synthesized their findings to answer our RQs.

In the final step and Section 5, we formulated a research agenda for future work. Our research method allows us to address the RQs with the findings presented in the next section.

4 FINDINGS

The SLR identified nine digital technologies: Artificial Intelligence (AI), the Internet of Things (IoT), Blockchain, simulation, cyber-physical systems (CPS), data analytics, DTs, robotics, and Extended Reality (XR). Figure 1 illustrates the share of publications mentioning the digital technologies. Some publications address multiple digital technologies. AI is the most frequently mentioned digital technology in the context of CE, appearing in over half of the 50 publications, followed by IoT at 46%. Only one publication addresses XR. Each identified digital technology, along with its corresponding functions and use cases synthesized from the SLR, is detailed in this section. For a brief overview, the functions derived from the detailed descriptions are summarized in Table 1.

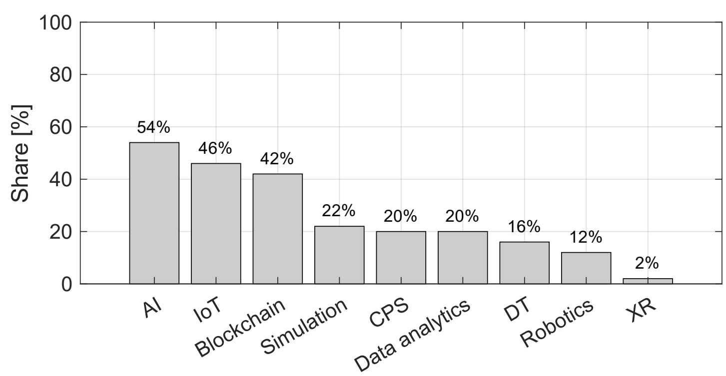

Figure 1: Share of publications mentioning a digital technology.

Table 1: Identified functions of digital technologies.

Digital technology	Identified functions
AI	Consumer behavior analysis; Demand prediction; Disassembly and remanufacturing assistance; Energy usage optimization; Personalized

	production; Predictive maintenance; Quality control; Waste sorting automatization and classification
IoT	Environmental impact monitoring; Life cycle data tracking and transmission; Predictive maintenance; Process automatization; Process management enhancements; Product design improvement
Blockchain	Data traceability; Tamper-proofing of data
Simulation	Condition assessment; Energy demand assessment; Energy usage optimization; Predictive maintenance; Process improvement; Product design improvement; Scenario analysis and decision support
CPS	Data-driven decision support; Energy and resource usage monitoring; Process automatization; Waste collection optimization; Waste sorting automatization
Data analytics	Consumer behavior analysis; Data-driven decision support; Environmental impact assessment; Financial management; Predictive maintenance; Product design improvement; Route optimization
DT	Condition monitoring; Data collection and representation; Data-driven decision support; Key performance indicator assessment; Smart contracts
Robotics	Dangerous task handling; Disassembly; Process automatization; Waste sorting automatization
XR	Immersive learning and training

4.1 Artificial Intelligence

AI supports CE by optimizing resource use, minimizing waste, and improving efficiency, thereby reducing environmental impact and enhancing sustainability (Hegab et al. 2023; Narula et al. 2024). Using AI algorithms and cameras, waste can be automatically and accurately sorted by identifying and distinguishing between different materials (Kurniawan et al. 2023a). By processing data collected from smart sensors, AI can rapidly classify complex waste streams (Kurniawan et al. 2023b), for example, batteries reaching end-of-life (Harper et al. 2023). In this context, AI can infer missing information, such as battery condition, from historical data, which is particularly beneficial for non-disassemblable battery packs (Harper et al. 2023). AI also enhances product disassembly by enabling systems to respond dynamically to specific contexts, thereby increasing flexibility and autonomy in production (Liu et al. 2023).

AI algorithms can analyze data to detect consumer preferences, offering more profound insights into consumer behavior (Liu et al. 2023). Understanding consumption patterns helps reduce material waste from overproduction (Sánchez-García et al. 2024), aligning with the most circular R-principle, Refuse (see Section 2). Consumer preferences can also be considered through AI-enabled personalized production, reducing waste from large-scale manufacturing (Liu et al. 2023). In product design, AI can support resource efficiency by suggesting materials and design choices after evaluating different options (Narula et al. 2024).

AI can improve energy efficiency by optimizing production scheduling based on renewable energy availability (Okorie et al. 2023) and enhancing energy management through AI-driven smart home systems (AlWadi et al. 2023).

In CE applications, AI is already being used for quality control of recovered non-biodegradable waste, enabling its reintegration into production as secondary raw materials and improving recycling efficiency (Kurniawan et al. 2023a). In remanufacturing, AI is applied in robotic assistance, order processing, inventory management, predictive maintenance, and automation of shop floor processes with minimal human intervention. Machine learning is also used to detect patterns that improve system efficiency (Govindan 2023). Schöggl et al. (2023) report that AI is most commonly used for predictive maintenance, demand forecasting, and inventory management, with the highest adoption levels found in the construction, wood, and electronics industries.

4.2 Internet of Things

IoT enables device interconnectedness, creating new information networks (Rusch et al. 2023). Businesses can leverage IoT to monitor and assess their environmental impact (Sharma et al. 2023), such as tracking CO_2 emissions in production through connected devices (Kusi-Sarpong et al. 2023). Consumers also benefit from IoT home applications like smart meters, so that they can optimize their energy use (AlWadi et al. 2023). Additionally, IoT helps to automate processes in the CE (Kusi-Sarpong et al. 2023). Through the data transfer and processing by interconnecting devices and facilities, automatic process identification and management can be facilitated (Jiang et al. 2023). Smart waste bins equipped with IoT sensors monitor fill levels and waste generation patterns to optimize collection routes (Kumar and Singh 2024). This cuts fuel consumption and CO_2 emissions in waste management.

IoT enhances tracking and tracing along the SC by enabling real-time status updates. This allows businesses to efficiently manage green-fueled autonomous vehicles for long-distance distribution, minimizing CO_2 emissions and optimizing working hours (Liu et al. 2023). Tracked life cycle data supports end-of-life decision-making and is stored in digital product passports, facilitating reuse, such as for batteries and product design assessment (Schöggl et al. 2023), as seen in IoT-enabled data collection from household appliances (Rusch et al. 2023). By collecting real-time machine health information for predictive maintenance through IoT, maintenance costs and machine downtime can be reduced (Okorie et al. 2023). This reduces resource consumption by extending the lifespan of machines (Kurniawan et al. 2023b).

A use case for this is Thyssenkrupp who use IoT for predictive maintenance of elevators (Narula et al. 2024). IoT is further utilized for intelligent identification and connectivity in waste management (Jiang et al. 2023) and for tracking energy use. Rolls Royce uses IoT to monitor engine data in cars to extend their lifespan (Rusch et al. 2023). The company HP employs IoT-enabled sensors in ink cartridges to track usage and notify users when replacements are needed, streamlining the return process (Rusch et al. 2023). IoT is primarily used for data acquisition in production, followed by data collection during the use phase, with end-of-life data collection being the least common. The electronics industry (Schöggl et al. 2023) and manufacturing industry (Pandey et al. 2023) are the most frequent users of IoT.

4.3 Blockchain

Blockchain can be used to trace battery materials and their origins, ensuring ethical sourcing and enabling improved recycling processes (Harper et al. 2023). Stored data may include material composition, carbon footprint, and recycled content, such as in the case of aluminum (Alkaraan et al. 2023).

Due to its immutable nature, Blockchain ensures the trustworthiness of stored data. Smart contracts operating on a blockchain can automate waste management protocols, reducing reliance on intermediaries (Jiang et al. 2023). Blockchain's decentralized data processing is also a foundational element for implementing digital product passports. By storing tamper-proof data decentralized, Blockchain enhances transparency across supply chains and promotes equal data access (Da Ribeiro Silva et al. 2023). This can foster trust among SC partners and incentivize data sharing, a critical factor in the CE (Da Ribeiro Silva et al. 2023), for example, for digital product passports (Nowacki et al. 2023). Blockchain can also motivate consumers to participate in CE initiatives. For instance, automated payments as incentives can be issued when consumers dispose of waste using IoT-enabled bins (Kurniawan et al. 2023b).

Despite its potential, Blockchain currently has low implementation in CE-related industries. The most common use case is product origin tracking, followed by compliance management, ecological footprint tracking, and smart contracts (Schöggl et al. 2023). For instance, IKEA uses Blockchain technology to verify that environmentally labeled products meet sustainability standards (Rusch et al. 2023), while BMW uses it to trace cobalt sources for battery production (Rusch et al. 2023). Blockchain is also employed for reverse logistics data disclosure and by startups for tracking raw materials and textiles (Trevisan et al. 2023).

4.4 Simulation

Based on the analyzed literature, simulation is utilized to address various challenges in the CE. Liu et al. (2023) and Piyathanavong et al. (2024) describe simulation as a valuable tool for testing and improving product designs, leading to higher-quality products that are likely to generate less waste. Furthermore, simulation can be applied to optimize processes (Andooz et al. 2023), enhancing efficiency and sustainability. Simulation can also enhance condition assessment and maintenance of physical objects (Xie et al. 2023), thereby optimizing the exploitation of their remaining useful lifetimes. Another function is scenario analysis (Liu et al. 2023), which enables more informed decision-making processes. Pachouri et al. (2024) and Dervishaj and Gudmundsson (2024) highlight the importance of simulation in the energy sector, particularly for analyzing energy demand to improve planning for electricity generation and storage. Some publications refer to simulation exclusively in the context of DTs without elaborating further details (Govindan 2024).

Use cases for simulation within the CE include its application by Xie et al. (2023), who utilized a Bayes-Hermite Monte Carlo simulation approach to examine the remaining useful lifetime of lithium-ion batteries. Govindan (2023) applied simulation alongside mathematical optimization to reduce emissions in SCs, demonstrating this approach with a case study on Iran's wire and cable industry. Liu et al. (2023) report an industrial use case where simulation was employed to monitor and analyze lean operations and waste production at a medicine manufacturing company. An example of successful utilization of simulation in innovate process improvement is provided by Andooz et al. (2023), who identified a process for reusing pyrolyzed wood waste to produce pyrolytic oil and gas.

4.5 Cyber-Physical Systems

CPS support the automation of manufacturing processes (Kusi-Sarpong et al. 2023), optimizing resource efficiency, reducing waste, and enabling adaptive production systems for remanufacturing and recycling. Data-driven decision-making based on CPS further enhances CE practices (Kazancoglu et al. 2023).

Sensors are crucial for CPS, enabling data collection for sustainability goals (Kusi-Sarpong et al. 2023). Ultrasonic sensors, for example, assist in automated waste separation by detecting objects on conveyor belts (Nafiz et al. 2023), while material classification sensors help identify different components (Kurniawan et al. 2024). Smart waste bins with fill-level sensors optimize collection by reducing unnecessary pickups (Kumar and Singh 2024), improving tracking and decision-making in the CE (Narula et al. 2024). Sensors also monitor energy, water, and gas consumption in smart homes, increasing resource efficiency (AlWadi et al. 2023).

Use cases for sensors in CE include bins equipped with sensors to alert owners of their monthly waste generation, while waste collection trucks receive information on the fill levels to optimize pickup routes. Pay-as-you-use models, enabled by these sensors, encourage waste reduction by replacing fixed fees with usage-based pricing (Kurniawan et al. 2023a). For example, sensors for real-time energy monitoring have been installed in the Empire State Building to reduce energy consumption (AlWadi et al. 2023).

4.6 Data Analytics

Data analytics transform data into valuable business insights, enhancing managerial decision-making, for instance, in developing CE capabilities within SCs (Dwivedi et al. 2023). Collaboration with reverse SC partners can be improved through data analytics (Kazancoglu et al. 2023). Functions include environmental impact assessment, predictive maintenance to extend product lifetimes, evaluation and improvement of energy efficiency, consumer behavior analysis, and product design optimization (Schöggl et al. 2023). Data analytics can also support route optimization for fleet and distribution management, thereby reducing fuel consumption (Rusch et al. 2023).

The most frequently reported functions are customer behavior analysis, predictive maintenance, and financial management. Data analytics have been applied in real-life use cases across various industries, including electronics, machinery, and metals. However, most sectors have not yet progressed beyond pilot projects (Schöggl et al. 2023). In contrast, the energy sector anticipates a growing role for data analytics as a key enabler of smart energy management, which is critical for reducing energy consumption (Pachouri et al. 2024).

4.7 Digital Twins

DTs are increasingly recognized as an important digital technology for collecting, integrating, and leveraging data within a cohesive framework. While some publications describe DTs merely as digital representations that store data (Nowacki et al. 2023), other publications emphasize their broader functionality. For instance, Kaewunruen et al. (2022) and Pachouri et al. (2024) highlight the role of DTs in enabling data-driven and automated decision-making processes within the context of CE. Medaglia et al. (2024) underscore the potential of utilizing DTs for CE in the building industry as a promising approach.

Specific applications of DTs in the CE include their use for gathering data to support recycling processes, optimizing battery usage, and simplifying the disassembly of lithium-ion batteries (Harper et al. 2023). Remanufacturing companies also leverage DTs for monitoring, inspecting, and maintaining machinery (Govindan 2024). Additionally, Ghobakhloo et al. (2023) discuss how DTs could support smart contract implementation within CE frameworks. Another example is the work of Dervishaj and Gudmundsson (2024), who propose using DTs to calculate and monitor key performance indicators for assessing building circularity, such as the *Building Circularity Index*.

4.8 Robotics

Robotic arms play a crucial role in the CE by automating waste separation, which helps lower labor costs and speeds up the process of returning materials to the production cycle (Kurniawan et al. 2023a). This boosts material recovery rates and ensures that valuable resources are reintegrated into manufacturing instead of being thrown away. Additionally, autonomous or semi-autonomous robots can facilitate disassembly, a key aspect of reuse and recycling in the CE, by retrieving information about components and visually inspecting items such as batteries (Harper et al. 2023).

Robots enhance workplace safety by handling repetitive and hazardous tasks (Duan et al. 2024), such as disassembling batteries, which pose risks like thermal runaway or toxic exposure. This ensures safe handling of end-of-life products. Furthermore, operating around the clock reduces downtime for remanufacturing or disassembly processes (Duan et al. 2024), ensuring a consistent supply of recovered resources.

Current robotic applications in the CE include collaborative robots, or cobots, which assist human workers with various tasks on assembly and disassembly lines during remanufacturing (Govindan 2023).

4.9 Extended Reality

XR enables users to engage in immersive training within a virtual environment, offering employees an alternative way to learn about sustainable manufacturing practices (Ghobakhloo et al. 2023). For instance, it can be used to train disassembly processes relevant to the CE without consuming resources or risking damage to real equipment.

Use cases of XR for the CE have not been mentioned in the analyzed literature.

5 DISCUSSION

In the SLR, four publications reference additive manufacturing as a digital technology for the CE. However, we have opted not to classify it as a digital technology, as additive manufacturing primarily focuses on a physical production process rather than the digital components or concepts driving digital transformation. At its core, additive manufacturing is fundamentally a manufacturing technique. Nevertheless, it can be viewed as complementary to the identified digital technologies and can potentially reduce excess material waste (Ghobakhloo et al. 2023).

Similarly, cloud computing was mentioned in four publications but is also excluded from our classification of digital technologies in this paper. Rather than being a standalone digital technology, cloud computing functions as an enabling medium, like a computer or hardware, that facilitates the effective deployment of digital technologies.

Many publications tend to address specific digital technologies only superficially and often refer to them in broad terms, often using the overarching concept of Industry 4.0. This lack of detail makes it difficult to fully understand the functions and use cases of the specific digital technologies discussed. This tendency may arise from a focus on broad conceptual frameworks rather than detailed explorations of individual digital technologies, highlighting the research gap that this paper aims to address.

Frequently, authors emphasized that combining technologies is crucial for achieving optimal results in their proposed applications within the CE. For example, Pandey et al. (2023) highlight the critical role of IoT driven by AI in production automation. Furthermore, simulation can enhance other digital technologies, for example, for optimization purposes, when used in combination (Govindan 2023). Generally, a strong connection between AI and data analytics for finding resource inefficiencies and optimization is observed. Robotics and AI are commonly discussed together regarding automation tasks like waste sorting (Kurniawan et al. 2024). Simulation is closely linked with DTs to facilitate model analysis based on real-world data.

The SLR findings indicate that simulation plays a subordinate role compared to AI, IoT, and Blockchain in the analyzed literature. Simulation appears in only 22% of the publications, with four specific use cases reported. This suggests a lower level of awareness regarding the value of simulation within CE applications despite its recognized importance outlined in Section 2. Given its prominent application in related domains such as sustainability (see Section 2), there is a clear need for the simulation community to actively increase awareness about its potential contributions to CE. Future research should aim at adapting existing knowledge from other domains to effectively tackle CE-specific challenges, while exploring synergies between simulation and other digital technologies, particularly DTs, and considering interactions among all identified digital technologies.

In the reviewed literature, simulation is predominantly referred to as a broad, generic concept without detailing the specific simulation techniques used. Notably, only two of eleven contributions have specified the utilized simulation technique (Monte Carlo simulation and numerical simulation). This underscores that simulation in CE is often addressed superficially, as evidenced by the limited number of reported use cases (see Section 4.4).

Another observation is that about one-quarter of publications referencing simulation do not consider it an independent digital technology but instead include it within broader DT frameworks. To address this limitation, it is essential to emphasize that simulation should not merely be viewed as a subsidiary element within DTs but also as a standalone digital technology capable of addressing complex problems through dedicated simulation studies, independent of DT frameworks.

In the future, we expect that simulation will play an important role in CE applications, both independently and in combination with other digital technologies. Potential growth areas include quantifying the impact of CE approaches compared to linear economic models to support evidence-based decision-making among stakeholders (for example, resource savings), enabling lifecycle simulations for digital product passports, and facilitating the development of successful business models aligned with CE principles.

Beyond awareness issues, variations in how frequently the digital technologies are proposed could stem from their perceived versatility in different applications relevant to the CE, the degree of maturity, and trends. It should also be noted that other studies, such as Rusch et al. (2023), identified IoT as most frequently proposed, followed by AI and data analytics, underscoring how different research approaches can impact results.

The literature presents several use cases of digital technologies in waste management, primarily focusing on the R-principle Recycle, which, while valuable, is not highly circular. However, many proposed applications and real-world examples aim to reduce resource and energy input, aligning with the higher-level R-principle Reduce. Even the most circular principle, Refuse, has been identified as an area where AI can have an impact. When selecting appropriate digital technologies, priority should be given to those that support higher-level R-principles to maximize impact in the CE.

However, it is also important to recognize that implementing these digital technologies comes with certain prerequisites and barriers. For instance, the use of IoT requires internet coverage in relevant areas, which may not always be available (Trevisan et al. 2023). Regulations, data security, implementation costs, integration with existing technologies, and the risk of increased energy consumption offsetting potential savings are important factors that must be considered.

6 CONCLUSION AND OUTLOOK

In this paper, an SLR was conducted to identify digital technologies proposed in recent literature for CE, their functions, and current real-world applications, paying special attention to the role of simulation. Nine digital technologies were identified to support the CE: AI, IoT, Blockchain, simulation, CPS, data analytics, DTs, robotics, and XR. AI was proposed in over half of the analyzed literature, followed by IoT and Blockchain. Simulation plays a subordinate role compared to AI, IoT, and Blockchain, indicating a lower awareness in CE contexts. The least proposed digital technology is XR.

The identified digital technologies serve various functions, although there is some overlap among them. They are used for waste sorting and production automation, disassembly, demand analysis, data traceability, energy and resource monitoring, environmental impact assessment, product design improvement, condition assessment and predictive maintenance, process improvement, product design assessment, and immersive training. Use cases include assembly and disassembly in remanufacturing, real-time energy monitoring in buildings, smart bins and automated sorting in waste management, vehicle and production machinery monitoring, predictive maintenance of machinery, product origin tracking, and simulation for reusing wood waste or assessing battery reuse. Digital technologies are frequently proposed in combination with each other, suggesting synergies between them. However, their implementation requires considering infrastructure, regulations, costs, and potential trade-offs in energy consumption.

This work contributes to the scientific community by offering a structured overview of proposed digital technologies and their functions within CE, highlighting current use cases, and revealing that, compared to AI, IoT, and Blockchain, simulation appears to play a less prominent role. This finding underscores the need to raise awareness of simulation's potential for advancing CE. Businesses can leverage these insights to make more informed decisions when selecting and implementing digital technologies to enhance sustainability.

Given that the present study focuses on a general synthesis of digital technologies in CE, future research should consider conducting separate SLRs for each individual technology in the context of CE. This would enable the identification of more specific functions and use cases, as well as their quantitative evaluation. A focus could also be placed on the implementation barriers associated with each digital technology and the development of appropriate mitigation strategies. Additionally, the development of practical implementation guidelines could assist businesses in integrating digital technologies more effectively, thereby lowering entry barriers and promoting the adoption of CE practices. With regard to the use of simulation, its potential for addressing CE-related challenges should be explored in greater depth, along with its synergies with related digital technologies, such as DTs, to unlock further opportunities for advancing CE practices.

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