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RESEARCH ARTICLE

Barriers to the Adoption of Digital Technologies for a Circular Economy: Insights from the Manufacturing Industry

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Abstract

Academics, industry representatives, and policymakers widely recognize that adopting digital technologies is essential for successfully implementing circular economy solutions in manufacturing companies. However, many organizations still struggle to adopt these technologies effectively to achieve circularity. This study identifies and examines the barriers manufacturing companies encounter when leveraging digital technologies and data to implement circular economy solutions. Based on insights from 61 experts, the study provides robust empirical evidence on the barriers these companies face in transitioning to a smart circular economy. By offering an in-depth analysis of 13 distinct barrier dimensions, grouped into five broader themes embedded in the Natural Resource-Based View, this study presents a comprehensive framework. This framework deepens our understanding of the specific barriers impeding the transition to a smart circular economy, while identifying areas that demand targeted interventions.

Keywords Circular Economy · Digital Technologies · Industry 4.0 · Twin Transformation · Barriers · Qualitative Research

Introduction

Academics, industry representatives, and policymakers widely acknowledge that adopting digital technologies is crucial for successfully implementing circular economy (CE) solutions in manufacturing companies (Mishra et al., 2024; Papert et al., 2024; Schöggl et al., 2024). Manufacturing companies are a key focus, as they are major users of materials and energy, generate significant amounts of waste, and account for around 85 % of industrial value added in the EU (Leal et al., 2025). At the same time, they face increasing market instability, pressure to reduce costs, and growing expectations for sustainable value creation (Hopkinson et al., 2018; Rosa et al., 2019). Given this scale and impact, the manufacturing sector holds exceptional potential to decouple economic value creation from linear resource use (Scheel et al., 2020). As the concept of CE is increasingly

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explored by manufacturing companies, it becomes evident that digital technologies and data play a key role in its implementation by addressing key challenges arising from a lack of transparency and information asymmetries (Alcayaga & Hansen, 2025; Bressanelli et al., 2022; Neri et al., 2024). However, many companies still face challenges in adopting digital technologies for realizing a CE as highlighted in a Gartner study in 2020. At that time, only 12 % of companies had implemented digital technologies for CE solutions, while 35 % of respondents viewed such adoption as crucial. This discrepancy underscores a gap between the anticipated pace of technology adoption and the actual progress made (Gartner, 2020). This slow adoption can be primarily attributed to the fundamental barriers manufacturing companies need to overcome during this dual transformation (Christmann et al., 2024; Schallmo et al., 2025). These include the need for ambidextrous business models, high investment costs in new technologies, and increasing demands for data management across organizational processes (Denu et al., 2023; Galvão et al., 2022; Pigosso & McAloone, 2021).

Similarly, academic studies in the manufacturing sector indicate that the transformation process toward a smart circular economy (SCE) is still in its early stages (Bühler et al., 2025; Kristoffersen et al., 2020; Stucki et al., 2023; Uhrenholt et al., 2022). SCE refers to *all practices and activities that leverage digital technologies to discover (e.g., sensors), integrate (e.g., cloud platforms), analyze (e.g., machine learning), or apply data (e.g., robotics) with the goal of retaining resources, components, or products in the loop, reintegrating them into value-creating processes, extending product lifecycles, or reducing environmental impact.* This definition reflects the synergetic relationship between digital and sustainability transformations as outlined in the SCE Paradigm proposed by Bressanelli et al. (2022). According to this paradigm, digitalization - driven by the application of diverse digital technologies - enables the systemic redesign of products, business models, and value chains across all product life-cycle stages. The employment of digital technologies thus facilitates reduced material and energy use, supports product reuse, component remanufacturing, and material recycling, thereby fostering value creation and improving sustainability performance across environmental, economic, and social dimensions (Bressanelli et al., 2022; Liu et al., 2022; Neri et al., 2024).

To guide companies and the academic understanding of this new phenomenon, an increasing number of publications started to explore barriers and challenges that companies face in their transition toward a SCE (Lobo et al., 2022; Trevisan et al., 2023) over the last years. Nonetheless, some important research gaps persist in understanding the barriers of manufacturing companies to achieving a SCE, particularly due to the used methodology (e.g., limited to literature analysis), the specific areas of focus (e.g., inclusion of various industries or limited to non-manufacturing industry) and their scope of included digital technologies (e.g., limited to a particular technology). In this matter, it became obvious that early studies proposed literature-based lists of SCE barriers. For example, Lobo et al. (2022) identified barriers in manufacturing companies by analyzing scientific articles, similar to the approaches used Trevisan et al. (2021), Ozkan-Ozen et al. (2020) or Chhabra and Singh (2024). Others have acknowledged the relevance for empirical evidence to advance our understanding of SCE, which, according to Thirumal et al. (2024), is crucial for effectively identifying ongoing barriers in such a dynamic field. In this context, Trevisan et al. (2023) surveyed nine start-ups, only some of which belonged to the manufacturing sector. Likewise, Halse and Jaeger (2019) conducted 23 interviews with small and medium-sized companies across various industries to examine barriers to implementing Industry 4.0 and CE. Moreover, some studies transfer SCE barriers identified in sectors such as healthcare or textile industry to other industries, e.g. manufacturing companies (Hatzivasilis et al., 2019; Lobo et al., 2022). However, such transfers overlook the unique characteristics and challenges of specific industries, making this approach problematic and the identification of effective solutions more difficult. In addition, various studies concentrate on individual digital technologies and examine barriers associated with their use in CE contexts. Rejeb et al. (2023), Okorie et al. (2022), and Kumar and Chopra (2022) explore blockchain applications for CE implementation in the food supply chain. In contrast, Väsisänen et al (2019) examine barriers related to the use of software solutions for implementing CE, while Hettiarachchi et al. (2022) focus on challenges linked to additive manufacturing. In this context, Bressanelli et al. (2022) emphasize that the existing literature predominantly examines individual digital technologies in isolation, even though the effective implementation of CE practices often requires the coordinated deployment of multiple, complementary technologies. Therefore, Bressanelli et al. (2022) argue that relying on a single digital technology is generally insufficient, emphasizing the need for integration and interplay among multiple digital technologies to enable circular value creation. Finally, studies that address SCE barriers - whether broad in scope or focused on specific technologies - rarely link their analysis to established theoretical frameworks. This lack of conceptual grounding limits both the academic rigor and the practical relevance of the insights generated. Taken together, although prior research has advanced our understanding of the barriers associated with adopting digital technologies for CE purposes, relevant gaps remain. In particular, we argue that there remains a need for empirical studies that investigate the specific barriers manufacturing companies encounter when leveraging digital technologies to achieve circular economy objectives, especially when such analyses are embedded within a robust theoretical framework. Such research contributes to a deeper understanding of the findings and help improve their relevance and applicability within the manufacturing sector.

To address the identified research gap, this study provides empirical evidence on the barriers associated with implementing and using digital technologies to realize a CE in manufacturing companies. More specifically, it examines a broad spectrum of digital technologies rather than focusing on specific technology groups, and considers all stages of the product lifecycle. With these objectives, the study contributes to the existing literature by offering an empirically grounded overview of the barriers manufacturing firms encounter when leveraging digital technologies and data to implement CE solutions. The evidence stems from insights gathered from 61 experts, which revealed a wide range of barriers faced by manufacturing companies. These barriers were identified through inductive analysis and subsequently structured and interpreted using the Natural Resource-Based View (NRBV) as the guiding theoretical framework. Embedding the barriers within this framework enables systematic categorization across organizational levels and strategic capabilities, providing a coherent lens to examine the multifaceted nature of digital-enabled circular transformation. This approach supports a structured interpretation of the findings and connects them to established theoretical concepts, thereby strengthening the overall contribution of the study.

The remainder of the study is structured as follows: First, we present the methodology, including a detailed description of the data collection and analysis processes. Next, we describe the identified barriers to SCE in manufacturing companies. Following this, we discuss the findings, outline the study's limitations, and provide managerial recommendations along with implications for future research.

Methodology

To achieve the objectives of this study, a qualitative research design was employed, centering on expert interviews, and guided by the methodological recommendations of Strauss and Corbin (1998). A purposeful sampling strategy (Palinkas et al., 2015) was applied to ensure the selection of information-rich participants who could provide deep insights into the use of digital technologies in CE initiatives within the manufacturing sector.

Participants were selected based on several key criteria, consistent with established methodological guidance (Creswell & Poth, 2016; Palinkas et al., 2015). First, experts needed to be directly involved in, or have substantial experience with, circular initiatives that integrate digital technologies. Second, participants were required to hold professional roles that indicated relevant domain expertise, such as sustainability managers, directors of research and development, or chief technology officers - roles that bridge both digitalization and sustainability. Third, participants were required to be affiliated with or connected to companies in the manufacturing sector, specifically within subfields classified under the European Community's statistical classification of economic activities (NACE) code C, encompassing both small and large enterprises. Finally, all participants were required to have a demonstrable professional connection to the manufacturing industry, either as internal actors (e.g., company employees) or as representatives of related ecosystem stakeholders (e.g., recyclers, reverse logistics providers, remanufacturers or academic and business knowledge providers).

Potential interviewees were identified via the professional social network LinkedIn and through the authors' network of project partners and industry contacts. Initial pre-screening discussions served to assess candidates' expertise and willingness to participate, as well as to identify additional suitable candidates if initial contacts did not meet the criteria. In total, 61 experts who met the pre-defined criteria were interviewed. The participants' backgrounds reflect the purposeful nature of the sampling strategy, encompassing diverse yet relevant expertise across the manufacturing sector and its extended ecosystem. The sample includes representatives from a broad spectrum of company sizes: 14 experts were from small enterprises with fewer than 250 employees, 16 from medium-sized companies with 250 to 4,999 employees, 17 from large companies with 5,000 to 49,999 employees, six from very large companies with 50,000 to 99,999 employees, and eight from major corporations exceeding 100,000 employees. This distribution aligns with the sampling objective of capturing perspectives from both small and large enterprises. Regarding sectoral representation, participants predominantly come from manufacturing-related subfields, consistent with the study's focus. Specifically, 14 participants represented companies in motor vehicle and parts manufacturing, 15 in mechanical engineering, seven in electrical equipment manufacturing, six in machinery repair and installation, three in computer, electronic, and optical products manufacturing, three in other goods manufacturing, one in rubber and plastic products manufacturing, three in scientific research and advisory services for the manufacturing industry, and nine in various other industrial classifications related to NACE code C (Manufacturing). Appendix A provides an overview of the interviewed experts.

Before conducting the semi-structured expert interviews, an interview guide (see appendix B) was created following the recommendations of Kvale (2009). To prepare for the interviews, the interview guidelines were sent via email to all participating experts in advance. All interviews were conducted by using MS Teams as the primary platform. The shortest interview lasted 25 minutes, and the longest lasted 90 minutes, with the average interview duration being approximately 47 minutes. The interviews were conducted between October 2021 and January 2023. The expert interviews were recorded, transcribed, and anonymized. The transcription followed standard academic practices, such as smoothing language and applying simple transcription rules (i.e., omitting non-verbal and para-verbal events) (Braun & Clarke, 2006). The total length of all interviews amounted to 2220 minutes, or approximately 37 hours.

To derive insights from the textual data collected in the interviews, a rigorous qualitative content analysis was employed using thematic theme coding. This approach followed the methodology proposed by Gioia et al. (2013), which ensures a structured examination of emerging themes and patterns (Corbin & Strauss, 2008; Kvale, 2009). To enhance analytical rigor, we applied a three-stage coding process as recommended by Williams and Moser (2019), enabling systematic progression from raw textual data to well-defined thematic structures. This approach mirrors the process described by Takacs et al. (2022), which facilitates structured theory development from qualitative data and supports the integration of themes into a broader framework. In the open coding phase, key terms, sentences, and passages were labeled based on emerging concepts, guided by the topics covered during data collection. The subsequent axial coding step grouped similar codes into broader categories while identifying relationships among them. Finally, selective coding consolidated these categories into higher-order abstractions, forming a cohesive analytical structure (Williams & Moser, 2019).

All interview transcripts were imported into the qualitative data analysis software MAXQDA22 to ensure a transparent and traceable coding process. In the first phase, open coding, the researchers examined the transcripts from all 61 interviewees line by line. Descriptive labels were assigned to words, phrases, or passages that reflected meaningful content, following an inductive approach. This process resulted in 899 open codes. For example, the statement '*We often lack reliable data about the product's previous usage*' was coded as '*missing data during product usage*'. Similar codes were then clustered into 108 first-order categories. In this example, '*missing data during product usage*' as well as '*insufficient product data from user*' were clustered into the first-order category '*lack of data collection of smart products during usage*'. These first-order categories were labelled as '**Aspect of Barriers'**[4], which supported the identification of cross-cutting issues and relational patterns.

These first-order categories were further abstracted during the axial coding phase into 36 second-order themes, representing specific barriers to implementing digital technologies for realizing circular solutions in

[4] Definition of 'Aspects of the Barrier': Distinct components or characteristics that make up a broader SCE barrier identified during the coding process.

the manufacturing sector. These second-order themes reflect the ‘**SCE Barriers’**[5] identified in this study. For example, the categories ‘*lack of data collection of smart products during usage*’, ‘*no condition monitoring in the product*’, and ‘*limited hardware*’ were consolidated into the overarching SCE barrier ‘*limitations regarding the SCE capability of products*’. The coding and categorization process was conducted independently by multiple co-authors to ensure analytical rigor and minimize the potential bias of individual researchers. The independent analyses were then reviewed iteratively to reach consensus and resolve any discrepancies. This iterative process was crucial for ensuring consistency and reliability throughout the thematic analysis. During the axial coding phase, the 36 second-order themes were inductively aggregated and synthesized into 13 higher-level categories, referred to as ‘**Barrier Dimension’**[6]**.** In the final step, selective coding was guided by the theoretical lens of the NRBV (Hart, 1995; Hart & Dowell, 2011), representing the deductive component of the analysis. The NRBV is particularly appropriate for this study, as it emphasizes how firms can achieve competitive advantage by developing capabilities that address environmental challenges and manage natural resources strategically (Coppola et al., 2023; Samadhiya et al., 2023). Since SCE practices involve the use of digital technologies to retain resource value and reduce environmental impact, the NRBV offers a fitting conceptual framework to examine barriers that companies face when using digital technologies for realizing a CE (Chaudhuri et al., 2022).

The NRBV outlines three interrelated strategic capabilities: pollution prevention, product stewardship, and sustainable development (Hart, 1995; Hart & Dowell, 2011). These pathways align closely with our selective themes. Pollution prevention corresponds to value processes aimed at reducing waste and inefficiencies. Product stewardship relates to the design and lifecycle management of products. Sustainable development reflects the organizational structures and capabilities required to embed environmental objectives in firm strategy. In addition, Hart and Dowell (2011) identified clean technologies, understood as the development and deployment of technological innovations that reduce environmental impact, as crucial enablers of environmental transformation. This parallels the enabling role that digital technologies play in the context of SCE implementation.

Applying this lens allowed us to embed the inductively identified barriers into four core ‘**Selective Themes’**[7] - (1) technologies, (2) organization, (3) products, and (4) value processes - that reflect the capabilities and resource configurations required for SCE implementation. To complement the NRBV and account for broader contextual influences that emerged from the data, a fifth selective theme (5) meso-macro-system was added, capturing external barriers situated at the meso- and macro-levels of the manufacturing ecosystem. This addition ensures that systemic and institutional factors beyond firm-level capabilities are also considered.

Results

The results section is structured according to five overarching themes: (1) technologies, (2) organization, (3) products, (4) value processes, and (5) meso-macro-system. These themes encompass 13 barrier dimensions and a total of 36 specific SCE barriers identified through our systematic analysis.

Figure 1 provides an overview of this structure, illustrating how the 13 barrier dimensions are grouped within the five NRBV-based selective themes. The identified dimensions are: (1.1) data-related, (1.2) technology-related, (2.1) organizational culture-related, (2.2) competence-related, (2.3) organizational structure-related, (2.4) strategy-related, (2.5) business model-related, (2.6) financial, (3) product-related, (4)

[5] Definition of ‘SCE Barriers’: Specific obstacles that hinder the adoption and implementation of digital technologies for realizing CE solutions.

[6] Definition of ‘Barrier Dimensions’: High-level themes that aggregate related second-order themes, representing overarching areas of obstacles.

[7] A selective theme refers to a higher-level conceptual category, deductively derived from the NRBV, that groups and integrates related barrier dimensions into a coherent narrative.

process-related, (5.1) ecosystem-related, (5.2) market-related, and (5.3) regulatory aspects. Each of these dimensions and their associated barriers are described in the following sections.

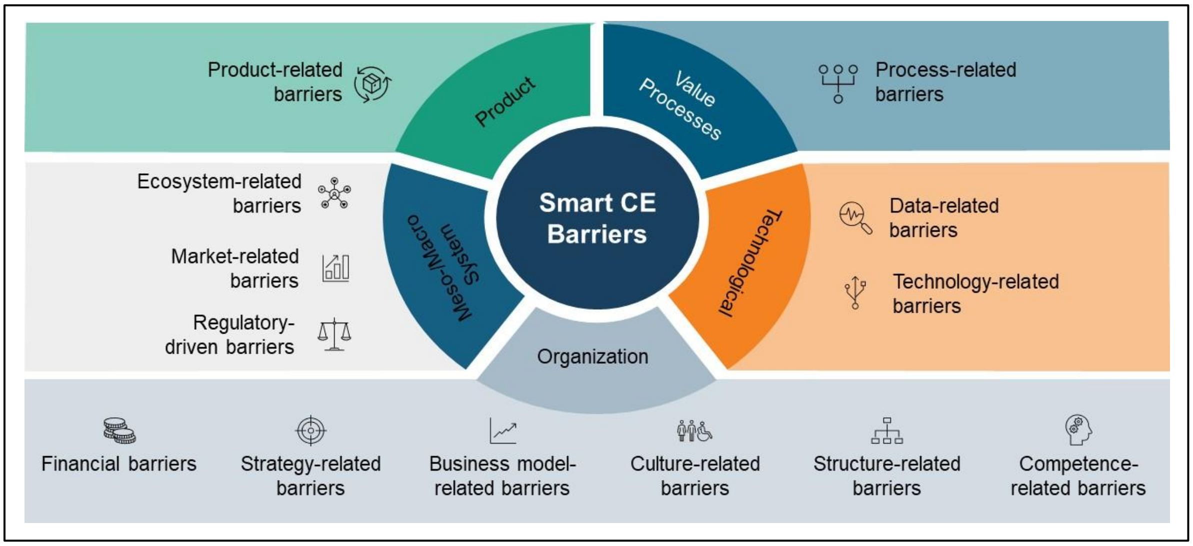

Figure 1 Overview of Barrier Dimensions Clustered in Five Broader Themes

Technological Barrier Theme

This theme focuses on barriers that arise specifically from the implementation and use of digital technologies and data in applying CE strategies in business practice. It includes two barrier dimensions - (1.1) data-related and (1.2) technology-related - which are described in the following section.

Data-related Barrier Dimension This barrier dimension encompasses barriers related to the use and analysis of data for implementing CE practices. Two experts emphasized the **complexity of data analysis** and noted that their companies encountered difficulties in analyzing large, heterogeneous data sets and ensuring their comparability for decision-making. They also pointed to the lack of standardized logics, such as semantics and ontology, for context data, as different systems (e.g., ERP, production planning) and software solutions are used. The use of data for the simulation of different CE options and alternatives was also identified as a challenge, illustrating the complexity of data analysis involved in leveraging diverse and non-standardized context data. Six experts reported **difficulties in data integration and sharing**, citing the absence of a common data pool and data silos arising from machine heterogeneity and incompatible data sources. The challenge of linking data through harmonized exchange interfaces was also mentioned. Additionally, experts raised **concerns about data security and privacy**, particularly with cloud-based solutions. They noted that the perceived risks often outweigh the benefits, and customer expectations around privacy further contribute to company hesitancy. Inadequate data quality was the most frequently cited data-related barrier, mentioned in 20 interviews. Thirteen experts identified that limited access to essential data, especially among companies in the upstream stages of the value chain, contributes significantly to this issue. Additionally, **poor data quality** was frequently associated with inconsistencies, insufficient granularity, and a lack of comparability, which often resulted from evolving data formats over time. A summary of the barriers in the data-related SCE barrier dimension identified in the interviews is presented in Table 1.

Table 1 Data-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Data-related Barriers	High Complexity of Data Analysis	Heterogeneous data complicates data analysis and limits the applicability of standard methods Challenges in conducting comparable evaluations across diverse data sources and systems
	Inadequate Data Integration and Sharing	Historically grown data silos Lack of harmonized data for data exchange
	Inappropriate Data Privacy	Insufficient data encryption and security measures Inadequate compliance with data protection regulations
	Insufficient Data Quality	Unavailability or limited access to data Poor data quality Insufficient granularity of data Lack of data consistency Incomplete data

Technology-related Barrier Dimension Several technology-related barriers hinder the implementation of CE strategies, especially due to a lack of infrastructure. Key barriers include the **lack of interoperability** between systems, caused by various technical solutions that make data exchange between components and machines difficult. This also impedes the implementation of smart services. Experts also noted that complex software and hardware systems often restrict access to collected data, such as component status. Four experts pointed to the **absence of adequate technological solutions** as a key barrier. This includes the lack of digital product passports, missing digital tools to support CE decision-making, the absence of shared data spaces for secure data exchange, and inefficient technologies for tracking material flows at a detailed level. In addition, the **technological maturity** of existing solutions, particularly for applications like automated disassembly, was considered inadequate. Finally, five experts emphasized that the **negative environmental impact of digital technologies**, such as increased resource and energy consumption, may offset their intended ecological benefits. Table 2 summarizes the technology-related SCE barrier dimension.

Table 2 Technology-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Technology-related Barriers	Lack of System Interoperability	Interface issues between systems Heterogeneous software solutions/isolated solutions
	Absence of Technological Solutions or Technology Limits	Need for a digital product passport Missing tools for supporting CE decision-making Lack of data space for secure data sharing Technological solutions for tracking at the material level
	Insufficient Technological Maturity	Insufficient maturity of digital technologies
	Negative Environmental Impact from Digitalization	High resource (raw materials & energy) consumption by digital technologies Negative side effects of digital business models Environmental impact from data storage

Organizational Barrier Theme

This theme comprises six barrier dimensions - (2.1) organizational culture, (2.2) competence, (2.3) organizational structure, (2.4) strategy, (2.5) business model, and (2.6) financial - which together account for 15 of the 36 identified SCE barriers.

Organizational Culture-related Barrier Dimension Twenty experts emphasized organizational culture as a significant barrier to the transformation toward a SCE. A key issue was the **lack of openness and willingness** to collaborate in data exchange, with companies struggling to cooperate due to concerns about competition and the protection of proprietary knowledge. In this context, the need for transparency in product and material data - crucial for implementing a SCE - was also emphasized, particularly regarding digital product passports. These passports require the sharing of information on resources, production processes, repair strategies, and recycling practices.

Another barrier is the **resistance to change** within companies, as noted by four experts. The transformation to SCE is seen as a long-term, disruptive process that affects all aspects of the business, including products and business models. One expert described it as a transformation that could take years and would impact every department, suggesting that such disruption can be overwhelming for many companies.

Finally, a **lack of an innovation-driven culture** hinders SCE adoption. Twelve experts pointed out that their companies are not data-oriented and hesitant to embrace new digital technologies for realizing circular solutions. They also noted a missing supportive mindset towards SCE, with some departments, such as sales and development, failing to prioritize environmental objectives. Additionally, one expert noted a tendency to prioritize smaller, more manageable initiatives over more profound business model changes, reflecting a degree of organizational inertia. See Table 3**Error! Reference source not found.** for a summary of the organizational culture-related SCE barrier dimension.

Table 3 Organizational Culture-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Culture-related Barriers	Lack of Openness and Willingness to Collaborate	Lack of willingness to cooperate Lack of openness regarding transparency and data exchange
	Resistance to Change	Fear of changes due to SCE-related transformations
	Insufficient Innovation Culture for SCE	Lack of digital and data-oriented organizational culture Lack of SCE mindset Organizational inertia toward digital-supported circular business models

Competence-related Barrier Dimension A recurring issue in this dimension, highlighted by six experts, was the **lack of SCE expertise**, particularly in data analysis and interpretation methods, along with insufficient digital skills for effectively applying digital technologies in CE initiatives. Four experts highlighted the lack of skills in designing data collection processes, particularly regarding the accuracy and relevance of data for CE projects. They emphasized that managing large volumes of data remains a significant challenge, pointing to a broader competence gap in effectively utilizing data for CE initiatives. Nine experts pointed to a lack of awareness regarding the potential of digital technologies to reduce information asymmetries and support CE strategies. As one expert explained, "I think this [awareness] is missing. The more information we have, the smarter decisions we can make, and the more efficiently we can design our systems" (Interview 1). Another issue identified by six experts was the absence of software development expertise related to circular innovations and new business models. As one expert put it, "We have the know-how about remanufacturing, but what else is possible [once the data is available] with regard to new business models, I don't see in the organization" (Interview 27). The barrier of **building new SCE competencies** within organizations was emphasized by four experts, particularly in the context of international locations, where effectively transferring competencies remains a significant hurdle. One expert noted that companies still lack effective knowledge management for SCE, employees struggle with its complexity, and there is insufficient attention given to the topic. Additionally, the **lack of leadership competencies** for SCE has been noted as another barrier. One expert pointed out that many managers often fail to prioritize circular objectives when implementing digital technologies or fully understand the economic potential of SCE. The expert elaborated: "[…], we need to better understand what the benefit is of implementing smart circularity or smart products. The relationship between investment and the business case might be a barrier" (Interview 27). Table 4 provides an overview of the identified competence-related SCE barrier dimension.

Table 4 Competence-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Competence-related Barriers	Lack of Expertise with SCE	Limited expertise in data analysis and interpretation Lack of digitalization skills for applying digital technologies to CE strategies Challenges in designing data collection and handling large data volumes. Lack of awareness about the potential of digital technologies and data for implementing CE Insufficient expertise in software development Insufficient expertise in digital innovations and digital business models
	Challenges in building new competencies	Challenges in building SCE competencies abroad Lack of support in building new competencies Lack of knowledge management and attention to the topic Insufficient communication of best practices and publicly available information on the topic
	Lack of leadership competencies	Lack of quality and competence of leadership personnel Lack of conviction among senior management Lack of understanding of the economic potential of SCE

Organizational Structure-related Barrier Dimension Organizational structure refers to the systems designed to align employees' behavior with company goals, with three key SCE-related barriers being identified. Thirteen experts observed that a **restrictive vertical organizational structure** within companies often impedes the implementation of SCE by fostering conflicts of interest between departments, such as sales and service. These silos not only create organizational misalignment but also complicate the effective use of digital technologies, which rely on integrated data flows and cross-functional collaboration. One expert vividly illustrated this tension by stating, "Sales wants to sell a new machine, while service is interested in maintaining existing machines" (Interview 44), highlighting how diverging departmental goals can undermine circular strategies such as lifecycle extension, even when digital tools are in place to support them. Conflicts also arise with controlling, which prioritizes economic indicators over environmental factors, thereby hindering the implementation of digital innovations for CE that have a long amortization period. Seven experts noted that vertical structures also create communication issues and silo thinking, limiting information exchange across departments.

Another barrier highlighted by five experts was the **absence of organizational roles with shared responsibility for digitalization and CE**, as companies often lack the necessary resources or assign these tasks alongside employees' regular duties.

Finally, **challenges in implementing new organizational structures** required for SCE transformation were emphasized, particularly with regard to aligning employee engagement and operational integration in increasingly digitalized environments. These difficulties were especially evident when companies shifted from traditional product sales toward digital-enabled, service-oriented business models. In this regard, two experts emphasized that success depends on all employees embracing supportive structures grounded in digital technologies. Table 5 provides a summary of all aspects associated with the organizational structure-related SCE barrier dimension.

Table 5 Organizational Structure-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Structure-related Barriers	Restrictive Vertical Organizational Structure	Conflicts of interest between different organizational departments Communication problems between organizational units Silo thinking due to the vertical structure of the company
	Lack of Position for Digitization & CE	No dedicated position to connect digitization and CE within the structure Lack of human capital to fill in required roles
	Challenges in Implementing New Organizational Structures	Resistance to adopting organizational structures that enable both digitalization and circular transformation

Strategy-related Barrier Dimension In this barrier dimension, **missing strategy and difficulties with strategic alignment** emerged as a key issue in the interviews. The findings revealed that some companies have not yet integrated digitalization aspects into their sustainability strategy or even lack such a strategy altogether. In other instances, there was a noticeable disconnect between CE and digitalization in their strategic agenda. In this matter, seven experts highlighted internal misalignments in strategy formulation and inconsistent execution across organizational units. These shortcomings often prevent companies from translating sustainability awareness into concrete initiatives supported by digital technologies. As one expert emphasized: "I think we are all very aware of the potential, but we have not yet fully leveraged this awareness to drive actions, activities, and initiate projects. Awareness, yes; activity, no" (Interview 19). In conclusion, while digital tools hold significant potential to enable data-driven decision-making for CE initiatives and support the operationalization of SCE strategies, this potential often remains underutilized due to a lack of strategic clarity and organizational alignment. Table 6 provides an overview of the strategy-related SCE barrier dimension.

Table 6 Strategy-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Strategy-related Barriers	Missing Strategy and Difficulties with Strategic Alignment	Lack of SCE Strategy Difficulties with Strategic Alignment

Business Model-related Barrier Dimension Fourteen experts emphasized **challenges implementing SCE business models**. In this context, eight experts pointed to a lack of approaches for leveraging data (e.g., product lifecycle data) to create value and transform business models. One expert provided a concrete example of such data-driven business opportunities, highlighting the detection of water leaks through smart sensors, which offers both economic and environmental benefits by preventing water waste. In this context, the expert expressed, "… [although] data is being generated now in a quantity that cannot even be compared to what we had before, […] [we] believe that [we are] only at the tip of the iceberg in terms of truly using these data" (Interview 9). Other aspects of barrier included implementing service-based business models using digital technologies, as outlined by four experts. One expert specifically mentioned the need for sensor technologies and suitable data to monitor and bill additional service offerings. Two other experts stated customers are unwilling to share data for smart services, preferring to develop them in-house, limiting the possibility of advancing the current business model. Another challenge mentioned by six experts was the low digital maturity of both their own companies and their ecosystem partners, which prevents the development and execution of SCE business models. As one expert noted, without this maturity, manufacturing companies struggle to implement smart services and launch new business models: “The companies we are working with are just experimenting with sensors and RFID [in their products]. It’s really still in its infancy” (Interview 2).

Finally, five experts highlighted **conflicts between current linear and future digital circular business models** and that the shift from product sales to digitally-enabled service-based business models causes internal friction. In Table 7, the business model-related SCE barrier dimension is illustrated.

Table 7 Business Model-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Business Model-related Barrier	Challenges in implementing smart CE business models	Lack of approaches and concepts for generating value from data in business models
		Challenges in realizing service-based business models and offering smart services
		Insufficient or missing digital maturity for SCE business models
	Conflict between current business model and the implementation of digital circular business models (Ambidexterity)	CE strategy contradicts the existing business model

Financial Barrier Dimension The interviews revealed three main financial barriers for realizing a SCE. Three experts highlighted a **lack of financing options for implementing SCE initiatives,** particularly in cases where companies aim to retain product ownership and offer only the function or performance as a service.

Furthermore, ten experts pointed out that significant **financial risks** arise when business cases for the implementation of digital technologies for circular purposes are unclear, as traditional metrics are insufficient to evaluate their benefits and successful examples are scarce. Additionally, one expert pointed out that new financial flows introduced by SCE models create uncertainty, and that selling equipment, instead of offering pay-per-use options, remains a safer financial choice. Two experts emphasize that they still face difficulties in predicting the success of new SCE processes and calculating associated costs and that low margins for business models related to SCE products further add to the financial risk.

Finally, eight experts highlighted the **high initial investment costs** associated with implementing digital technologies for circular solutions, particularly in international companies with heterogeneous IT infrastructures, noting that the development of smart services to support CE initiatives such as condition monitoring and predictive maintenance can also be financially demanding. Table 8 gives an overview of the financial SCE barriers that manufacturing companies face.

Table 8 Financial Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Financial Barriers	Lack of financing options	Limited financing options for SCE initiatives
	High financial risk	Financial risk due to lack of business cases High financial risk due to uncertain revenue streams of SCE initiatives High financial risk due to uncertainties and low profit margins for SCE products
	High initial investment costs	High investment costs for new technologies and technological infrastructure High expenses for building SCE competencies High expenses for circular transformation High expenses for establishing new partnerships High investment costs for the development of smart services

Product-related Barrier Theme

Only nine experts mentioned barriers related to company products (3), specifically highlighting **limitations regarding the SCE capability of their current products**. Three experts linked this barrier partly to limitations in their products' ability to support data collection during use, while five experts emphasized difficulties in systematically and continuously monitoring the condition of their products. However, such information is crucial for initiating smart services, such as predictive maintenance, which can, in turn, extend the product lifespan. Three experts emphasized that old components and products in the field are like a „black box", incapable of collecting and transmitting usable data. They described the retrofitting of old machines with sensors and the unsuitability of outdated hardware for more precise data analysis applications as significant challenges. Table 9 provides a summary of the product-related SCE barrier dimension.

Table 9 Product-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Product-related Barriers	Limitations regarding the SCE capability of products	Lack of data collection of smart products during usage No condition monitoring in the product Limited hardware capabilities

Value Process-Related Barrier Theme

The value process-related barrier theme covers one dimension (4) with two value process-related SCE barriers: First, challenges arising from **the realignment of established processes** with the help of digital technologies. A total of 15 experts mentioned reasons for this barrier. Two experts indicated that existing processes focused on linear economy models cause frictions when planning the use of digital technologies for circular solutions. In contrast, five experts pointed out the lack of digital processes aligned with circular approaches. Three further experts specified this issue by mentioning the absence of smart reverse logistics processes or the lack of repair and remanufacturing structures. In particular, they highlighted that digital support systems such as tracking technologies, data-driven return systems, or predictive maintenance tools are either not in place or not sufficiently integrated, making it difficult to efficiently coordinate and scale circular operations. Furthermore, four experts emphasized that aligning processes for SCE requires a fundamental shift in the logic and nature of process and product innovations. This shift also affects requirements for product design processes and the design of SCE-related services. Specifically, experts emphasized that digital technologies, such as digital product passports, smart modular design tools, and IoT-based service platforms, are pivotal in advancing value processes. These smart value processes foster circular innovations by enabling data-driven design decisions, facilitating circular service models, and ensuring product traceability throughout the lifecycle. For example, value processes must support the continuous updating of products and the ongoing collection of condition data to allow timely adaptation to new regulations or standards. One expert elaborated on these aspects by stating: "additionally, it's not made easier by the fact that product development often works with 'gates' and 'stages' or is waterfall-driven. Depending on the product, there are long development cycles, with versions one, two, three, four, five already planned years ahead, and they follow entirely different milestones compared to service development or business model innovation, which is much more agile and digital. When using digital technologies, you know, such as data platforms or digital twins, they often need faster iterations and cross-functional collaboration, which don't fit easily into these rigid structures. Some companies have tried it with hybrid models, but there's also this challenge of when and how to embed digital innovation into existing development processes" (Interview 2).

Furthermore, six experts mentioned the adjustment of established procurement processes in manufacturing companies towards more digitally enabled circular procurement practices as a significant challenge. This was particularly linked to the data on the availability of suitable secondary raw materials and spare parts. In this matter, experts emphasized that digital marketplaces, blockchain-based material traceability, and digital procurement platforms, which allow real-time data analytics for providing such data, are not yet widely adopted or sufficiently integrated into existing procurement systems. As a result, manufacturing companies face difficulties in sourcing high-quality secondary materials reliably and in aligning procurement decisions with circularity goals. The lack of standardized digital interfaces and poor data quality further complicates the inclusion of secondary inputs in automated procurement routines.

Second, the **insufficient or missing implementation and execution of SCE processes** was identified as a barrier. As a reason for this, 13 experts identified a lack of the right data needed to efficiently coordinate operations, resulting in poorly functioning data-driven processes. In contrast, six experts attributed the shortcomings to insufficient automation and digitalization of processes, rather than to the data itself. Additionally, five experts cited the low overall level of digital maturity in value-creation processes as a key reason why implementing SCE processes in practice remains a challenge. In this context, three experts highlighted a lack of fully transparent internal processes, such as tracking waste generation in each production process. Table 10 presents the value-related SCE barrier dimension.

Table 10 Value Process-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Value process-related Barriers	Challenges in realigning established processes	Existing non-digital processes hinder the implementation of new SCE processes
		Lack of processes aligned with SCE
		Missing data-driven reverse logistics processes
		Challenges in redesigning non-digital processes
		Challenges in implementing CE-related requirements for smart product and service design processes
		Difficulties and uncertainties in integrating digital innovations into current procurement processes
	Difficulties in implementing and executing SCE processes	Poor data-driven processes
		Insufficient automation and digitization of processes
		Lack of digital maturity in value creation processes
		Insufficient internal process transparency

Meso- and Macro- System-related Barrier Theme

In the course of this study, it became apparent that the experts were referring to a variety of barriers not directly related to the manufacturing companies themselves, i.e., at the micro- (e.g. corporate, business unit) and nano-

(products, components), but rather at the meso- and macro-system levels, which lie beyond the direct influence of the company. Three of ten identified meso- and macro-system-related SCE barriers are related to the business ecosystem (5.1) of manufacturing companies and therefore belong to the meso-level. The remaining seven barriers can be attributed to the macro-level and are clustered into market-related (5.2) and regulatory (5.3) SCE barriers.

Ecosystem-related Barrier Dimension Three SCE barriers are related to the establishment and management of smart circular ecosystems. A circular ecosystems is “a system of interdependent and heterogeneous actors that go beyond industrial boundaries and direct the collective efforts toward a circular value proposition, providing opportunities for economic and environmental sustainability” (Trevisan et al., 2022, p. 296). The first barrier that hinders the establishment of smart circular ecosystems is the **difficulty of creating these ecosystems**. Two experts highlighted that, for many manufacturers, creating the necessary circular ecosystem in their dual transformation process is accompanied by significant uncertainty, particularly regarding the emergence of unseen digitalized forms of value creation. Five experts mentioned the lack of SCE readiness among key actors as a challenge, often due to the absence of a compelling business case or limited interoperability of their company-specific IT infrastructures. Six experts highlighted dependencies within the value chain as a critical challenge, citing issues such as contractual obligations, power imbalances, and customer demands that lead to a disrupted flow of information. These issues are further exacerbated by the limited use of digital technologies that could improve transparency and coordination across value chain partners. For example, the absence of interoperable data-sharing platforms hinders real-time collaboration on circular initiatives. Moreover, without blockchain or distributed ledger technologies, it is difficult to build trust in shared data on material flows, product use histories, or mutual sustainability performance. Experts also noted that digital tools for lifecycle tracking or smart contracting are often not integrated into supplier management systems, limiting the ability to align incentives or manage responsibilities across organizational boundaries. Other concerns raised by seven experts included a lack of SCE competencies of their ecosystem partners, particularly across foreign subsidiaries, as well as the challenges posed by new forms of digital-supported collaboration.

Seven experts identified **the lack of specialized ecosystem partners**, such as a dense network of reverse logistics providers and service providers for implementing circular solutions as a key barrier. They emphasized that limited digital integration, such as missing real-time data exchange for partner coordination, makes collaboration inefficient and hinders the development of a smart circular value network.

The most frequently mentioned barrier, highlighted in 19 interviews, was the **lack of transparency in the ecosystem**, due to the absence of interoperable data exchange platforms, leading to manual processes in information exchange. Additional challenges included inconsistent IT infrastructure caused by poorly maintained and fragmented systems among ecosystem partners. Finally, five experts pointed to challenges arising from insufficient digital connectivity across the value network, while nine experts emphasized concerns about data privacy and a lack of trust concerning data exchanges within the ecosystem. Table 11 provides a summary of the ecosystem-related SCE barrier dimension.

Table 11 Ecosystem-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Ecosystem-related Barriers	Challenges in creating SCE ecosystems	High uncertainty in building digital-supported ecosystems
		Challenges due to digital forms of value creation
		Lack of SCE readiness among actors in the value network
		Difficulties due to dependencies in the value network
		Concerns about building CE knowledge abroad
		Uncertainties due to new forms of collaboration and partnerships
	Lack of infrastructure and actors for SCE	Lack of infrastructure, particularly for data-driven reverse logistics
		Shortage of suitable actors with compatible IT infrastructure
	Difficulties in establishing transparency in the ecosystem	Challenges in intercompany data exchange
		Inconsistent or missing IT infrastructure
		Lack of digital connectivity
		Lack of trust in data exchange within the value network

Market-related Barrier Dimension Among the market-related barrier dimension, the **lack of customer acceptance for SCE products and services** was mentioned most frequently (nine experts). This barrier primarily concerns the use of data in implementing CE practices or circular business models, such as pay-per-X or result-oriented models.

Additionally, six experts criticized the **lack of transparency regarding supply and demand for circular products and services.** One expert noted a lack of data on acrylic materials, partly attributing this to the limited acceptance of data-driven marketplaces and digital tracking systems that could enable real-time visibility and transparent material flows. Furthermore, two experts emphasized that customers need reliable predictions of the availability of refurbished parts and secondary materials, as maintaining SCE business models requires a certain level of predictability and stability. In this context, three experts suggested the need for virtual marketplaces or platforms to better connect suppliers and buyers of used parts, secondary materials, and recyclable waste.

A third market-related barrier, highlighted by three experts, was the presence of **constraining power dynamics**, for example due to asymmetric power relations within the value network. In digitally connected ecosystems, such concentration may allow dominant actors to exert control over data flows, restrict transparency, and limit access to digital resources, which undermines cooperation and fair allocation of resources among stakeholders. In Table 12, all identified market-related SCE barriers are displayed.

Table 12 Market-Related Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Market-related Barriers	Lack of customer acceptance for SCE products and services	Lack of customer acceptance regarding the use of digital technologies and the utilization of data for implementing CE
	Lack of transparency regarding the supply and demand of circular products and services	Lack of accessible information on waste material supply and demand
		Lack of predictability regarding the availability of used parts and secondary materials
		Lack of transparency regarding the supply of CE products and components
		Need to create a platform as a 'marketplace' to bring supply and demand together
	Constraining power dynamics in supplier structures	Asymmetric power relations

Regulatory Barrier Dimension Four regulatory SCE barriers were identified at the macro level. These barriers are related to both laws and directives on one hand, and to norms and standards on the other. Laws and directives are legally binding regulations, while norms and standards are typically voluntary guidelines established by organizations such as ISO or DIN. Standards may also be incorporated into laws, particularly within EU legislation, under the principle of harmonization. The first regulatory barrier, mentioned by 19 experts, is the **absence of clear or sufficient regulations to promote SCE** practices in manufacturing companies. One example is the lack of incentive systems to encourage the implementation of digital innovations for CE solutions. Two experts from international companies highlighted the lack of uniform international legislation on CE, noting that varying national laws require different certified disposal systems and hinder the development of standardized digital solutions for tracking, documenting, and managing circular processes across borders. Additionally, four experts noted that lobbying efforts have slowed legislative progress on strengthening extended producer responsibility and enforcing digital tracking systems and data transparency requirements to support better monitoring and accountability. Four experts also pointed out unclear legal frameworks surrounding data ownership, while five experts highlighted the absence of consistent regulations on sustainability reporting and the calculation of sustainability indicators, such as the Product Carbon Footprint (PCF), as a significant issue.

A second regulatory barrier involves **existing laws that restrict the implementation of SCE**, as indicated by a total of 19 experts. For instance, several mentioned that antitrust and competition laws hinder the data sharing and digital collaboration needed between companies to enable smart circular solutions. Three experts noted that current laws limit the scope for digital innovation, particularly concerning data sharing and digital collaboration, whereas four experts stated that existing regulations even prevent the implementation of digital technologies for CE strategies. Additionally, nine experts highlighted data protection rules and international trade restrictions, such as tariffs, as further obstacles.

A third regulatory barrier identified by 17 experts is the **lack of norms and standards that promote SCE**. Seven experts highlighted the absence of uniform CE metrics or measurement systems, noting that existing evaluation tools are often inconsistent and lack seamless integration with digital data platforms. This gap hinders effective data collection, real-time analysis, and benchmarking across organizations. Eight experts emphasized the lack of standardized digital frameworks that enable secure and efficient data exchange between companies across global value chains, which is crucial for coordinated circular practices. Additionally, nine experts stressed the importance of assessment systems for monitoring and managing progress for realizing a SCE.

At the same time, two experts expressed concerns that **standardization hinders the implementation of SCE**, noted that digital standardization bodies could gain disproportionate influence over data governance and control within SCE ecosystems. Table 13 summarizes the regulatory SCE barrier dimension.

Table 13 Regulatory Barriers

Barrier Dimension	SCE Barrier	Aspects of the Barrier
Regulatory Barriers	Lack of or unclear legislation to promote SCE	Lack of a government incentive system for the implementation of SCE
		Insufficient international legislation for SCE
		Too slow legislation
		Lack of coherent legislation
		Unclear and diffuse legislation on data ownership
		Lack of legislation on sustainability reporting
		Missing legislation on product responsibility and product take-back
		Lack of legislation for sustainable alternatives
	Legislation restricts the implementation of SCE	Regulatory ambiguity leading to misalignment
		Legislation complicates the implementation of SCE products and services
		Hindering data protection regulations
		National differences in legislation affect international competitiveness
	Lack of standards to promote SCE	Lack of uniform metrics for assessment systems, especially for sustainability assessment
		Lack of standardization for data exchange
		Lack of an assessment system for SCE
	Standardization hinders the implementation of SCE	Obstacles due to norms and standards

Discussion

The findings of this study provide comprehensive insights into the barriers that manufacturing companies face in their transition toward a SCE. Our results suggest five overarching themes: technological, organizational, product-related, value-process-related, and external (meso- and macro-level), which encompass 13 distinct barrier dimensions. This thematic categorization, grounded in the NRBV (Hart, 1995; Hart & Dowell, 2011), offers a structured and holistic analytical lens to assess the scope and complexity of adaptations that companies must undertake to realize a SCE. The results emphasize that transitioning to SCE demands more than technological upgrades (Lobo et al., 2022) but requires deep, systemic changes across multiple organizational domains (Rehman et al., 2023). Consequently, manufacturing companies must reconsider and reconfigure not only their technological infrastructure but also their products, value-creation processes, and organizational design, encompassing substantial shifts in structures, cultures, competencies, and business models. These findings underscore that manufacturing companies undergo a dual transformation journey, digital and circular, which must be managed in parallel (Christmann et al., 2024). However, these two trajectories are frequently treated as separate endeavors, rather than as integrated pathways (Rehman et al., 2023). As a consequence, opportunities to exploit potential synergies, such as leveraging digital technologies for transparency, traceability, predictive maintenance, or enabling closed-loop systems, remain underutilized or unrealized in practice (Breiter et al., 2024). Our NRBV-informed categorization offers an alternative perspective to existing functionally-oriented taxonomies of barriers (Bag et al., 2022; Trevisan et al., 2023). For instance, Trevisan et al. (2023) classified barriers according to organizational action fields (e.g., knowledge management, governance, technological systems, and regulatory environments), providing a broad view of where challenges arise in firms' operations. Similarly, Bag et al. (2022) propose seven key barrier dimensions, including process, human resources, financial, collaboration, technological, security, and leadership-related challenges, reflecting practical concerns across functional areas. Although these approaches provide valuable and practical insights into the variety of challenges firms encounter, they tend to concentrate on organizational actions and the ways in which barriers appear within particular operational areas.

In contrast, our NRBV-informed approach transcends this functional segmentation by emphasizing the development of strategic capabilities that integrate technological, organizational, product, and value process domains. Rather than treating these areas as isolated challenges, we view them as interconnected elements of a firm's internal resource base that must be aligned holistically. This perspective shifts attention from discrete organizational activities to the underlying dynamic capabilities essential for managing complex, systemic change (Neri et al., 2023). By clustering the identified barriers into four NRBV-informed domains technology, organization, product, and value creation, we propose the key areas in which firms must evolve to realize a SCE. This clustering moves beyond a simple listing of functional or procedural obstacles and instead reveals deeper structural and systemic misalignments that impede circular transformation. In addition, by introducing a fifth, external dimension that captures macro- and meso-level conditions such as regulatory frameworks, infrastructure readiness, and ecosystem coordination, our framework extends the NRBV. It does so by drawing attention to the enabling environment necessary for effective implementation. Taken together, our study offers an integrated understanding of the transformation processes required for achieving systemic circularity (Mäkitie et al., 2023).

Furthermore, the empirical evidence generated in this study responds to recent calls for greater empirical granularity to deepen our understanding of barriers to SCE implementation (Thirumal et al., 2024). Based on insights from a diverse sample of manufacturing firms, the findings provide various indications that the nature and severity of SCE barriers are influenced by contextual factors. While the primary aim was to identify a broad range of barriers, the findings suggest that firm-specific and product-specific characteristics significantly shape how these barriers are experienced. Relevant organizational factors include firm size, degree of internationalization, ownership structure, and position within the value chain. Likewise, product attributes such as complexity, standardization, economic value, digital features, and batch size appear to affect the manifestation and intensity of certain challenges. These findings indicate that SCE transformation is inherently context-sensitive. Future research should explore these relationships more systematically to support the development of targeted strategies that facilitate circular and digitally-enabled transitions in manufacturing companies

Implications, Limitations and Suggestions for Further Research

This study makes several contributions to theory and practice by adding further empirical evidence regarding the barriers that manufacturing companies face in their efforts to transition to a SCE. From a theoretical perspective, our findings contribute to the growing literature on SCE barriers by proposing a categorization framework for barriers grounded in the NRBV. While existing frameworks such as those by Trevisan et al. (2023) and Bag et al. (2022) use more functional categories to map SCE barriers, our lens encourages reflection on the strategic fields firms require to manage circular and digital transformations simultaneously. By framing barriers as reflections of deeper structural challenges, our approach offers a complementary perspective that facilitates a more integrated understanding of both internal and external transformation dynamics. The inclusion of meso- and macro-level barriers within this framework further encourages scholars and practitioners to adopt a multilevel perspective, situating firm-level transformation processes within a wider systemic context.

For practitioners, this study gives guidance as it offers a structured overview of the types of barriers manufacturing firms may encounter when pursuing SCE goals. Systematic engagement with this categorization framework can help organizations identify key fields of action, such as product design, organizational culture, or ecosystem collaboration, which may need prioritized attention. This critical reflection process can foster awareness for the need and possibilities of fundamental change and function as an initial self-assessment of a company's SCE readiness. The findings also highlight the importance of treating digital and circular transformations as interdependent rather than separate efforts. Recognizing and leveraging potential synergies between the two can improve implementation outcomes, for instance by using digital technologies to enable more effective material tracking, predictive maintenance, or reverse logistics.

For policymakers, the study highlights the critical need for targeted regulatory frameworks and supportive policy measures to address the specific barriers identified. Policymakers can use these insights to design interventions that encourage SCE innovation, incentivize circular business models, and foster cross-sector collaboration, ultimately accelerating the transformation to a SCE. Through the raised awareness about possible regulatory gaps or misalignments, this research can inform prospective policy reforms that will help manufacturing companies and related sectors to overcome the barriers they face in adopting SCE practices.

While this study provides valuable insights, it is not without limitations. The focus on manufacturing firms may limit the generalizability of the findings to other sectors, such as food, textiles, healthcare, or services, which may face unique challenges. Each sector encounters its own set of specific barriers, which can differ in nature and scope. Therefore, we recommend that future research extend the scope of this study to other industries, examining which barriers are universally present and which are sector-specific. Comparative studies across industries could offer deeper insights into how sector-specific characteristics influence the ability to implement digital technologies for a circular transition. Additionally, while this study systematically uncovers a broad set of barriers, it does not address the relative severity or importance of these barriers, nor does it provide insights into which barriers are easier or harder to overcome. Moreover, barriers may mutually influence one another or occur simultaneously; however, this study did not analyze the interrelationships between barriers. Understanding the impact and interplay of these barriers is crucial for prioritizing effective interventions. Furthermore, the study assumes that all manufacturing companies face the same barriers in a similar manner, without considering potential variations based on organizational characteristics (e.g., size, international scope, ownership type, and position within the value chain) or product characteristics (e.g., product value, variety, batch size, and complexity). Future research should explore how these factors influence the occurrence and severity of barriers. An important avenue for future work would be to assess the relative importance and severity of the identified barriers, enabling companies to prioritize specific actions in their roadmaps or action plans and facilitating more targeted interventions to overcome barriers in the CE transition. In addition to assessing the severity of barriers, future studies should also focus on identifying concrete solutions for the most pressing barriers that many companies face. By developing and evaluating practical strategies for overcoming these obstacles, researchers can provide actionable insights that enable companies to not only identify the barriers but also implement effective measures to address them.

In conclusion, this study provides a comprehensive framework for understanding the barriers to transitioning to a SCE, offering valuable insights for academia, practitioners, and policymakers, while also highlighting key areas for future research to further support the successful implementation of SCE practices in manufacturing companies.

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References

Alcayaga, A., & Hansen, E. G. (2025). Smart circular economy as a service business model: an activity system framework and research agenda. *R&D Management*, *55*(2), 508–530.

Bag, S., Sahu, A. K [Atul Kumar], Kilbourn, P., Pisa, N., Dhamija, P., & Sahu, A. K [Anoop Kumar] (2022). Modeling barriers of digital manufacturing in a circular economy for enhancing sustainability. *International Journal of Productivity and Performance Management*, *71*(3), 833–869.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.

Breiter, K., Crome, C., Oberländer, A. M., & Schnaak, F. (2024). Dynamic capabilities for the Twin Transformation climb: A capability Maturity Model. *Information Systems Frontiers*, *26*(1), 2205–2226.

Bressanelli, G., Adrodegari, F., Pigosso, D. C. A., & Parida, V. (2022). Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda. *Sustainability*, *14*(9), 1–20. https://doi.org/10.3390/su14094960

Bühler, L., Schuster, T., & Pflaum, A. (2025). Twin Transformation — The Case of Smart Circular Economy in Manufacturing Industries: Insights from an Umbrella Review. *International Journal of Innovation Management*, *29*(05/06), 2540007. https://doi.org/10.1142/S1363919625400079

Chaudhuri, A., Subramanian, N., & Dora, M. (2022). Circular economy and digital capabilities of SMEs for providing value to customers: Combined resource-based view and ambidexterity perspective. *Journal of Business Research*, *142*(1), 32–44. https://doi.org/10.1016/j.jbusres.2021.12.039

Chhabra, D., & Singh, R. (2024). Analyzing barriers to green logistics in context of Circular Economy and Industry 4.0 in the Indian manufacturing industry. *International Journal of Logistics Research and Applications*, *27*(11), 1939–1952.

Christmann, A.-S., Crome, C., Graf-Drasch, V., Oberländer, A. M., & Schmidt, L. (2024). The Twin Transformation Butterfly: Capabilities for an Integrated Digital and Sustainability Transformation. *Business & Information Systems Engineering*, *66*(4), 489–505.

Coppola, C., Vollero, A., & Siano, A. (2023). Developing dynamic capabilities for the circular economy in the textile and clothing industry in Italy: A natural-resource-based view. *Business Strategy and the Environment*, *32*(7), 4798–4820. https://doi.org/10.1002/bse.3394

Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (3. Edition). SAGE.

Creswell, J. W., & Poth, C. N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. SAGE Publications.

Denu, M., David, P., Landry, A., & Mangione, F. (2023). Exploring opportunities and barriers of digital technologies in circular manufacturing systems: An overview and a research roadmap. *Sustainable Production and Consumption*, *43*(1), 400–421.

Galvão, G. D. A., Evans, S., Ferrer, P. S. S., & Carvalho, M. M. (2022). Circular business model: Breaking down barriers towards sustainable development. *Business Strategy and the Environment*, *31*(4), 1504–1524.

Gartner. (2020). *Gartner Survey Shows 70% of Supply Chain Leaders Plan to Invest in the Circular Economy*. https://www.gartner.com/en/newsroom/press-releases/2020-02-26-gartner-survey-shows-70--of-supply-chain-leaders-plan

Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking Qualitative Rigor in Inductive Research. *Organizational Research Methods*, *16*(1), 15–31. https://doi.org/10.1177/1094428112452151

Halse, L. L., & Jæger, B. (2019). Operationalizing Industry 4.0: Understanding Barriers of Industry 4.0 and Circular Economy. In F. Ameri, K. Stecke, G. von Cieminski, & D. Kiritsis (Eds.), *IFIP Advances in Information and Communication Technology* (pp. 135–142). Springer. https://doi.org/10.1007/978-3-030-29996-5_16 (Original work published 2019)

Hart, S. L. (1995). A Natural-Resource-Based View of the Firm. *The Academy of Management Review*, *20*(4), 986–1014. https://doi.org/10.2307/258963

Hart, S. L., & Dowell, G. (2011). A Natural-Resource-Based A Natural-Resource-Based View of the Firm: Fifteen Years After. *Journal of Management*, *37*(5), 1464–1479. https://doi.org/10.1177/0149206310390219

Hatzivasilis, G., Soultatos, O., Ioannidis, S., Verikoukis, C., Demetriou, G., & Tsatsoulis, C. (2019). Review of Security and Privacy for the Internet of Medical Things (IoMT). In *15th Annual International Conference on Distributed Computing in Sensor Systems: Dcoss 2019 : Proceedings : 29-31 May 2019, Santorini Island, Greece* (pp. 457–464). IEEE. https://doi.org/10.1109/DCOSS.2019.00091

Hettiarachchi, B. D., Sudusinghe, J. I., Seuring, S., & Brandenburg, M. (2022). Challenges and Opportunities for Implementing Additive Manufacturing Supply Chains in Circular Economy. *IFAC-PapersOnLine*, *55*(10), 1153–1158. https://doi.org/10.1016/j.ifacol.2022.09.545

Hopkinson, P., Zils, M., Hawkins, P., & Roper, S. (2018). Managing a complex global circular economy business model: Opportunities and challenges. *California Management Review*, *60*(3), 71–94.

Kristoffersen, E., Blomsma, F., Mikalef, P., & Li, J. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of Business Research*, *120*(1), 241–261. https://doi.org/10.1016/j.jbusres.2020.07.044

Kumar, N. M., & Chopra, S. S. (2022). Leveraging Blockchain and Smart Contract Technologies to Overcome Circular Economy Implementation Challenges. *Sustainability*, *14*(15), 1–18. https://doi.org/10.3390/su14159492

Kvale, S. (2009). *Interviews: Learning the craft of qualitative research interviewing*. SAGE Publications.

Leal, G. G., Castro Vila, R. de, Dorado, A. B., & Jäger, A. (2025). Circular Economy Adoption in Manufacturing Firms: Evidence From Germany. *Business Strategy and the Environment*, *34*(2), 1574–1589.

Liu, Q., Trevisan, A. H., Yang, M., & Mascarenhas, J [Janaina] (2022). A framework of digital technologies for the circular economy: Digital functions and mechanisms. *Business Strategy and the Environment*, *31*(5), 1–22. https://doi.org/10.1002/bse.3015

Lobo, A., Trevisan, A. H., Liu, Q., Yang, M., & Mascarenhas, J [Janaina]. (2022). Barriers to Transitioning Towards Smart Circular Economy: A Systematic Literature Review. In S. G. Scholz (Ed.), *Smart Innovation, Systems and Technologies Ser: v.262. Sustainable Design and Manufacturing: Proceedings of the 8th International Conference on Sustainable Design and Manufacturing (KES-SDM 2021)* (pp. 1–12). Springer Singapore Pte. Limited. https://doi.org/10.1007/978-981-16-6128-0_24

Mäkitie, T., Hanson, J., Damman, S., & Wardeberg, M. (2023). Digital innovation's contribution to sustainability transitions. *Technology in Society*, *73*, 102255.

Mishra, R., Singh, R. K., & Rana, N. P. (2024). Digital orientation, digital eco-innovation and circular economy in the context of sustainable development goals. *Business Strategy and the Environment*, *33*(4), 2752–2770.

Neri, A., Cagno, E., Susur, E., Urueña, A., Nuur, C., Kumar, V., Franchi, S., & Sorrentino, C. (2024). The relationship between digital technologies and the circular economy: A systematic literature review and a research agenda. *R&D Management*, *55*(3), 617–713.

Neri, A., Negri, M., Cagno, E., Kumar, V., & Garza-Reyes, J. A. (2023). What digital-enabled dynamic capabilities support the circular economy? A multiple case study approach. *Business Strategy and the Environment*, *32*(7), 5083–5101.

Okorie, O., & Russell, J. D. (2022). Exploring the Risks of Blockchain and Circular Economy Initiatives in Food Supply Chains: A Hybrid Model Practice Framework. In S. G. Scholz (Ed.), *Smart Innovation, Systems and Technologies Ser: v.262. Sustainable Design and Manufacturing: Proceedings of the 8th International Conference on Sustainable Design and Manufacturing (KES-SDM 2021)* (Vol. 262, pp. 290–303). Springer Singapore Pte. Limited. https://doi.org/10.1007/978-981-16-6128-0_28

Ozkan-Ozen, Y. D., Kazancoglu, Y., & Mangla, S. K. (2020). Synchronized barriers for circular supply chains in industry 3.5/industry 4.0 transition for sustainable resource management. *Resources, Conservation and Recycling*, *161*, 104986.

Palinkas, L. A., Horwitz, S. M., Green, C. A., Wisdom, J. P., Duan, N., & Hoagwood, K. (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and Policy in Mental Health and Mental Health Services Research*, *42*, 533–544.

Papert, M., Hamper, A., Zimmermann-Hoßbach, N., Schuster, T., Bühler, L., & Pflaum, A. (2024). Towards the data-driven circular and embedded supply chain: Considerations from an ICT perspective. *Hawaiian International Conference on Systems Sciences*.

Pigosso, D. C., & McAloone, T. C. (2021). Making the transition to a Circular Economy within manufacturing companies: the development and implementation of a self-assessment readiness tool. *Sustainable Production and Consumption*, *28*, 346–358. https://doi.org/10.1016/j.spc.2021.05.011

Rehman, S. U., Giordino, D., Zhang, Q., & Alam, G. M. (2023). Twin transitions & industry 4.0: Unpacking the relationship between digital and green factors to determine green competitive advantage. *Technology in Society*, *73*, 102227.

Rejeb, A., Appolloni, A., Rejeb, K., Treiblmaier, H., Iranmanesh, M., & Keogh, J. G. (2023). The role of blockchain technology in the transition toward the circular economy: Findings from a systematic literature review. *Resources, Conservation & Recycling Advances*, *17*, 1–14. https://doi.org/10.1016/j.rcradv.2022.200126

Rosa, P., Sassanelli, C., & Terzi, S. (2019). Towards Circular Business Models: A systematic literature review on classification frameworks and archetypes. *Journal of Cleaner Production*, *236*, 117696.

Samadhiya, A., Agrawal, R., Kumar, A., & Garza-Reyes, J. A. (2023). Blockchain technology and circular economy in the environment of total productive maintenance: a natural resource-based view perspective. *Journal of Manufacturing Technology Management*, *34*(2), 293–314.

Schallmo, D., Kolb, J., Schuster, T., Athanassopoulou, N., & Sepetis, A. (2025). Twin Transformation: Understanding The Nature And Combination Of Digital And Sustainability Transformation. *International Journal of Innovation Management*, *29*(05/06), 1–10. https://doi.org/10.1142/S1363919625010017

Scheel, C., Aguiñaga, E., & Bello, B. (2020). Decoupling economic development from the consumption of finite resources using circular economy. A model for developing countries. *Sustainability*, *12*(4), 1291.

Schöggl, J.-P., Stumpf, L., & Baumgartner, R. (2024). The role of interorganizational collaboration and digital technologies in the implementation of circular economy practices—Empirical evidence from manufacturing firms. *Business Strategy and the Environment*, *33*(3), 2225–2249.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research techniques*. SAGE Publications.

Stucki, T., Woerter, M., & Loumeau, N. (2023). Clearing the fog: How circular economy transition can be measured at the company level. *Journal of Environmental Management*, *326*(B), 1–17. https://doi.org/10.1016/j.jenvman.2022.116749

Takacs, F., Brunner, D., & Frankenberger, K. (2022). Barriers to a circular economy in small- and medium-sized enterprises and their integration in a sustainable strategic management framework. *Journal of Cleaner Production*, *362*, 1–16. https://doi.org/10.1016/j.jclepro.2022.132227

Thirumal, S., Udawatta, N., Karunasena, G., & Al-Ameri, R. (2024). Barriers to adopting digital technologies to implement circular economy practices in the construction industry: a systematic literature review. *Sustainability*, *16*(8), 1–24.

Trevisan, A. H., Castro, C. G., Gomes, L., & Mascarenhas, J [J.] (2022). Unlocking the circular ecosystem concept: Evolution, current research, and future directions. *Sustainable Production and Consumption*, *29*, 286–298. https://doi.org/10.1016/j.spc.2021.10.020

Trevisan, A. H., Lobo, A., Guzzo, D., Gomes, Leonardo Augusto de Vasconcelos, & Mascarenhas, J [Janaina] (2023). Barriers to employing digital technologies for a circular economy: A multi-level perspective. *Journal of Environmental Management*, *332*, 1–13. https://doi.org/10.1016/j.jenvman.2023.117437

Trevisan, A. H., Zacharias, I. S., Liu, Q., Yang, M., & Mascarenhas, J [Janaina] (2021). Circular Economy and Digital Technologies: A Review of the Current Research Streams. *Proceedings of the Design Society*, *1*, 621–630. https://doi.org/10.1017/pds.2021.62

Uhrenholt, J. N., Kristensen, J. H., Adamsen, S., Jensen, S. F., Colli, M., & Waehrens, B. V. (2022). Twin transition: synergies between circular economy and internet of things-a study of Danish manufacturers. *Journal of Circular Economy*, *1*(1), 1–19.

Väisänen, J.-M., Ranta, V., & Aarikka-Stenroos, L. (2019). Enabling Circular Economy with Software: A Multi-level Approach to Benefits, Requirements and Barriers. In S. Hyrynsalmi, M. Suoranta, A. Nguyen-Duc, P. Tyrväinen, & P. Abrahamsson (Eds.), *Springer eBooks Computer Science: Vol. 370. Software Business: 10th International Conference, ICSOB 2019, Jyväskylä, Finland, November 18–20, 2019, Proceedings* (1. Auflage, pp. 252–259). Springer. https://doi.org/10.1007/978-3-030-33742-1_20

Williams, M., & Moser, T. (2019). The Art of Coding and Thematic Exploration in Qualitative Research. *International Management Review*, *15*(1), 45–55.

Appendix A: Overview of 61 Interview Partners with Characteristics

Nr.	Position	Industry	Company Size
1	Senior Project Manager for CE & Sustainability	Manufacture of motor vehicles and parts	> 100.000
2	Engagement Manager	Manufacture of computer, electronic & optical products	> 100.000
3	Coordinator Product Sustainability	Mechanical engineering	5.000–49.999
4	Sustainability Manager	Mechanical engineering	5.000–49.999
5	Sales Development Manager	Mechanical engineering	250–4.999
6	Product & Innovation Manager	Mechanical engineering	< 250
7	Head of Safety & Environmental Protection	Manufacture of other goods	5.000–49.999
8	Project Management CE	Manufacture of motor vehicles and parts	> 100.000
9	Sustainability Strategy & Projects	Manufacture of motor vehicles and parts	50.000–100.000
10	Innovation Manager, R&D	Manufacture of motor vehicles and parts	50.000–100.000
11	Senior Customer Success Manager	Mechanical engineering	5.000–49.999
12	Managing Director	Mechanical engineering	5.000–49.1000
13	Corporate Sales Manager	Mechanical engineering	5.000–49.999
14	Sustainability Specialist	Mechanical engineering	5.000–49.999
15	Head of Innovation Lab	Mechanical engineering	250–4.999
16	Project Lead Sustainability	Mechanical engineering	5.000–49.999
17	Head of Retrofit	Repair/Installation of machinery and equipment	250–4.999
18	Chief Technology Officer	Mechanical engineering	250–4.999
19	Strategic Marketing Manager	Mechanical engineering	250–4.999
20	Director of Corporate Development	Mechanical engineering	250–4.999
21	Vice President Product Management	Mechanical engineering	250–4.999
22	Head of Sustainability	Manufacture of rubber and plastic products	5.000–49.999
23	Scientific Advisor	Scientific research and development	5.000–49.999
24	Scientific Advisor	Scientific research and development	5.000–49.999
25	Scientific Advisor	Scientific research and development	5.000–49.999
26	Project Officer	Manufacturing	< 250
27	Manager for Research Collaborations	Manufacture of electrical equipment	5.000–49.999
28	Head of Service Support & Spare Parts	Manufacture of electrical equipment	250–4.999
29	Project Manager Waste & Circular Economy	Manufacturing	< 250
30	Head of Environmental / Safety Engineering	Manufacture of other goods	5.000–49.999
31	Chief Executive Officer	Manufacturing	< 250
32	Key Account Product Manager	Manufacture of electrical equipment	250–4.999
33	Portfolio Manager (Standardization/Committee Work)	Manufacture of electrical equipment	250–4.999
34	Sustainability Manager	Manufacture of electrical equipment	250–4.999
35	Senior Product Manager Lifecycle Service	Mechanical engineering	250–4.999
36	Head of Sales / Member of Executive Management	Repair and installation of machinery and equipment	250–4.999
37	Technical Director (Executive Management Team)	Repair and installation of machinery and equipment	250–4.999

38	Quality & Environmental Manager	Repair and installation of machinery and equipment	250–4.999
39	Global Service Manager	Repair and installation of machinery and equipment	250–4.999
40	Quality & Environmental Manager	Repair and installation of machinery and equipment	250–4.999
41	Innovation Manager, Central Development	Manufacture of electrical equipment	5.000–49.999
42	Head of Process & Project Mgt and Digitalization	Manufacture and processing of basic metals	250–4.999
43	Head of Quality Assurance & Mgt and Environment	Manufacture and processing of basic metals	250–4.999
44	Head of Device Production & Repair	Manufacture of computer, electronic & optical products	> 100.000
45	Sustainability Strategy & Projects	Manufacture of motor vehicles and parts	50.000–100.000
46	Sustainability Specialist	Manufacture of motor vehicles and parts	50.000–100.000
47	Head of Solution / Business Development	Repair and installation of machinery and equipment	< 250
48	Sustainability Lead	Manufacture of motor vehicles and parts	> 100.000
49	Head of Research & Development	Mechanical engineering	250–4.999
50	Managing Director	Manufacture of computer, electronic & optical products	< 250
51	Head of Aftersales Sustainability Consulting	Repair and installation of machinery and equipment	< 250
52	Chief Executive Officer	Manufacture of motor vehicles and parts	< 250
53	Sustainability Strategy Expert	Manufacture of motor vehicles and parts	> 100.000
54	Sustainability and Circular Economy Manager	Manufacture of motor vehicles and parts	250–4.999
55	Standardization, Open Source & IP	Manufacture of electrical equipment	> 100.000
56	Manager CE & Ecodesign	Manufacturing	250–4.999
57	Senior Product Marketing Manager	Manufacturing	< 250
58	Team Lead Sustainability	Manufacture of electrical equipment	< 250
59	Group Lead Sustainability	Manufacture of motor vehicles and parts	5.000–49.999
60	Head of Customer Service	Manufacture of motor vehicles and parts	5.000–49.999
61	Project Lead CE, Project Manager R&D	Manufacture of motor vehicles and parts	5.000–49.999

Appendix B: Overview of Interview Guideline

Question Block	Description	Example Questions	Objective
1. Job Title, Professional Experience, and Product Information	Introductory questions about the interviewee's job profile, professional experience, and related products.	What experience do you have with sustainability and the Circular Economy? What experience do you have with digitalization and Industry 4.0? Please name and briefly describe the product or product family you will refer to during the interview.	To open the interview, qualify the experts, and gather information about the products discussed.
2. Understanding of CE and CE-Strategies	Questions about the company's understanding of CE, its relevance, goals in implementing CE, and any R-strategies.	What do you understand by Circular Economy, and how relevant is the topic within your company? Which Circular Economy strategies (R-Strategies) are you already implementing or planning to implement?	To understand the company's approach to CE, the goals of the transformation, and the role of circular business ecosystems.
3. Digital Technologies for Implementing CE-Strategies	Questions on the digital technologies used in the company or in collaboration with ecosystem partners to implement CE, and planned activities.	Which digital technologies are you using to collect, integrate, analyze, and apply data in order to enable a Circular Economy? Which digital technologies and data do your external ecosystem partners already need or use to implement a Circular Economy?	To explore digital technologies enabling a CE and their practical application in the company.
4. Barriers to Implementing SCE	Questions about existing barriers in the company regarding the implementation and use of digital technologies for realizing a CE.	What barriers does your company encounter when implementing and using digital technologies to realize circular solutions or develop circular practices? Follow-up questions: Could you please elaborate on the specific technical / organizational / … / product-related challenges your company faces when implementing a smart Circular Economy?	To identify barriers hindering the implementation of SCE practices in the company.