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POTENTIALS AND BARRIERS OF THE METAVERSE FOR CIRCULAR ECONOMY

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ABSTRACT

Sustainability is a challenge for society that circular economy tries to tackle. The metaverse, as an emerging technology that incorporates digital twins and simulation in an immersive virtual environment, has not been thoroughly investigated in connection to circular economy. Thus, the purpose of this study is to summarize the potentials and barriers of the use of the metaverse for circular economy. By conducting a structured literature review, this paper categorizes the findings into dimensions that are important for both the metaverse and circular economy. A variety of potentials and barriers that cover different perspectives important for businesses aiming to comply with circular economy principles is discovered. The findings include potentials and barriers in several areas, like the access to the metaverse, connected costs, data, knowledge transfer, collaboration, innovation, product design, production planning, training of employees, and transportation. The results can be used to promote the implementation of circular economy principles.

1 INTRODUCTION

The metaverse is an immersive digital environment that users can interact with in real-time. Although the metaverse is still in its early phase of development, its use for businesses is anticipated to increase soon, as the metaverse in the industrial context alone is predicted to generate considerable revenues in the next years (Edwin et al. 2023; Kshetri 2023). Common applications in the metaverse are using digital twin (DT) technology (Edwin et al. 2023) and simulation (Khanna et al. 2024). Previous studies have shown that technology use correlates with economic, social, and environmental sustainability (Al-Emran 2023). However, the link between the metaverse and circular economy (CE) has not been examined. In that regard, the research question is: *What are the potentials and barriers of the metaverse for CE?* This is important to answer because global warming, greenhouse gas emissions, and unsustainable economic growth are just a few examples of pressing issues society currently faces (Hoppe et al. 2023). To answer the research question, a structured literature review has been conducted, to synthesize findings that connect the metaverse to CE principles. Consequently, this work contributes to the scientific community and businesses by offering insights into how using the metaverse can contribute to reaching sustainability goals through improving CE and which barriers must be considered in that regard.

The paper is structured as follows: First, in Section 2, the theoretical basis for this work is built by defining the metaverse and CE, as well as giving an overview of related work. The research approach is explained in Section 3. Section 4 describes our findings, and Section 5 offers final remarks.

2 RESEARCH BACKGROUND

2.1 Metaverse

The metaverse is a symbiosis of the physical and the virtual world (Wang et al. 2023c). The physical and virtual worlds are fused as a permanent environment for an unrestricted amount of users, where there is no distinct differentiation between both worlds (Mystakidis 2022). The metaverse does not necessarily need to be a 3D environment (Dwivedi et al. 2022). However, the use of Extended Reality (XR) lets the user immerse more into the metaverse (Dwivedi et al. 2022). XR includes the technologies augmented reality (AR), virtual reality (VR), and mixed reality (MR). Users can interact in the metaverse, navigating the so-called avatars, a representation of themselves. With their avatars, the users can work, communicate, and collaborate with others (Wang et al. 2023c).

The metaverse has a strong connection to digital twins and simulation. Simulation is the core part of digital twins that facilitates prediction and decision-making for real-world systems. The metaverse, especially in the industrial context, incorporates digital twins to reproduce scenarios in the industrial domain. Therefore, simulation is a key technology in the metaverse (Zheng et al. 2022). After explaining the metaverse as the first relevant concept in this paper, the next subsection will define the second important concept, CE.

2.2 Circular Economy

Sustainability aims for the balance of economic prosperity, social equity, and environmental resilience, serving the interests of both present and future generations. CE is a key element in achieving sustainable development (Geissdoerfer et al. 2017). CE was first proposed by (Boulding 1966), who argues that since resources are finite, it is inevitable that they have to be recovered and used again as secondary resources. Since then, CE's significance in research and application has grown (Frishammar and Parida 2019).

Kirchherr et al. (2017) define CE as an economic system that is based on business models that replace the 'end-of-life' concept with reducing, reusing, recycling and recovering materials to accomplish sustainable development to benefit current and future generations.

CE as a system is regenerative in which emissions, resource input, and waste, as well as energy inefficiency, are minimized by slowing, constricting, and closing material and energy cycles (Geissdoerfer et al. 2017). This can be accomplished with the 9R Framework by Potting et al. (2017). The framework proposes ten measures for increased circularity: *Refuse*, *Rethink*, *Reduce*, *Reuse*, *Repair*, *Refurbish*, *Remanufacture*, *Repurpose*, *Recycle*, and *Recover*. These measures are ranked, with *Refuse* contributing the most to circularity and *Recover* contributing the least. With these actions, the end-of-life concept can be replaced by business models targeting sustainable development (Kirchherr et al. 2017). Thus, CE can help to solve environmental, social, and economic challenges (Schroeder et al. 2019). In the following subsection, related work that addresses the two concepts of the metaverse and CE together is discussed.

2.3 Related Work

As stated by Al-Emran (2023), technology significantly influences sustainability. Thus, the interactions between technological innovation, like the metaverse, and the principles of CE are examined in this work. Papamichael et al. (2023) address the connection of the metaverse and CE in an editorial. However, to our knowledge, the research topic of potentials and barriers has not been covered with the structured research method used in this paper. Das et al. (2023) address the topic as well, but we could not find a traceable research approach in their work. Therefore, our paper provides different insights collected from a broad body of literature, with the findings newly structured into nine dimensions, offering novel insights.

3 RESEARCH METHOD

To disclose the potentials and barriers of the metaverse in a CE, our research design is structured with a five-step approach, adopting the methods of vom Brocke et al. (2009) for structured literature reviews in information systems. The approach consists of an appropriate review scope, conceptualizing the topic, the literature search, the literature analysis and synthesis, and defining the research agenda. This ensures methodological rigor, reproducibility, transparency, and traceability, which enhances the legitimacy of our work and helps us achieve our objective of summarizing prior knowledge (Paré et al. 2016).

First, we limited the review scope to English peer-reviewed publications on the metaverse, sustainability, and CE. We also included the search for papers dealing with XR in the context of sustainability and CE, as XR is an important factor for the metaverse (Dwivedi et al. 2022). For these four concepts, papers from the commonly used databases Scopus and IEEE Xplore have been scanned.

Second, to conceptualize the topic, we searched for papers covering the current state of the metaverse and for aspects of sustainability and CE. Accordingly, in step three, the actual literature search, we searched the databases using the search string: (sustaina* OR (circular AND economy)) AND (metaverse OR (extended AND reality)). We limited the search to scientific work published from 2021 until the end of the literature gathering for this work, January of 2024, as the number of publications on the metaverse started ascending steeply in 2021 (Scopus 2024), and only the recent state of the metaverse is of importance for our topic. We limited the subject areas to computer science, social sciences, engineering, environmental sciences, business, management and accounting, energy, economics, econometrics, and finance. We considered journal articles and conference papers in their final publication stage. This resulted in a match of 267 papers in total.

In step four, the analysis and synthesis, duplicate papers, as well as papers we could not access were removed, leaving 92 papers. Papers that did not match our topic after reading the abstract and the full paper were also eliminated. We applied quality criteria, e.g., sound argumentation and the use of an established research methodology (Levy and Ellis 2006), which resulted in 49 papers remaining. We analyzed them and synthesized the findings to answer the research question. Lastly, in step five and the conclusion of this work (Section 5), we formulated a research agenda for future work. This research method enables answering the research question with the findings described in the following Section 4.

4 FINDINGS

It was identified that the findings can be categorized into nine dimensions. Initially, the individual potentials and barriers of the metaverse for CE were examined and it was found that they could be grouped into specific dimensions, named based on their shared characteristics. The dimensions *Data* and *Production Planning and Prediction* were most discussed in the literature, followed by *Product Design*, *Collaboration*, *Learning and Training*, and *Access*. The nine dimensions structure the remainder of this work. Notably, the discussion of these dimensions in the literature has surged recently, with most relevant studies from 2023. Each dimension with its potentials and barriers is detailed in this section. For a brief overview, the main potentials and barriers, that were extracted from the detailed descriptions, are summarized in Figure 1.

4.1 Collaboration

As for the first dimension in Figure 1, *Collaboration*, the metaverse allows users to cooperate virtually and three-dimensionally in real-time (Zawish et al. 2024). This is enabled by real-time audio and text chat, intuitive and user-friendly interfaces, interaction with the virtual environment through haptic feedback, shared object interaction, and gesture controls (Khanna et al. 2024). VR headsets, haptic vests, and AR glasses can also be used to engage with others (Khanna et al. 2024). The real-world experiences can be simulated through the metaverse's capacity to integrate live data and real-time updates (Qadir and Fatah 2023). Through these characteristics, the metaverse allows for unprecedented interaction (Queiroz et al. 2023).

Because of the immersive communication in the metaverse, virtual meetings can be held (Zawish et al. 2024). The authors state that through virtual meetings, businesses can further promote work-from-home culture, although physical meetings cannot completely be replaced, carbon dioxide (CO_2) emissions from traveling can be reduced. Reducing emissions makes collaboration more sustainable, but it also makes cooperation faster and more flexible, benefiting CE.

Furthermore, as physical events and conferences can be replaced virtually, the ecological impact of constructing and maintaining large venues can also be reduced (Zawish et al. 2024). In that context, Al-Emran (2023) states that the number of large, physical office spaces could shrink. Considering the aforementioned 9R Framework for CE, this aspect aligns with the principle of *Refuse* by opting out of building physical infrastructure and replacing it within the metaverse.

For these reasons, metaverse users can collaborate more effectively (Zawish et al. 2024). As the users can be businesses along the supply chain, more effective collaboration is beneficial for CE because it stimulates innovation in circular products and business models. Additionally, collective optimization of environmental impacts across industries along the supply chain via metaverse collaboration can help to achieve more efficient resource utilization, further benefitting CE (Zhong and Zhao 2024).

Collaboration	Innovation	Product Design
↗ more flexibility ↗ less space needed ↗ less traveling needed ↗ more efficiency ↘ high energy consumption through communication	↗ new circular business models, products, and services ↗ more human resources available ↗ new experiments ↘ difficult implementation of DTs	↗ facilitated showcasing ↗ substitution of physical products ↗ testing ↘ complex data transmission and sensor network system ↘ high computing power necessary
Learning and Training	**Data**	**Transportation**
↗ independency of real training environment ↗ improved efficiency ↗ facilitated knowledge transfer ↘ equipment requires rare materials ↘ realism difficult to obtain	↗ enhanced productivity ↗ more realistic simulations ↗ secure data transmission ↘ reluctance to data sharing ↘ high energy consumption ↘ complicated data management ↘ unauthorized access	↗ improved efficiency, controllability, adaptability, and decision-making ↗ more sustainable transportation planning ↘ complicated data management
Production Planning and Prediction	**Costs**	**Access and Use**
↗ on-demand production ↗ risk reduction ↗ more transparency and efficiency ↗ optimized DTs ↘ increased complexity	↗ cost reduction ↗ higher revenues ↘ initial expenses ↘ partly costly equipment ↘ higher electricity costs ↘ health treatment costs ↘ product cannibalization	↗ theoretically open to anyone ↘ requires robust internet connection, equipment, and IT systems ↘ health issues prevent from (prolonged) use ↘ reluctance to change ↘ difficult integration of legacy systems

Figure 1: Potentials and barriers of the metaverse for CE.

Users of the same domain, e.g., of the agricultural sector, can cooperate in the metaverse, for example, to create disease-diagnosis models for plants, simulate dynamic digital plants, and generally coordinate the agricultural system more effectively (Kang et al. 2023). This example shows as well that collaboration in the metaverse can create value for CE, as energy and resource efficiency can potentially be increased.

However, through a high number of co-current and co-located requests for communicating in the metaverse, the energy consumption for collaborating is high (Huang et al. 2023). This reduces the energy-saving potential of the metaverse. Therefore, the previously mentioned principle *Refuse* to substitute physical infrastructure for gatherings through virtual meetings has to be degraded to *Reduce*.

4.2 Innovation

The metaverse can enhance innovation for circular products and business models. This can be achieved by simulating the full life cycle of systems in the supply chain and improving it (Wang et al. 2023a). Through the interaction of many users on a digital platform like the metaverse the life cycle can be better understood and, therefore, better modeled, as well as the metaverse can provide better data for improved parametrization of simulation models. As the life cycle of complete systems can be simulated and developed using the metaverse, life cycles of products can be simulated, too, and products can be produced in a more circular and, thus, sustainable way. This can be achieved by decreasing the resources needed for production through optimization of the supply chain, reverse supply chain, and identifying more innovative ways to use already produced products, following multiple principles of the 9R Framework.

Another way the metaverse can positively influence innovation is by shifting from a system where humans are actively involved in every step to one where they oversee automated processes, requiring less direct human interaction in the production environment (Yao et al. 2024). Thus, human resources can be used more efficiently, allowing for greater innovation in the production system and benefiting CE.

Additionally, the immersive and interactive space in the metaverse fosters innovation and experimentation for new solutions, driving economic progress. Da Silva et al. (2023) propose a framework combining immersive experiences and DTs, enabling innovative circular designs using XR, tested with real-time data simulations.

Ultimately, digital technologies like the metaverse can be seen as a catalyst for innovation, which can lead to new products, services, increased competitiveness among businesses, and business models that can create new industries (Al-Emran 2023). Increased competitiveness, for example, can lead to an increased adherence to the principles of CE, as businesses can seek to differentiate themselves from others by improving their environmental footprint.

Simulating life cycles in the metaverse can benefit CE. However, the DTs used for simulation to replicate the physical world in the virtual world require many sensors, much computation power, and reconstruction and rendering tools, so a lot of energy is necessary (Wang et al. 2023b).

4.3 Product Design

Product design is essential for CE, influencing the resource consumption of products and considering their disassembly for easy refurbishing and remanufacturing. The metaverse can reshape this process.

On the one hand, companies can showcase designed products in the metaverse so that clients can comprehend the engineering framework and design concept (De Felice et al. 2023). For example, an already existing metaverse-based real-estate project allows virtual tours of properties (Zawish et al. 2024). Similarly, clients of companies can be integrated into the design process of products, and changes can be made before any prototype has been built. The substitution of physical goods, e.g., prototypes, through digital representation, reduces the energy consumed as well as overall emissions (Allam et al. 2022).

On the other hand, through live data integration, DT models of products can become more realistic. Accordingly, product design can be tested through experiments and simulations in life-like environments, enhancing the final product (Qadir and Fatah 2023). This can lead to optimally designed products whose disassembly and resource consumption have been tested beforehand.

However, mapping the products virtually with DTs requires a reliable sensor network system, the proper sensitivity of the sensors, and accurate data transmission, which can be challenging to obtain (Tan et al. 2023). The authors emphasize that even for technically capable companies, data security for the collected data can be problematic (De Giovanni 2023), because data in the metaverse can be vulnerable to hacking (Zawish et al. 2024). For the storage of data, as well as for the use of XR and possible artificial intelligence (AI) technologies in product design, a high amount of computing power is needed (De Giovanni 2023). According to the authors, this results in a high amount of energy required.

4.4 Learning and Training

Learning and training processes are vital in CE as novelty is often introduced to the usual business processes for many. In the production area, for example, this can mean that a user has to assemble components and disassemble returned parts, and the user must be trained accordingly.

The application possibilities of the metaverse in learning and training are, thus, very diverse. The metaverse can provide learning and training scenarios, an immersive teaching environment, and generally enhance different aspects of learning (Wang et al. 2023a). First, the metaverse makes it possible to carry out physical training independent of the real-world system, e.g., using XR equipment that can be beneficial in industrial workspaces (Zawish et al. 2024). Incorrect movements while training do not immediately damage a system component or interrupt a process, resulting in fewer resources wasted through training errors in real environments, and the assembly and disassembly of parts in CE can become less time-consuming through the training options in the metaverse. For example, in aircraft manufacturing that is supposed to become more sustainable, the first-person experiences via virtual training with XR can be helpful to abide by intensive quality requirements (Tsang et al. 2022).

The virtual training opportunities can also enhance employee efficiency and enable data analysis for performance evaluation (Zawish et al. 2024). The authors state that in the metaverse, trainees can go beyond simply comprehending and remembering work exercises to perform procedures themselves.

Second, the metaverse offers potential when it comes to providing virtual learning spaces. Productive environments where people can connect and learn together can be offered (Zawish et al. 2024). Thus, people can learn about CE principles more engagingly and share their knowledge, as learning in the metaverse can help overcome environmental hurdles concerning sustainability (Zawish et al. 2024). Plus, advanced technologies have been shown to revolutionize education (Al-Emran 2023) and to enhance the inclusivity of education (Al-Emran 2023). This provides people with new access to learning about CE.

Additionally, in the metaverse, training is independent of location, as previously mentioned in the *Collaboration* dimension. Especially when introducing new systems, users do not have to travel to central training stations, but they can do this at their home locations, saving emissions.

However, ensuring realistic virtual environments for learning and training purposes in industrial workspaces requires high-end digital infrastructure, including physics-based interactions and realistic graphics. This can be costly (Khanna et al. 2024), as well as technologically challenging. Additionally, the production of equipment for accessing the metaverse, e.g., a VR helmet that can be necessary for training purposes, requires rare materials, negatively impacting the environment (De Giovanni 2023).

4.5 Data

Data play a crucial role in CE (Winkelmann et al. 2023). Collecting, representing, and sharing data are essential for sustainable processes in a CE (Ixmeier et al. 2023), for example, by developing information management systems (Schmidt et al. 2009) and waste management solutions (Hoffmann and Pfeiffer 2022). Within the metaverse, data can be considered as a part of its foundation (De Felice et al. 2023).

As for the first potential, using structured and up-to-date data in the metaverse can lead to significant time savings, increasing overall productivity levels across the economy (Al-Emran 2023). Data can benefit product construction, advertisement evaluation, content personalization, and content strategies (Venugopal et al. 2023), which are important potentials to foster in the framework of CE.

Second, the realism of DT models in the metaverse can be enhanced by data, creating realistic simulations of products and processes. This enables engagement with digital products or specific environments, simulating real-world experiences (Qadir and Fatah 2023).

Third, blockchain data is time-stamped, jointly validated, and recorded by consensus nodes and cannot be tampered with or falsified, ensuring the reliability of peer-to-peer exchange. Thus, blockchains facilitate secure data transmission (Yu et al. 2018) and ensure trustworthy data through the elimination of the possibility of duplicated data (Venugopal et al. 2023). This results in an improved information flow and tracking of product lifecycles, especially for sustainable management of resources (Zhong and Zhao 2024).

However, there are also barriers to data in the metaverse. In line with De Giovanni (2023), it is argued that the metaverse requires numerous data centers and storage spaces, which require enormous data streams and a thousand-fold increase in computing power (Aung et al. 2024). Evidence shows that using big data requires an annual global consumption of around 200 terawatt hours in data centers, which is more than the energy consumption of some countries, e.g., Argentina, Ukraine, and Thailand (De Giovanni 2023), again showing that a barrier is the metaverse's high energy consumption.

Another barrier arises in data management. The metaverse handles enormous volumes of data at high velocities and varieties. Data management and presentation are difficult for system interfaces, particularly when working with real-time data, complicated data structures, and data visualization (Khanna et al. 2024).

Working in the metaverse requires data sharing, such as tracking product life cycles or sharing sustainability data. This is a concern, as supply chain partners may be reluctant to share data (Davies et al. 2024), e.g., due to a need for blockchain governance (Lee 2023), as well as the in the *Product Design* dimension described vulnerability of data to hacking poses data security risks. Therefore, keeping data from unauthorized access is a challenge (Khanna et al. 2024).

4.6 Transportation

Transportation of goods in global trade significantly contributes to greenhouse gas (GHG) emissions, making it imperative to adopt efficient and sustainable practices in transportation planning. The concept of the metaverse offers promising solutions for achieving efficiency and sustainability and can potentially replicate the entire life cycle of an actual transportation system, enhancing its efficiency, dependability, controllability, and adaptability (Li et al. 2017). Aldweesh et al. (2023) argue that in both virtual and real-world settings, the metaverse can facilitate more environmentally friendly transportation planning and provide information for decision-making processes. For example, based on the metaverse data, routing algorithms can be used to optimize routes and transport management strategies can be tested (Ostroukh et al. 2023). This leads to a reduction in transportation costs and a possible reduction of GHG emissions, supporting sustainable development and CE standards.

Accessing the metaverse encourages users to decrease their overall mobility, implying a reduction of carbon dioxide emissions linked to transportation (De Giovanni 2023). For instance, as stated before, the metaverse enables professionals to collaborate without having to travel physically, minimizing travel-related emissions. By offering additional information and directives for managing network resources, the metaverse acts as a catalyst for improving transport networks. Represented as a collection of guidelines, variables, and limitations governing ideal network performance, the metaverse ensures seamless coordination between different stakeholders involved in transportation planning and operations (Ostroukh et al. 2023). Real-time information is needed to optimize routes and lower the possibility of delays or accidents (Reddy et al. 2023), which, as described in the prior *Data* dimension, can be challenging to handle.

4.7 Production Planning and Prediction

Integrating the metaverse into production processes can enhance crucial aspects of CE implementation. Businesses can involve customers directly while reducing waste by enabling on-demand production via AR/VR technologies (De Giovanni 2023). Furthermore, transparency, optimization, and efficiency in production processes and planning can be promoted. Sustainability can be achieved by producing goods on demand, saving material and reducing energy consumption. On-demand production helps to conserve natural resources and reduce waste, which are essential goals of CE. Such production requires significant customer involvement in the production process, which can be facilitated using AR/VR technologies in the metaverse (De Giovanni 2023), as described before in the *Product Design* dimension.

Additionally, virtual remote collaboration with partners and customers can reduce production and quality assurance risks (De Felice et al. 2023), leading to greater efficiency through increased transparency (Dolgui and Ivanov 2023). Real-time monitoring of inventory, equipment health, and logistics can identify bottlenecks early (Hajian et al. 2024; Khanna et al. 2024), promoting transparency, which is crucial for CE.

For example, the usage of the Internet of Things, as well as AI can enable real-time monitoring of supply chain operations (Zhong and Zhao 2024).

In addition to the mentioned substitution of physical goods, logistical and production processes can be replaced and simulated (Dolgui and Ivanov 2023; Hajian et al. 2024). This offers several advantages in terms of CE, including low scrap rates, high production facility saturation, low waste, and improved energy efficiency (De Giovanni 2023). Simulation, e.g., in DTs, can be utilized to analyze production processes in different scenarios to identify bottlenecks (Dolgui and Ivanov 2023). This enables organizations to optimize their supply chain management (Hajian et al. 2024). Virtual scenarios are emerging as an important tool within the metaverse (Zhong and Zhao 2024). DT has further applications in logistics, traceability, energy, processes, and material inputs, which can be optimized for more sustainability (Zawish et al. 2024).

Prediction and forecasting are crucial aspects of production planning. They can support the decision-making of organizations (Dolgui and Ivanov 2023; Zhong and Zhao 2024). It enables data-driven decisions through profound insights into the data (Khanna et al. 2024). For example, harvesting rich data from the metaverse can be used for decision-making and forecasting (Zhong and Zhao 2024).

However, this dimension does not only offer potential. On-demand production leads to increasing complexity and a growing carbon footprint due to the integration between physical and digital facilities. This integration may result in additional energy consumption (De Giovanni 2023). Furthermore, connecting these facilities presents a challenge (Yao et al. 2024). Changes in production systems and atypical investments may create further complexity (De Giovanni 2023).

4.8 Costs

When looking at CE, it is clear that costs are one of the significant obstacles to implementing CE (Stumpf et al. 2021). Accordingly, using the metaverse for CE also shows an ambivalent picture regarding costs. All the described advantages and potentials of the metaverse contribute to optimization and cost reduction. The metaverse can create new business models that significantly reduce costs and greatly increase revenues. More deeply targeted and tailored advertising to the end user is possible via the metaverse (De Felice et al. 2023). The metaverse is always available and offers hardly any restrictions in the virtual world regarding targeting users. Another example of improving the cost ratio is the already mentioned metaverse's ability to obsolete business trips (De Giovanni 2023). Additionally, the costs of trust for worldwide collaboration can be reduced through smart contracts facilitated by the blockchain (Zhou et al. 2023).

Unfortunately, the metaverse also brings hurdles when it comes to costs. In addition to the initial modeling expenses, there can also be high costs for the technical equipment required for a user to participate in the metaverse (Khanna et al. 2024), although Zawish et al. (2024) state that AR and VR equipment has become more reasonably priced due to increasing popularity. Users must also be comprehensively trained in using the metaverse, which implies further expenses (Siahaan et al. 2022).

Energy consumption is another major cost factor (Zawish et al. 2024). Metaverse applications consume considerably more energy than conventional computer systems. Large amounts of data must be stored persistently and yet be available worldwide with low latency times. This requires comprehensive computing and storage options on large server farms (Wang et al. 2023b). Here, too, the high electricity consumption causes direct costs, but at the same time, indirect costs are also caused by the high environmental impact that the high electricity consumption entails, for example, in CO2 emissions (Jauhiainen et al. 2023). Related CO2 certificates cause major expenses for companies, and social costs must also be considered.

Finally, the use of the metaverse can undoubtedly have health consequences, be it the potential for addiction or the loss of a sense of reality (De Felice et al. 2023). Costs for treating such health problems must be considered. Using the metaverse can also have further indirect consequences for a company if, for example, the metaverse already covers customer needs. Therefore, no physical product that promises a higher profit margin for the company is sold (Zawish et al. 2024), leading to product cannibalization.

4.9 Access and Use

No matter the potential benefits the metaverse has for CE, its accessibility and will to use it are important factors for harvesting these benefits. Generally, the metaverse is free and open to anyone without any limitations other than owning the necessary devices (De Felice et al. 2023). The metaverse can provide educational opportunities for people who might otherwise be excluded due to various reasons (Al-Emran 2023). This potentially grants a bigger audience the opportunity to interact virtually with measures to adopt CE, e.g., incentivizing consumers to use recycled products (Zawish et al. 2024).

However, several barriers to adaptation exist. First, the use of the metaverse requires a robust internet connection and IT infrastructure, which might not align with the state of every link in international supply chains (Davies et al. 2024). Thus, the adoption and development levels are still limited (Siahaan et al. 2022), consequently limiting the connected development of CE through metaverse adoption.

Second, using the metaverse needs hardware like haptic gloves, vests, VR headsets, AR glasses, etc. Such equipment can be expensive, mitigating incentives to use the metaverse (Khanna et al. 2024).

Third, health issues related to VR, like nausea and motion sickness, are common (De Felice et al. 2023), which can result in not being able to use metaverse technology. Additionally, not all businesses are well acquainted with the metaverse, so they do not have enough knowledge to use it (Al-Hachim and Al-Sukaini 2023). Due to the novelty of the metaverse, decision-makers might also be reluctant to adopt it as they do not believe in its benefits (Gokasar et al. 2023). Acceptance of the metaverse is needed, but resistance to change is another reason for a lack of adaptation (Khanna et al. 2024).

Even if businesses want to use it, the management and user-friendly presentation of data, especially for the mentioned possible complex data structures, pose a challenge. As businesses will still rely on legacy systems and infrastructures, integrating these into the metaverse is another barrier (Khanna et al. 2024).

5 CONCLUSION

In this paper, a structured literature review was conducted to identify potentials and barriers that the metaverse provides for CE. After laying the theoretical foundation of the metaverse and CE, nine dimensions are identified that cluster the plethora of findings into groups that are important for businesses. Our findings show that there are many potentials of the metaverse for CE and generally more potentials than barriers, although the potentials and barriers of the dimensions *Data*, *Costs*, and *Access and Use* apply to nearly all other dimensions, giving more weight to their specific potentials and barriers. To answer the research question, the potentials include enhanced collaboration along the supply chain, innovative circular products and business models, optimized product design, immersive training, detailed simulations, secure data transmission, a more efficient and traceable transportation network, immersive learning about CE principles, reduced costs, and increased revenues. The barriers involve high complexity of implementation, enormous computing power necessary, immense data streams, too complex data structures, unauthorized access to data, reluctance to data sharing and adoption of metaverse technologies, health issues, and an ambivalent cost structure. Some principles of the 9R Framework that highly contribute to circularity are, thus, mitigated to less circular principles, e.g., through high energy consumption.

This work contributes to the scientific community by showing how the metaverse can support sustainable development by considering CE principles and identifying barriers to address. The managerial contributions consist of insights to inform decision-makers about the impact of using the metaverse for CE and can result in the creation and modification of more sustainable business strategies and practices.

This paper's findings are based on current data and only represent a snapshot in time in the dynamic field of the metaverse and CE. As this work is limited to a synthesis of findings to provide an overview, in future work, each dimension can be investigated more in depth and more focus can be laid on a qualitative evaluation using the 9R Framework for all potentials and barriers. For further qualitative evaluation, an interview survey with experts can be conducted to identify the intersection and join of the findings. Subsequently, a comprehensive description of the metaverse within the CE, highlighting its potentials and barriers, can be created and used as a reference when developing a decision model for technology selection in businesses. Plus, requirements to overcome the barriers and foster the potentials can be formulated.

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REFERENCES

Aldweesh, A., M. Alauthman, M. Al-Khaldy, A. Ishtaiai, A. al-Qerem, and A. Almoman. 2023. "The Meta-Fusion: A Cloud-Integrated Study on Blockchain Technology Enabling Secure and Efficient Virtual Worlds". *International Journal of Cloud Applications and Computing* 13(1):162–185.

Al-Emran, M. 2023. "Beyond Technology Acceptance: Development and Evaluation of Technology-Environmental, Economic, and Social Sustainability Theory". *Technology in Society* 75(1):102383.

Al-Hachim, H. N. H. and A. S. T. Al-Sukaini. 2023. "Measuring the Possibility of Adopting Metaverse Technology as an Appropriate Strategy to Achieve a Sustainable Competitive Advantage". In *Beyond Reality: Navigating the Power of Metaverse and Its Applications,* edited by M. Al-Emran, J. H. Ali, M. Valeri, A. Alnoor, and Z. A. Hussien, 69–82. Cham: Springer Nature Switzerland.

Allam, Z., A. Sharifi, S. E. Bibri, D. S. Jones, and J. Krogstie. 2022. "The Metaverse as a Virtual Form of Smart Cities: Opportunities and Challenges for Environmental, Economic, and Social Sustainability in Urban Futures". *Smart Cities* 5(3):771–801.

Aung, N., S. Dhelim, L. Chen, H. Ning, L. Atzori, and T. Kechadi. 2024. "Edge-Enabled Metaverse: The Convergence of Metaverse and Mobile Edge Computing". *Tsinghua Science and Technology* 29(3):795–805.

Boulding, K. E. 1966. "The Economics of the Coming Spaceship Earth". In *Environmental Quality in a Growing,* edited by H. Jarrett, 3–14. Baltimore, Maryland: Johns Hopkins University Press.

Da Silva, I. N., J. García-Zubía, U. Hernández-Jayo, J. B. M. Da Alves, and G. A. Dandolini. 2023. "Design, Implementation and Evaluation of Deusto XRL, a Reference Architecture for Extended Remote Laboratories (XRLs)". *Electronics* 12(23):4812.

Das, S., S. Mondal, F. Struck, J. Eissfeldt, L. Beernink, V. Sigouras, S. Hoose, and L. Kopac. 2023. "What Can we See Inside the Crystal Ball? Exploring Opportunities and Challenges for Metaverse and Circular Economy". *Academic Journal of Interdisciplinary Studies* 12(6):221–237.

Davies, J., H. Sharifi, A. Lyons, R. Forster, and O. K. S. M. Elsayed. 2024. "Non-Fungible Tokens: The Missing Ingredient for Sustainable Supply Chains in the Metaverse Age?". *Transportation Research Part E: Logistics and Transportation Review* 182(1):103412.

De Felice, F., M. Rehman, A. Petrillo, and I. Baffo. 2023. "A Metaworld: Implications, Opportunities and Risks of the Metaverse". *IET Collaborative Intelligent Manufacturing* 5(3):12079.

De Giovanni, P. 2023. "Sustainability of the Metaverse: A Transition to Industry 5.0". *Sustainability* 15(7):1–29.

Dolgui, A. and D. Ivanov. 2023. "Metaverse Supply Chain and Operations Management". *International Journal of Production Research* 61(23):8179–8191.

Dwivedi, Y. K., L. Hughes, A. M. Baabdullah, S. Ribeiro-Navarrete, M. Giannakis, Al-Debei, Mutaz M. et al. 2022. "Metaverse Beyond the Hype: Multidisciplinary Perspectives on Emerging Challenges, Opportunities, and Agenda for Research, Practice and Policy". *International Journal of Information Management* 66(1):102542.

Edwin, M., M. Saranya Nair, and V. A. Nagarajan. 2023. "The Metaverse in Industry and Logistics". In *Metaverse and Immersive Technologies,* edited by A. Chandrashekhar, S. H. Saheb, S. K. Panda, S. Balamurugan, and S.-L. Peng, 295–323. Hoboken, New Jersey: John Wiley & Sons, Ltd.

Frishammar, J. and V. Parida. 2019. "Circular Business Model Transformation: A Roadmap for Incumbent Firms". *California Management Review* 61(2):5–29.

Geissdoerfer, M., P. Savaget, N. M. P. Bocken, and E.-J. Hultink. 2017. "The Circular Economy – A New Sustainability Paradigm?". *Journal of Cleaner Production* 143(1):757–768.

Gokasar, I., D. Pamucar, M. Deveci, B. B. Gupta, L. Martinez, and O. Castillo. 2023. "Metaverse Integration Alternatives of Connected Autonomous Vehicles with Self-Powered Sensors Using Fuzzy Decision Making Model". *Information Sciences* 642(1):119192.

Hajian, A., S. Daneshgar, K. Sadeghi R., D. Ojha, and G. Katiyar. 2024. "From Theory to Practice: Empirical Perspectives on the Metaverse's Potential". *Technological Forecasting and Social Change* 201(1):123224.

Hoffmann, G. and J. Pfeiffer. 2022. "Gameful Learning for a More Sustainable World". *Business & Information Systems Engineering* 64(4):459–482.

Hoppe, C., R. Schmelzer, F. Möller, and T. Schoormann. 2023. "Data Spaces as Enablers for Sustainability". In *INFORMATIK 2023 - Designing Futures: Zukünfte Gestalten.*: *Ökologische Nachhaltigkeit - Nachhaltige Wertschöpfungssysteme (NaWerSys) III,* edited by Gesellschaft für Informatik e.V., 1323–1334. Bonn: Gesellschaft für Informatik e.V.

Huang, X., Y. Wu, J. Kang, J. Nie, W. Zhong, D. I. Kim, and S. Xie. 2023. "Service Reservation and Pricing for Green Metaverses: A Stackelberg Game Approach". *IEEE Wireless Communications* 30(5):86–94.

Ixmeier, A., J. J. Kranz, J. Recker, and R. Zeiss. 2023. "How to Unlock the Potential of Information Systems for a Circular Economy". In *Research Handbook on Information Systems and the Environment,* edited by V. A. Cooper, J. J. Kranz, S. K. Mathew, and R. T. Watson, 74–99. Cheltenham: Edward Elgar Publishing.

Jauhiainen, J. S., C. Krohn, and J. Junnila. 2023. "Metaverse and Sustainability: Systematic Review of Scientific Publications until 2022 and Beyond". *Sustainability* 15(1):346.

Kang, M., X. Wang, H. Wang, J. Hua, P. de Reffye, and F.-Y. Wang. 2023. "The Development of AgriVerse: Past, Present, and Future". *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 53(6):3718–3727.

Khanna, P., R. Karim, and J. Kumari. 2024. "Issues and Challenges in Implementing the Metaverse in the Industrial Contexts from a Human-System Interaction Perspective". In *International Congress and Workshop on Industrial AI and eMaintenance 2023,* edited by U. Kumar, R. Karim, D. Galar, and R. Kour, 303–318. Cham: Springer Nature Switzerland.

Kirchherr, J., D. Reike, and M. Hekkert. 2017. "Conceptualizing the Circular Economy: An Analysis of 114 Definitions". *Resources, Conservation and Recycling* 127(1):221–232.

Kshetri, N. 2023. "The Economics of the Industrial Metaverse". *IT Professional* 25(1):84–88.

Lee, C.-S. 2023. "An Exploration Towards Sustainable Metaverse Systems for E-Learning by Student Designers: A Meta-analysis". In *Computational Science and Its Applications – ICCSA 2023 Workshops,* edited by O. Gervasi, B. Murgante, A. M. A. C. Rocha, C. Garau, F. Scorza, Y. Karaca, and C. M. Torre, 511–530. Cham: Springer Nature Switzerland.

Levy, Y. and T. Ellis. 2006. "A Systems Approach to Conduct an Effective Literature Review in Support of Information Systems Research". *Informing Science: The International Journal of an Emerging Transdiscipline* 9(1):181–212.

Li, L., L. Yilun, D.-P. Cao, N.-N. Zheng, and F.-Y. Wang. 2017. "Parallel Learning - A New Framework for Machine Learning". *IEEE/CAA Journal of Automatica Sinica* 4(3):389–395.

Mystakidis, S. 2022. "Metaverse". *Encyclopedia* 2(1):486–497.

Ostroukh, A. V., N. G. Kuftinova, A. A. Podberezkin, B. S. Subbotin, and A. V. Podgornyi. 2023. "Use Digital Twins and the Metaverse to Analysis Data in the Agglomeration Transport Network". In *2023 Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED),* 1–5. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Papamichael, I., G. Pappas, J. E. Siegel, V. J. Inglezakis, G. Demetriou, A. A. Zorpas, and C. Hadjisavvas. 2023. "Metaverse and Circular Economy". *Waste Management & Research : the Journal of the International Solid Wastes and Public Cleansing Association, ISWA* 41(9):1393–1398.

Paré, G., M. Tate, D. Johnstone, and S. Kitsiou. 2016. "Contextualizing the Twin Concepts of Systematicity and Transparency in Information Systems Literature Reviews". *European Journal of Information Systems* 25(6):493–508.

Potting, J., M. Hekkert, E. Worrell, and A. Hanemaaijer. 2017. *Circular Economy: Measuring Innovation in the Product Chain*. The Hague: PBL Netherlands Environmental Assessment Agency.

Qadir, A. M.-A. and A. O. Fatah. 2023. "Platformization and the Metaverse: Opportunities and Challenges for Urban Sustainability and Economic Development". *EAI Endorsed Transactions on Energy Web* 10(1):3842.

Queiroz, M. M., S. Fosso Wamba, S. C. F. Pereira, and C. J. Chiappetta Jabbour. 2023. "The Metaverse as a Breakthrough for Operations and Supply Chain Management: Implications and Call for Action". *International Journal of Operations & Production Management* 43(10):1539–1553.

Reddy, G. V., K. Hemachandran, H. K. Devaki, and Z. Z. Paprika. 2023. "Impact of Metaverse in the Supply Chain, Logistics, and Manufacturing Sector". In *The Business of the Metaverse,* edited by K. Hemachandran and R. V. Rodriguez, 132–140. New York: Productivity Press.

Schmidt, N.-H., K. Erek, L. M. Kolbe, and R. Zarnekow. 2009. "Sustainable Information Systems Management". *Business & Information Systems Engineering* 1(5):400–402.

Schroeder, P., K. Anggraeni, and U. Weber. 2019. "The Relevance of Circular Economy Practices to the Sustainable Development Goals". *Journal of Industrial Ecology* 23(1):77–95.

Scopus: Analyze Search Results - Metaverse. 2024. https://www.scopus.com, accessed 12th April.

Siahaan, B. P., T. M. Simatupang, and L. Okdinawati. 2022. "Logistics Landscape for Metaverse". In *2022 IEEE International Conference of Computer Science and Information Technology (ICOSNIKOM),* 1–6. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Stumpf, L., J.-P. Schöggl, and R. J. Baumgartner. 2021. "Climbing up the Circularity Ladder? – A Mixed-Methods Analysis of Circular Economy in Business Practice". *Journal of Cleaner Production* 316(1):128158.

Tan, G. W.-H., E. C.-X. Aw, T.-H. Cham, K.-B. Ooi, Y. K. Dwivedi, Alalwan, Ali Abdallah et al. 2023. "Metaverse in Marketing and Logistics: The State of the Art and the Path forward". *Asia Pacific Journal of Marketing and Logistics* 35(12):2932–2946.

Tsang, Y. P., T. Yang, Z. S. Chen, C. H. Wu, and K. H. Tan. 2022. "How is Extended Reality Bridging Human and Cyber-physical Systems in the IoT-empowered Logistics and Supply Chain Management?". *Internet of Things* 20(1):100623.

Venugopal, J. P., A. A. V. Subramanian, and J. Peatchimuthu. 2023. "The Realm of Metaverse: A Survey". *Computer Animation and Virtual Worlds* 34(5):2150.

vom Brocke, J., A. Simons, B. Niehaves, K. Riemer, R. Plattfaut, and A. Cleven. 2009. "Reconstructing the Giant - On the Importance of Rigour in Documenting the Literature Search Process". In *Proceedings of the 17th European Conference on Information Systems (ECIS)*. June 8th-10th, Verona, 2206–2217.

Wang, F.-Y., Y. Tang, and P. J. Werbos. 2023a. "Guest Editorial: Cyber–Physical–Social Intelligence: Toward Metaverse-Based Smart Societies of 6I and 6S". *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 53(4):2018–2024.

Wang, R., J. Wang, Y. Hao, L. Hu, S. A. Alqahtani, and M. Chen. 2023b. "C3Meta: A Context-Aware Cloud-Edge-End Collaboration Framework Toward Green Metaverse". *IEEE Wireless Communications* 30(5):144–150.

Wang, Y., Z. Su, N. Zhang, R. Xing, D. Liu, Luan, Tom H. et al. 2023c. "A Survey on Metaverse: Fundamentals, Security, and Privacy". *IEEE Communications Surveys & Tutorials* 25(1):319–352.

Winkelmann, S., J. Schweihoff, I. Jussen, and F. Möller. 2023. "Turning Old into New – the Lane Change to a Circular Economy in the Automotive Industry". In *INFORMATIK 2023 - Designing Futures: Zukünfte Gestalten.*: *Ökologische Nachhaltigkeit - Nachhaltige Wertschöpfungssysteme (NaWerSys) III,* edited by Gesellschaft für Informatik e.V., 1309–1321. Bonn: Gesellschaft für Informatik e.V.

Yao, X., N. Ma, J. Zhang, K. Wang, E. Yang, and M. Faccio. 2024. "Enhancing Wisdom Manufacturing as Industrial Metaverse for Industry and Society 5.0". *Journal of Intelligent Manufacturing* 35(1):235–255.

Yu, T., Z. Lin, and Q. Tang. 2018. "Blockchain: The Introduction and Its Application in Financial Accounting". *Journal of Corporate Accounting & Finance* 29(4):37–47.

Zawish, M., F. A. Dharejo, S. A. Khowaja, S. Raza, S. Davy, K. Dev, and P. Bellavista. 2024. "AI and 6G Into the Metaverse: Fundamentals, Challenges and Future Research Trends". *IEEE Open Journal of the Communications Society* (5):730–778.

Zheng, Z., T. Li, B. Li, X. Chai, W. Song, N. Chen, Y. Zhou, Y. Lin, and R. Li. 2022. "Industrial Metaverse: Connotation, Features, Technologies, Applications and Challenges". In *Methods and Applications for Modeling and Simulation of Complex Systems,* edited by W. Fan, L. Zhang, N. Li, and X. Song, 239–263. Singapore: Springer Nature Singapore.

Zhong, Z. Z. and E. Y. Zhao. 2024. "Collaborative Driving Mode of Sustainable Marketing and Supply Chain Management Supported by Metaverse Technology". *IEEE Transactions on Engineering Management* 71(1):1642–1654.

Zhou, C., H. Chen, S. Wang, X. Sun, A. El Saddik, and W. Cai. 2023. "Harnessing Web3 on Carbon Offset Market for Sustainability: Framework and A Case Study". *IEEE Wireless Communications* 30(5):104–111.

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