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Circularity and Digitalisation in German Textile Manufacturing: Towards a Blueprint for Strategy Development and Implementation

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Abstract: Textile and clothing (T&C) production and consumption have been steadily increasing for many years, accompanied by significant resource consumption, waste generation, and environmental impact. Germany holds a pivotal position in the industry, both within the EU and globally, as a leading producer, importer, and exporter of T&C. The circular economy (CE) concept has emerged as a promising solution to address the industry's negative impacts by emphasising the reduction, reuse, and recycling of resources across the value chain. Digital technologies (DTs) are increasingly recognised as key enablers and facilitators of this transition, promoting both efficiency and circularity in manufacturing processes. However, the extent to which these are implemented in the German T&C industry remains largely underexplored. This study seeks to investigate the role of DTs in advancing CE practices within German T&C manufacturing. Employing process mapping and technology profiling, this research adopts an inductive, qualitative approach based on primary interview data to explore three key areas: (1) current CE practices, (2) the deployment of supportive DTs, and (3) the challenges in implementing the CE and DTs. The findings reveal that CE adoption is set to accelerate among T&C manufacturers, driven by regulatory compliance and market pressures, with DTs playing a critical role in enabling this transition. This study proposes a new operational framework designed to facilitate the shift towards a more circular textile sector, aligning with the ambitious goals of the European Union and broader environmental and societal objectives.

Keywords: circular economy; CE; digital technologies; digitalisation; textile and clothing industry; manufacturing industry; strategic blueprint; value chain; 9-Rs

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1. Introduction

In recent decades, there has been a noticeable surge in textile and clothing (T&C) production and consumption, leading to environmental harm and resource depletion as goods are often discarded after a short use period, with minimal recycling [1]. This trend has positioned the T&C industry as the world's fourth-largest consumer of primary raw materials and water, and the fifth-largest emitter of greenhouse gases [2]. In response, the circular economy (CE) has emerged as a potential way forward that could address these challenges [3]. The CE aims to reduce, reuse, recycle, and recover resources and energy throughout the value chain to minimise waste and pollution [4].

While the CE concept is not new, it has gained momentum in recent years, featuring prominently in sustainability agendas at both governmental and supranational levels, such as in the United Nations Sustainable Development Goals [5] and as an element of the European Union's Green Deal [6]. The European Commission [3] recognised digital technology (DT) as a crucial facilitator for the comprehensive transition from a linear to a more circular economy.

There has also been growing interest in the integration of digitalisation and the CE in recent years [7], with findings increasingly highlighting the significant potential of DTs for companies to reduce resource and energy consumption, as well as waste generation and emissions, while improving efficiency and productivity [8–11].

The T&C industry is a key focus area within the European Union's Circular Economy Action Plan [12]. New regulatory measures include mandatory eco-design specifications, supply chain transparency, the implementation of a digital product passport (DPP), and the reduction in carbon and environmental footprints [13]. European companies are thus facing increasing pressure to reassess business models, products, and processes to align with circularity and sustainability principles, while also addressing competitive advantage and stakeholder interests [14–16].

However, the introduction of sustainable and circular processes, as well as the role of DTs in advancing circularity within the industry, remains largely underexplored in the scientific literature [17–19]. A recent comprehensive literature review by Neri et al. [7] revealed that research on the relationship between the CE and DTs in the manufacturing sector is highly fragmented, highlighting the "need for clearer guidance for industrial practitioners on properly using digital technologies to support the implementation of the circular economy" (page 1). Additionally, contextual factors such as sector-specific characteristics appear to play a significant role, but have scarcely been addressed. Notably, only 2 out of 170 analysed studies explicitly focus on the textile industry.

To address this gap, this article examines the relationship between the adoption of DTs and the transition to the CE within the German T&C manufacturing industry. Specifically, the research questions (RQs) addressed in this paper are as follows:

RQ1. How is the CE currently implemented in German T&C manufacturing companies?

RQ2. How are DTs being used to support and advance CE practices in German T&C manufacturing companies?

RQ3. What are the challenges and critical issues for current and future CE transition and digitalisation in the German T&C manufacturing sector?

The remainder of this paper is organised as follows: In Section 2, the relevant literature is reviewed and a provisional conceptual framework for the primary research is set out. Section 3 then describes the research design and methods applied in this study. Section 4 presents the results of the empirical research, and Section 5 discusses these results and emergent themes. Finally, Section 6 summarises the contribution of this research, discusses its limitations, and further points out some future research directions.

2. Literature Review

2.1. The German T&C Industry

Although the terms textiles and clothing are often used interchangeably, they are delineated and defined here for the purposes of this study. According to the classification of economic activities by the European Union (NACE) [20], the production and processing of textile fibres, yarns, and fabrics, as well as the manufacturing of industrial, technical, and home textiles, are categorised under the textile industry (NACE code 13). The clothing industry, on the other hand, encompasses the manufacturing of apparel such as outerwear, underwear, and workwear (NACE code 14).

The T&C value chain involves numerous actors and complex processes, making it one of the most globalised value chains today [21]. From an end-to-end perspective, eight main processes can be identified [1,22,23] (Figure 1). First, in fibre production, raw materials (whether natural or synthetic) are processed into fibres. This is followed by yarn production, where fibres are spun into yarns and prepared for further processing. The next process is fabric production, where yarns are transformed into woven, knitted, or nonwoven fabrics. The wet processing stage involves treatments such as washing, dyeing, or finishing textile products and materials. Subsequently, these materials are further processed into market-ready end products, representing the final step in manufacturing. The downstream processes, including distribution and retail, use, and end-of-life (EoL) treatment, are covered for completeness here but are not considered part of the core manufacturing processes. Throughout these processes, human and natural resources, as well as energy, are consumed and, as a result, waste is generated and emissions are released into the environment, among other impacts. It is thus evident that a remodelling of the T&C manufacturing processes can potentially make a significant contribution to addressing global environmental and waste challenges.

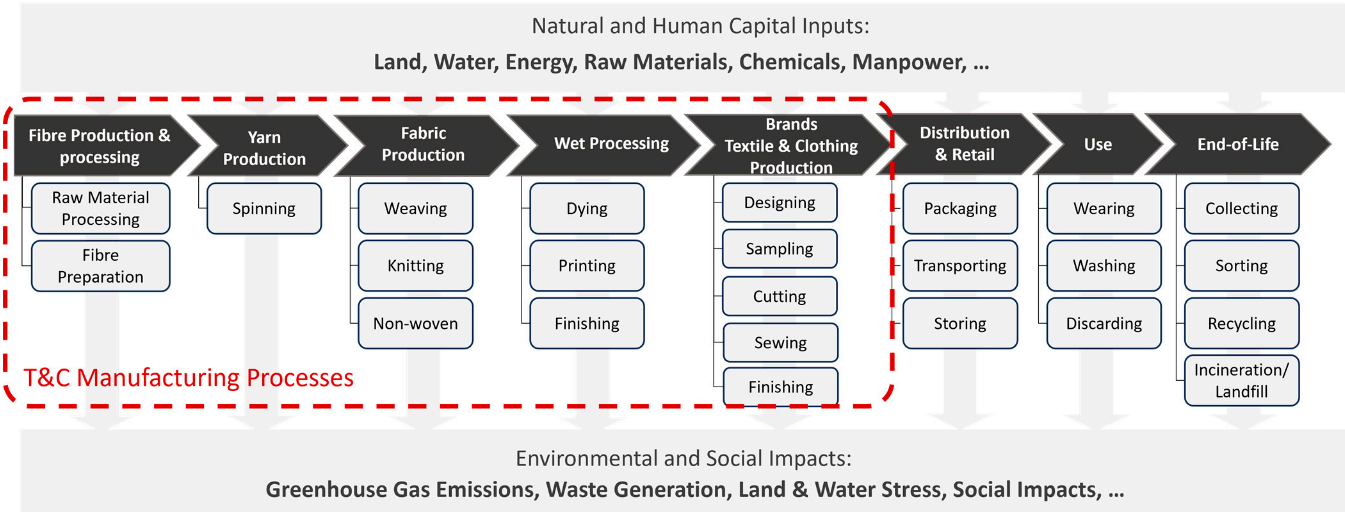

Figure 1. T&C value chain process clusters. Source: Adapted from [1,22,23].

Germany holds a central position both within the EU as the second-largest producer of textile products and the largest importer of clothing, as well as globally being the second-largest importer of clothing and the fifth-largest importer of textiles [24,25]. Moreover, Germany also plays a pivotal role on the global stage as a major exporter of textiles and clothing [25,26]. The emerging social, environmental, and waste problems resulting from these geographically fragmented flows underline the need for a holistic transformation of the T&C industry, shifting from the linear "take–make–dispose" model towards closed-loop textile systems. Gözet and Wilts [1] see Germany as a key player and "change-maker" in this effort.

The T&C industry in Germany had 879 companies in 2023, employing approximately 83,000 people. Of these companies, 689 (78%) are in the textile sector (NACE-13: manufacture of textiles) and 190 (22%) in the clothing sector (NACE-14: manufacture of clothing). The German T&C industry today has regional clusters in North Rhine-Westphalia (224 companies), Bavaria (190 companies), Baden-Württemberg (158 companies), and Saxony (120 companies), of which 94 percent are small and medium-sized enterprises (SMEs) with fewer than 250 employees [27].

2.2. The Circular Economy in T&C Manufacturing

The concept of the CE has evolved over recent decades. Originally focused on waste management, it has evolved and expanded into a systemic approach centred on resource preservation [28]. The CE envisions an industrial system that is restorative and regenerative, aiming to minimise waste and pollution while maximising resource efficiency [29,30]. This vision requires a paradigm shift toward reducing, reusing, recycling, and recovering materials, supported by technological innovation and collaboration among stakeholders along value chains [4]. Two main perspectives for CE implementation can be discerned in the literature, as illustrated in the left and right side of Figure 2. Firstly, from a resource-based perspective, three key strategies can be identified: narrowing, slowing, and closing resource loops [31,32]. According to Bocken et al. [31], "Narrowing" concerns reducing resource consumption related to the product, production, and use process and minimising the environmental impact—also referred to in other sources as resource efficiency [33,34] or eco-efficiency [35]. "Slowing" aims at extending the use and reuse of products and components, which can be achieved by developing durable products and maintaining the value of resources by extending the lifespan of materials, products, and machinery. "Closing" strategies focus on closing resource loops through material recycling and energy recovery. All these strategies emphasise the efficient use and value retention of resources, materials, and products.

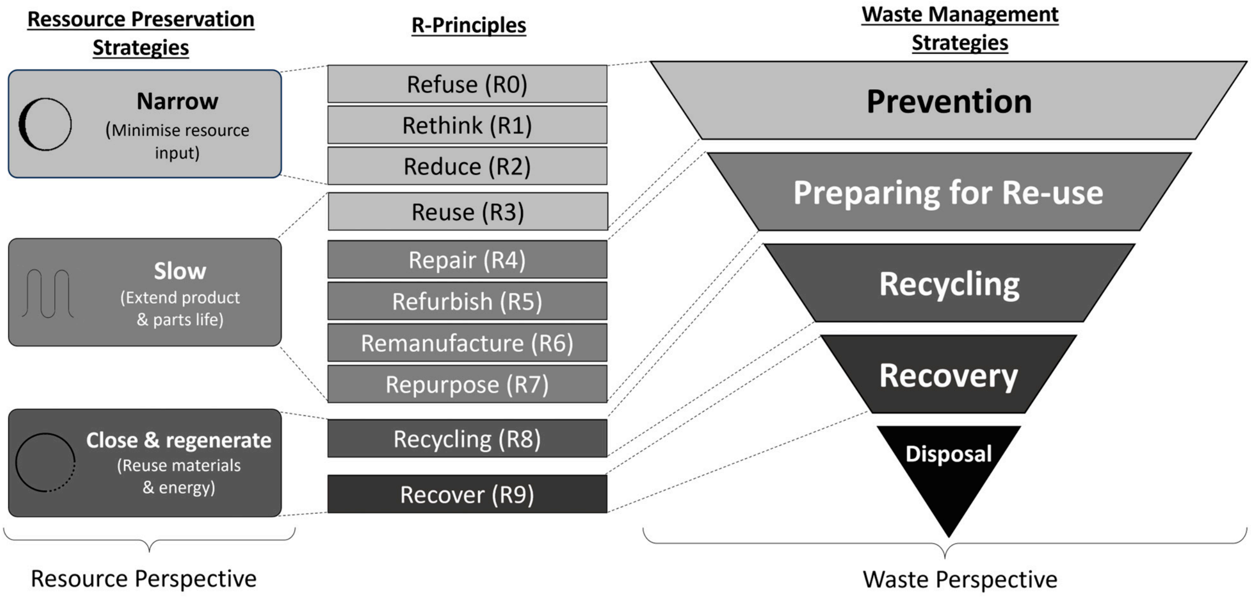

Figure 2. The R-principles and their relationship with resource preservation and waste management strategies. Source: Based on [4,31,32,36].

Secondly, from a waste-based perspective, five waste management strategies are identified that prioritise the prevention and proper treatment of waste [36]. The integration of these perspectives into actionable practices, often referred to as the R-principles, builds the core to guide implementation of the CE concept (centre of Figure 2) [4,28,37,38]. Strategies R0 to R2 primarily focus on the absolute reduction in resource consumption and the avoidance of negative environmental and social impacts through products and processes, making these principles essential for achieving the goals of the CE. Strategies R3 to R7 primarily aim to extend the lifespan of existing products and components. Strategies R8 and R9, known as traditional waste management, involve material recycling and energy recovery from waste, which are seen as the least desirable [28,37]. Furthermore, the use of renewable energy and emissions avoidance are central practices of the CE [29].

Recent research studies have increasingly focused on the practical implementation of CE strategies and practices across various sectors. However, for the T&C industry, existing studies remain fragmented. Franco's study [16] was one of the first to address the T&C industry, adopting a product-based perspective. The author highlights the unique complexity of textile products and value chains as key challenges to implementing circular design strategies, underscoring the need for further industry-specific studies to facilitate a smoother transition for companies in the sector. Country-specific studies from Italy [39] and Sweden [40] emphasise that a combination of diverse strategies and practices among all value chain actors, coupled with strong cooperation and collaboration, are critical for a successful CE transformation. In this context, digital technologies are recognised as enablers of circularity, and yet their role remains largely unexplored. Despite these contributions, there is a notable lack of country-specific studies addressing the CE transformation of European T&C companies. Wiegand and Wynn's analysis [17] provided some insights into the status of CE implementation, but gave an incomplete picture of the industry. Indeed, the authors highlight the need for further research based on industry case studies to investigate strategies and best practices to facilitate the transition to the CE. This study aimed to address that gap by examining the practices implemented in the German T&C manufacturing sector to narrow, slow, and close resource flows, contributing to the development of a more sustainable and circular industry.

2.3. Digital Technology Deployment in T&C Manufacturing

As previously noted, DTs are recognised as facilitators and enablers in CE transformation. A recent review [7] of the relationship between DTs and CE highlights the fragmented nature of the current research landscape. Existing studies tend to focus either on specific technologies or particular CE practices. Furthermore, industry-specific differences have been identified, with very few studies concentrating on the T&C industry. Therefore, Table 1 provides an overview of the current and potential applications of key digital technologies to advance circularity within the T&C industry. The technologies discussed are commonly categorised under the acronyms SMAC (social media, mobile, analytics, cloud) and BRAID (blockchain, robotics, artificial intelligence, Internet of Things, digital fabrication). As shown in the literature sources (Table 1, column 3), all nine SMAC/BRAID technologies are considered relevant for driving circularity in the T&C industry.

Table 1. DTs and their potential role in the CE in T&C manufacturing.

DT	Role of Advancing Circularity in T&C Manufacturing	References
Social media	• provides companies in the T&C industry with new avenues to reach consumers, communicate, inform, and educate them about products, services, innovations, and developments, and influence consumer behaviour.	[41,42]
Mobile computing	• offers diverse organisational opportunities, such as reducing employee travel activities or replacing paper-based processes with digital ones, making them more efficient. • particularly in the T&C industry, mobile applications provide the opportunity to extend product life cycles, for instance, through reselling platforms or to support new business models like rental, leasing, or repairing.	[43,44]
Analytics/Big data	• applications to analyse large and complex datasets, revealing patterns and relationships, fostering informed and data-driven decision-making, and monitoring and controlling CE and sustainability KPIs. • in the T&C value chain, the systematic analysis of data, such as inventory levels, customer activities, product returns, and consumer feedback—but also information regarding resource efficiency, waste generation, or emerging trends and competitor knowledge—enables integration and dissemination into management systems as well as supporting strategic and operational decision-making.	[45,46]
Cloud and edge computing	• provides the basis for networking systems and thereby ensures greater data and information availability and transparency, which enable data-driven decision-making and new business model development. • can contribute to reduced energy consumption and the reduction in physical goods in various locations.	[47,48]
Blockchain technology (BC)	• a distributed ledger database provides tamper-proof recording of transactional data and other information, thus enabling reliable, decentralised data exchange among partners and value chains. • in the complex and highly distributed textile value chain, BC offers various functions such as traceability of product and material data, recording and secure exchange of data between parties, and, within Smart Contract applications, efficient support for procurement management. • forms an essential basis for the development of a digital product passport for textiles.	[18,49–52]
Robotics	• are able to operate autonomously, to interact with each other and to cooperate with humans, e.g., in production or logistics processes. • in the T&C industry, it appears feasible to use robots to support circular strategies by, for instance, leveraging AI systems to undertake sorting or disassembly processes, making these processes economically viable and desirable for companies and contributing to increasing recycling rates.	[48,53,54]

Table 1. *Cont.*

DT	Role of Advancing Circularity in T&C Manufacturing	References
Artificial intelligence (AI)	• is based on the development of machines and systems that are designed to mimic human intelligence by applying machine learning techniques and processing unstructured data such as natural language or images. • some algorithms are used in the context of CE strategies that can help with prediction, decision-making, resource optimisation, and pattern recognition. • in the T&C context, AI could be used to predict trends and customer needs, for dynamic pricing, or in the context of virtual fitting rooms, while other techniques based on image recognition can be used in quality control or for automated textile waste detection and sorting.	[55–59]
Internet of Things (IoT)	• enables physical objects to communicate with each other by using sensors and connecting them with digital applications and systems. • allows for real-time monitoring, tracking, and analysis of product use, condition, or location throughout the life cycle, optimising process and resource efficiency and supporting new service-oriented business models. • in the T&C industry, few concrete real-world use cases aimed at supporting CE strategies could been identified.	[60–63]
Digital fabrication (DF)	• refers to processes where computer-controlled modelling and control tools are used to manufacture physical objects directly from design data. • these processes are often supported by digital, computer-aided design (CAD) tools, which can be directly transferred to manufacturing machines and systems such as milling and cutting machines, automatic assembly systems, or 3D printers (i.e., additive manufacturing). • additive manufacturing seems to be of particular importance for CE strategies, as it can reduce transportation, inventory, and material usage by producing prototypes, spare parts, or products on-demand and at the point of need, as well as implementing circular design strategies through the use of recycled materials in 3D printing. • the implementation of 3D printing processes for textile products is technologically demanding and remains in its early stages, but initial use cases show that utilising 3D-based modelling and manufacturing can enhance communication and collaboration among stakeholders, thereby reducing physical prototypes, incorrect patterns, and overproduction and thus decreasing resource consumption and waste generation. • digital twins—virtual representations of products or facilities—are also included under digital fabrication and allow for the simulation and optimisation of product properties or functions before physical production, as well as providing stakeholders with information on ingredients, manufacturing, disassembly, or repair requirements throughout the product life cycle.	[41,62,64–69]

However, despite the documented potential of DTs to support the CE transition—through, for example, secure database storage, data analytics, AI applications, and digital fabrication—the research lacks specific insights into the practical implementation, challenges, and critical issues faced by German T&C manufacturing companies in effectively adopting and executing these technologies. There is a dearth of detailed information and guidance on how DTs best support each stage of the value chain, and how structural and operational barriers within German T&C production can be overcome. This gap in the literature highlights the need for focused, industry-specific case studies that identify and examine the effective application of specific technologies and associated best practices to confront the challenges in successfully achieving circularity in the sector. This study contributes to closing that gap by seeking to connect the two concepts—the CE and digital technology deployment—and by deriving an operational framework and actionable strategies to support the industry's transition.

2.4. Provisional Conceptual Framework

The provisional conceptual framework (PCF) for this study (Figure 3) comprises three main dimensions identified in the literature review—the five manufacturing processes within the T&C value chain (the 'y'-axis in Figure 3), the nine DTs (SMAC/BRAID) (the 'x'-axis in Figure 3), and the three CE strategies of narrowing, slowing, and closing resource flows (the 'z'-axis in Figure 3). The nine DTs are seen as catalysts and drivers for the introduction and implementation of circular practices within companies and in cross-company processes along the value chain. The PCF was subsequently used as the initial framework for analysing the primary interview data.

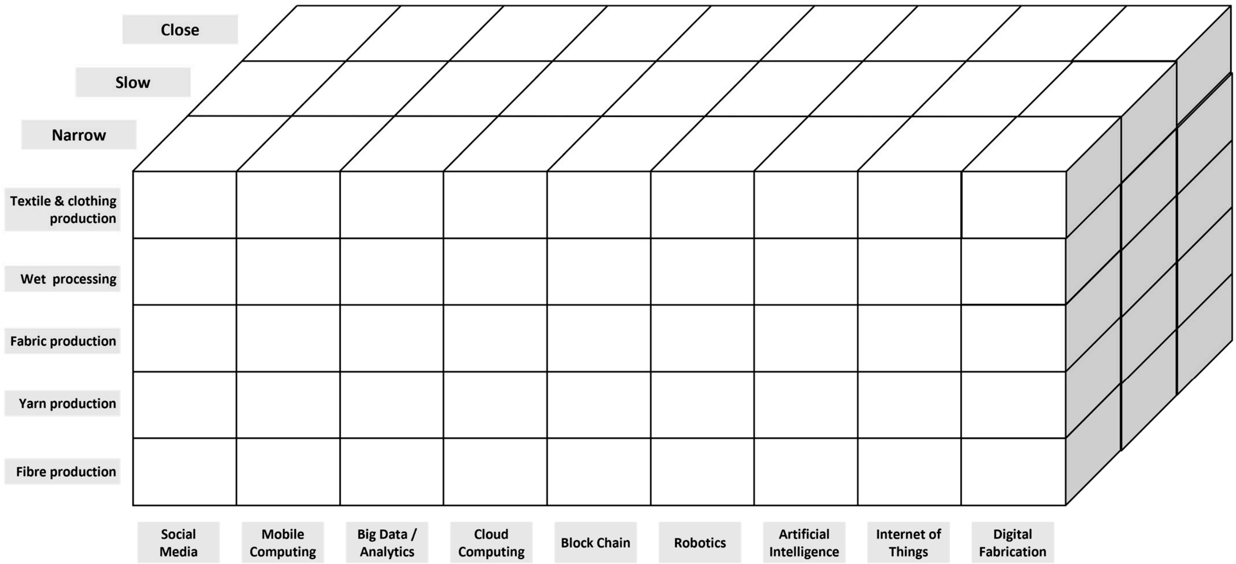

Figure 3. Provisional conceptual framework.

3. Research Method

The research method comprised three distinct phases (Figure 4). Phase one entailed a scoping review of the relevant literature, from which the PCF, outlined above, was developed. A scoping literature review can provide a summary of relevant concepts and pertinent literature, as shown, for example, in Figure 2 and Table 1. Various academic databases, including Web of Science, Google Scholar, and Scopus, were searched to provide a "broad scan of contextual literature" through which "topical relationships, research trends, and complementary capabilities can be discovered" [70] (p. 351). This provided the basis for the development of the PCF, which Miles et al. [71] suggest should identify the key elements to be investigated, as well as any potential relationships between them. It typically serves as the basis for further refinement into a more nuanced framework as the research progresses. In this instance, the PCF involved the mapping of industrial processes, CE strategies, and an initial assessment of which technologies could support the transition towards the CE. This involved mapping the complex manufacturing steps along the textile value chain in a process model and grouping them into process clusters. Relevant DTs enabling and promoting the transition towards the CE were identified. The conceptual framework provided a basis for the subsequent phases of the research. Phase two involved evaluating current circular activities and the use of DTs to promote the CE in German T&C manufacturing companies, through qualitative interviews with industry representatives from the respective T&C process clusters. There are only a few studies on the relationship between CE and DTs to date, but these indicate that DT deployment to support CE practices in manufacturing companies is still rather low, especially in the T&C industry [7,63]. Schöggl et al. [63] (p. 413) point out that "it is important to develop business cases to show/flagship what DTs can be used for and how they can enable better sustainability and circularity management". This study addresses this challenge in phase three of the research by developing a blueprint for strategy development and implementation for the use of DTs to progress the CE transition in the T&C industry.

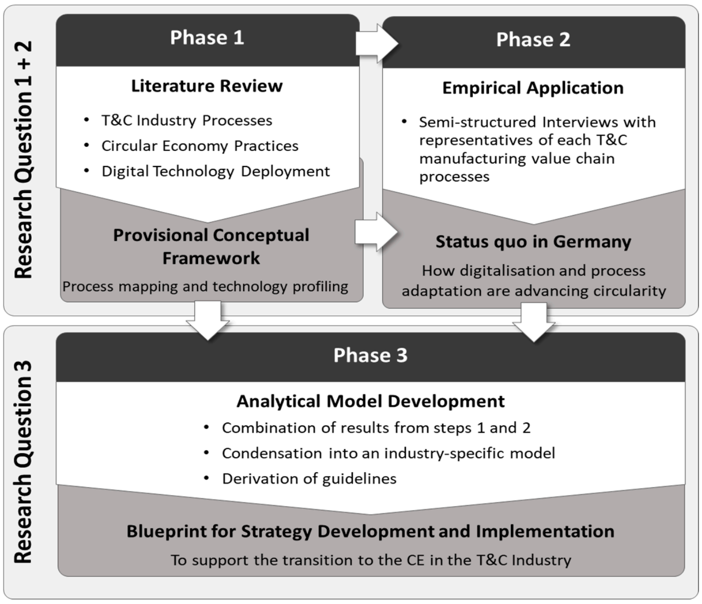

Figure 4. The 3 phases in the research process.

Given the exploratory nature of the research and the fact that knowledge about CE in the T&C industry is still in its infancy [17–19], surveying and interviewing industry experts is considered the most appropriate method for empirical investigation [71] of the current state of knowledge and implementation within the industry. Direct interaction with respondents can also reveal additional relevant areas that were not previously considered but are significant for understanding [72]. Thus, surveying and discussing with industry representatives provide insights into backgrounds, drivers, challenges, and future developments from their perspectives. Since research findings in this field of study are still scarce, an insider perspective also allows for expanding the PCF into areas that were not previously considered but are significant for understanding and developing guidelines for practical application.

To increase the reliability and validity of this study, a research protocol was used for the design of data collection, and for the analysis and formalisation of results. The selection of appropriate interviewees is critical in ensuring rigorous qualitative research [73]. A procedure for selecting company representatives was chosen to enable the researchers to collect sufficient and appropriate data to adequately address the research questions. Two main criteria were considered: firstly, at least one company should be represented from each of the process clusters; secondly, the companies should have incorporated the CE paradigm into their vision or mission statement. This is in line with Yin's [73] approach, which uses a purposive sampling method in case study research. This method is different from the sampling logic of surveys, but rather focuses on investigating specific topics in detail to develop new knowledge. Based on the authors' network, built from previous industry and research projects, a list of potential companies was compiled, and they were contacted and invited to participate in this study. Ten companies, evenly distributed across the process clusters, confirmed their willingness to participate. To ensure confidentiality, the identities of the companies and interviewees are anonymised. Figure 5 shows the allocation of the companies to the process clusters, and in Table 2, a brief description of companies and interviewees is given.

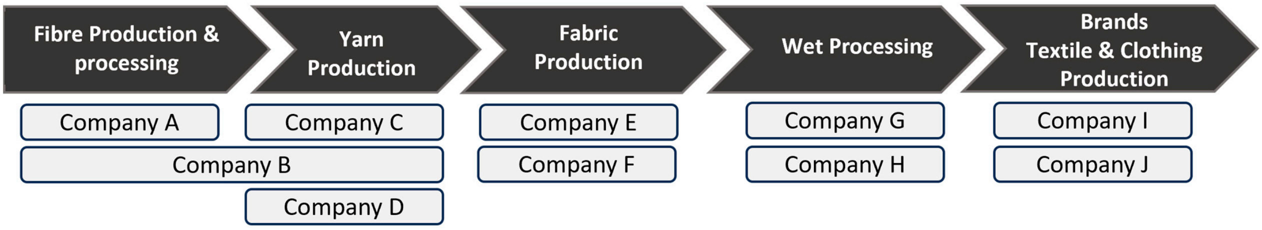

Figure 5. Companies in the T&C value chain process clusters.

Table 2. List of companies and interviewees involved in primary data collection.

Code	Description	Size	Interviewee
A	Manufacturer of manmade fibres for various applications	Large	Project Lead New Business Development
B	Processor of natural fibres and manufacturing of yarns	Medium	Certification and Sustainability Manager
C	Manufacturer of yarns (including dying) from natural fibres	Medium	Management Representative
D	Manufacturer of yarns (including dying) from natural and synthetic fibres	Large	Head of Quality Assurance
E	Manufacturer of nonwovens for various applications	Large	Sustainability Manager
F	Manufacturer of woven fabrics for home textiles	Medium	Head of Sustainability & Marketing
G	Manufacturer of printed fabrics for clothing textiles	Small	CEO
H	Manufacturer of dyed yarns for various applications	Medium	Head of Research and Development
I	Sports and outdoor clothing brand	Medium	Director of Quality and Corporate Responsibility
J	Sports and outdoor clothing brand	Large	Senior Innovation Manager Materials and Manufacturing

An interview guide was created, listing the topics and questions to be addressed [74], and semi-structured interviews were conducted with ten interviewees (one from each company). Outline questions, derived from the PCF, concerned sustainability and CE strategies and activities, and DTs deployed, as well as drivers, challenges, and future development. The interviews were conducted between June and August 2024. Each interview lasted between 50 and 70 minutes and was recorded, transcribed, and coded with the consent of the respondents. In phase three, the findings were integrated into a comprehensive framework with actionable recommendations for practical implementation. Data analysis was conducted using Braun and Clarke's [75] thematic analysis approach as a guide (Figure 6).

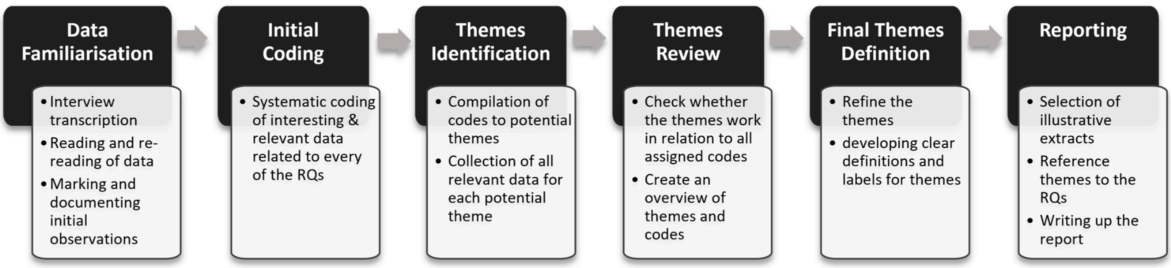

Figure 6. The six steps of thematic analysis. Source: Based on [75].

The first step involved transcribing the interviews and importing the text documents into NVivo, where they were read, and relevant findings were highlighted. In the second step, relevant text passages were coded according to the three RQs and subsequently grouped into themes. Through an iterative process, themes were reviewed, refined, and consolidated based on the assigned codes. Themes were then assigned a definition, and illustrative examples were selected. The final results are reported here in Section 4 below.

4. Results

The results section here is organised around the three RQs. First, in answer to RQ1, the twelve key themes identified in the analysis process outlined above are discussed, based on the current state of CE implementation in the companies studied (Table 2). To address RQ2, CE practices were mapped against the DTs deployed by the companies, while for RQ3, four types of challenges and three critical success factors for digital and circular transformation were identified. These results are detailed in Sections 4.1–4.3 below.

4.1. How Is the Circular Economy Currently Implemented in German T&C Manufacturing Companies? (RQ1)

4.1.1. Overview

In the thematic analysis of the interview responses, twelve CE practices were identified that address the three CE strategies of narrowing, slowing, and closing resource flows (Table 3). An overview of the themes along with corresponding examples of interviewee statements is provided in Tables A1–A3 in Appendix A.

Table 3. Practices from interview data for narrowing, slowing, and closing.

Narrowing	Slowing	Closing
• Reduce negative environmental impact • Reduce waste and scrap • Reduce resource consumption	• Durable products and materials • Extension of product lifespan • Extension of lifespan of machines and equipment • Waste utilisation	• Active recycling of products and materials • Design, development, and use of recyclable products and materials

These three strategies are not mutually exclusive but are complementary, meaning that they are all of relevance in the pursuit of a fully circular system. Table 4 shows in which companies each of the practices was evidenced. This allows for some comparisons between the three CE strategies, which are discussed in turn below.

Table 4. Applied CE strategies and practices in the companies studied.

T&C Process Clusters and Companies \ CE Strategies and Practices		Narrowing/Eco-Efficiency			Slowing				Closing	
		Reduce Negative Environmental Impact	Reduce Waste and Scrap	Reduce Resource Consumption	Waste Utilisation	Durable Products and Materials	Extend Product Lifespan	Extend Lifespan of Machines and Equipment	Recycling of Products and Materials	Recyclable Products and Materials
Fibre processing	A	x	x	x	x		x			x
	B	x	x	x		x		x	x	
Yarn production	C	x		x	x		x		x	
	D	x	x	x	x					
Fabric production	E	x	x	x	x				x	
	F	x	x	x	x	x	x		x	
Wet processing	G	x	x	x				x		x
	H	x	x	x	x	x	x	x	x	x
T&C brands/production	I	x			x	x	x		x	x
	J	x		x	x	x	x		x	
Total		10	7	9	8	5	6	3	7	4

4.1.2. Narrowing/Eco-Efficiency

Reduce Negative Environmental Impact

Companies are adopting eco-efficiency strategies to meet rising costs and comply with regulatory frameworks like the Corporate Sustainability Reporting Directive (CSRD) [76], which mandates that businesses reduce their negative environmental impacts. All interviewees highlighted measures to reduce these impacts, often following systematic approaches like life cycle assessments (LCAs) to identify key sources of waste and emissions. To reduce these, companies have adopted technologies such as wastewater treatment plants and air filtration systems, while seeking environmental certifications like ISO 14001 [77], GOTS [78], and Oeko-Tex [79].

Reduce Waste and Scrap

Waste reduction and prevention play a significant role in the companies studied, primarily driven by the costs associated with waste management and disposal. Across the value chain processes, various types of waste are generated, and yet the practices mentioned in the interviews appear consistent regardless of the specific process or company size. Waste management systems help effectively categorise waste types, enabling targeted reductions. Quality management systems further contribute by identifying defects early in production, preventing unnecessary material use. Order-based manufacturing minimises overproduction, and innovative production methods and technologies are increasingly employed to reduce process waste. Notably, brand manufacturers did not report engaging in waste reduction practices, likely due to their substantial reliance on outsourced production overseas.

Reduce Resource Consumption

Another key element of the narrowing strategy is reducing resource consumption, particularly water, energy, chemicals, and raw materials. The practices adopted vary depending on the manufacturing processes and products. While nearly all companies report on energy efficiency measures, likely driven by rising energy costs, companies in water-intensive processes place significant emphasis on reducing water consumption. Similarly, in chemical-intensive processes, companies are focusing on reducing the use of dyes and auxiliaries to reduce environmental harm and the volume of chemicals needed. Material use optimisation is particularly achieved by reusing offcuts and by-products in production, lessening the need for new raw materials.

In summary, the practices following the narrowing strategy are widespread in T&C manufacturing, driven by both environmental and economic factors. While effective in reducing resource consumption and waste generation, this approach primarily focuses on internal efficiency gains rather than fully addressing CE goals.

4.1.3. Slowing

This approach encompasses four main themes: waste utilisation, durability of products and materials, extending product lifespan, and extending the lifespan of machines and equipment. Each theme reflects distinct practices adopted by companies across various stages of the value chain. Overall, it is notable that this strategy is pursued far less frequently across the value chain compared to the narrowing strategy.

Waste Utilisation

The majority of the companies (8 of 10) actively engage in waste utilisation, which involves repurposing waste as a resource for other processes or products. Companies have developed systems for separating different types of waste and finding ways to either sell or upcycle these materials to avoid costly disposal. There are even markets for by-products, such as short fibres that cannot be used for yarn production but are valuable to other industries. Brand manufacturers, in particular, focus on upcycling leftover or waste materials into new products to be sold under their brand.

Durability of Products and Materials

Companies are designing their products to last longer, providing them with a competitive advantage, particularly against cheaper, lower-quality imports from Asia. This focus on quality and durability has become a core practice for 5 of the 10 companies. In particular, brands integrate this into their unique selling proposition. But durability and high quality is not only a selling point for finished goods; yarn and fabric manufacturers are also focusing on their material's durability.

Extend Product Lifespan

In addition to designing durable products, companies are actively working to extend the product lifespan through various services and innovations. Both the brands offer repair services, which not only maintain product value but also align with the growing consumer demand for sustainable practices. Additionally, companies in the earlier value chain stages are incorporating reusable packaging into their operations, which helps to extend the life cycle of packaging materials and reduce overall waste.

Extend Lifespan of Machines and Equipment

Lastly, the extension of the machine and equipment lifespan is an important part of the slowing strategy, where companies focus on maintaining and upgrading existing machinery rather than replacing it with new equipment. These measures are more motivated by cost considerations but also contribute to reducing waste and resource consumption.

In conclusion, the slowing strategy is a critical component of CE practices in T&C manufacturing companies. By focusing on maintaining the value of products, materials, and machinery for as long as possible, companies are not only reducing waste but also offering more sustainable and durable products. However, the measures to implement this strategy across the value chain are far less prevalent compared to efficiency strategies, which are often linked to direct cost reduction and potential efficiency improvement.

4.1.4. Closing

Two main clusters of activities emerge related to the closing strategy: process-oriented activities, which involve the recycling of materials and products, and design-oriented activities, which aim to develop materials and products that can be effectively recycled into equivalent products. While these practices are primarily driven by brand manufacturers, some earlier stages of the value chain also engage in relevant activities.

Recycling of Products and Materials

One of the key components of the closing strategy is the recycling of products and materials. Across the value chain, 70% of the companies are using recycled materials. Additionally companies are also looking at ways to recycle their own process waste. This is particularly important in earlier stages of the value chain, where these waste streams can be significant. These efforts help reduce the need for new resource inputs and minimise waste. A critical challenge in closing resource loops is ensuring that post-consumer waste is available for recycling. Companies have limited control over how consumers dispose of products, making it difficult to retrieve materials for recycling. To address this, brand manufacturers are developing take-back systems.

Recyclable Products and Materials

The second major cluster focuses on designing recyclable products and materials. To successfully close resource loops, products must be intentionally designed for ease of recycling. This process often demands collaboration across the value chain: on the one hand, with recyclers to clarify the requirements for recyclable products, and on the other, to ensure these requirements are adhered to at all stages of the value chain. However, only four of the companies studied reported implementing such practices.

In summary, the closing strategy involves both recycling existing materials and designing new products for future recyclability. While challenges remain, particularly with collecting post-consumer waste, companies are making some progress in closing resource loops by integrating recycled materials, improving recycling processes, and designing for recyclability.

4.1.5. Summary

The implementation of the three CE strategies—narrowing, slowing, and closing—reveals distinct patterns across German T&C manufacturing companies (Table 4), with company size appearing to have no significant influence on these variations. Narrowing is more widely adopted across various process clusters due to its focus on resource efficiency and waste reduction, which aligns with immediate regulatory and operational demands i.e., cost reduction. Its integration is relatively straightforward, providing immediate economic benefits with minimal adjustments to existing processes, making it attractive to many manufacturers. In contrast, slowing and closing require more extensive changes in product design, material sourcing, and business models, leading to slower adoption.

4.2. How Are DTs Being Used to Support and Advance CE Practices in German T&C Manufacturing Companies? (RQ2)

4.2.1. Overview

The findings reveal that companies have a similar perception of the role of digitalisation: overall, digital technologies are widely recognised as crucial for enhancing efficiency, productivity, and cost reduction across all stages of the value chain. However, company representatives acknowledge that the full potential of these technologies has yet to be realised. Nevertheless, the nine technologies identified in the literature review as having potential to support and promote circular strategies and practices are being utilised to varying extents, and for different purposes, in the companies interviewed.

Communication technologies, such as social media platforms, are being widely deployed. Similarly, cloud-based systems and data collection and analysis tools are commonly used across the industry. In contrast, technologies that require a higher degree of connectivity and more complex automation—such as blockchain, robotics, AI, the Internet of Things, and digital fabrication—are only being deployed sporadically and to a very limited extent (Table 5).

Table 5. Deployed and planned implementation of DTs in the studied companies.

		Social Media		Mobile Computing		Big Data/ Analytics		Cloud Computing		Blockchain		Robotics		Artificial Intelligence		Internet of Things		Digital Fabrication	
		deployed	**planned**	**deployed**	**planned**	**deployed**	**planned**	**deployed**	**planned**	**deployed**	**planned**	**deployed**	**planned**	**deployed**	**planned**	**deployed**	**planned**	**deployed**	**planned**
Fibre production	A	x		x		x		x		x						x			
	B	x		x		x		x								x			
Yarn production	C	x								x									
	D	x		x				x				x				x			
Fabric production	E	x		x		x		x		x			x	x		x		x	
	F	x																	
Wet processing	G	x				x		x						x	x			x	
	H	x		x			x		x			x			x				
Textile and clothing production	I	x		x		x		x							x		x		x
	J	x		x		x		x			x	x					x	x	
Total % of companies		100%	0%	70%	0%	60%	10%	70%	10%	30%	10%	30%	10%	20%	30%	40%	20%	30%	10%

Table 6 provides a systematic mapping of the DTs deployed and their role in supporting CE practices in the T&C companies based on the interview data. The role of each DT is explored in greater detail in the following sections.

Table 6. Digital technologies and their function to support CE strategies in T&C manufacturing.

	DT										**Other**			
CE Strategy	**Related DT Function and CE Practice**	**Social Media**	**Mobile Computing**	**Big Data/ Analytics**	**Cloud Computing**	**Blockchain**	**Robotics**	**Artificial Intelligence**	**Internet of Things**	**Digital Fabrication**	**Management System**	**ERP System**	**PDM System**	**E-Commerce/ Website**
Narrowing / Eco-efficiency	DT Function		Digital collaboration tools for meetings Virtual product presentation	Operational and strategic data analysis	Online platform for chemical management Document sharing with stakeholders	Traceability and transparency	Process automation	Image recognition for quality control Image generation/design	Traceability of materials (physical tracers) Real-time data collection	Digital printing on fabrics Digital colour management 3D design	Centralised data collection for process control and certification	Centralised data collection for operational data and process integration	Centralised product data collection for data and process integration	
	CE Practice		Reduce negative environmental impact Reduce material use and consumption	Reduce negative environmental impact Reduce energy consumption Reduce waste and scrap	Reduce chemical consumption Reduce material use and consumption	Reduce negative environmental impact Reduce resource consumption	Reduce waste and scrap Reduce material use and consumption	Reduce waste and scrap Reduce negative environmental impact Reduce material use and consumption	Reduce negative environmental Reduce waste and scrap	Reduce negative environmental impact Reduce waste and scrap Reduce chemical consumption Reduce water consumption Reduce material use and consumption	Reduce negative environmental impact Reduce chemical consumption	Reduce negative environmental impact Reduce waste and scrap Reduce material use and consumption	Reduce negative environmental impact	
Slowing	DT Function	Consumer education about care and maintenance				Traceability and transparency			Traceability of materials (physical tracers) Digital tags for consumer information					Online marketplace for scrap and secondary raw materials

Table 6. *Cont.*

	DT										Other			
CE Strategy	**Related DT Function and CE Practice**	**Social Media**	**Mobile Computing**	**Big Data/ Analytics**	**Cloud Computing**	**Blockchain**	**Robotics**	**Artificial Intelligence**	**Internet of Things**	**Digital Fabrication**	**Management System**	**ERP System**	**PDM System**	**E-Commerce/ Website**
Slowing	CE Practice	Extend product lifespan				Durable products and materials			Durable products and materials Extend product lifespan					Waste utilisation
Closing	DT Function						Process automation		Digital tags for consumer information					
	CE Practice						Recyclable products and materials		Recycling of products and materials					

4.2.2. Social Media and Digital Collaboration

Social media platforms are widely used in T&C companies (Table 5), primarily for marketing purposes. However, their application for CE-related activities is limited, predominantly employed by brands and, in one case, a fabric manufacturer. These companies utilise social media to communicate with consumers, providing information on care and maintenance for textile and clothing products.

4.2.3. Mobile Computing

Mobile computing tools, including smartphone apps and tablets, are widely used across T&C companies, primarily for communication, project management, and sales presentations. These tools enhance efficiency by reducing the need for travel and improving communication processes. Company J noted that the use of tools like MS Teams had "significantly improved efficiency and reduced travel needs, contributing to resource efficiency". It also contributes to reducing resource use by enabling virtual product presentations. While mobile computing has improved communication and project management processes, its potential to advance circular business models like rental or leasing [43] remains untapped.

4.2.4. Big Data and Analytics

Big data and analytics play a crucial role in supporting CE practices by enabling companies to monitor and optimise resource use, waste generation, and overall efficiency. Data collection occurs primarily through, e.g., spinning, weaving, and dying machines that generate vast amounts of data, although the level of data integration varies between companies. However, many companies are still in the early stages of integrating data analytics into their CE strategies. For example, company F stated, "We can only analyse data retrospectively, but we do not have real-time data showing us error rates or inefficiencies". This lack of real-time data limits the ability to optimise processes and reduce waste proactively. For companies with explicit CE goals, such as reducing environmental impact or increasing the use of secondary raw materials, big data analytics help monitor progress and ensure compliance with sustainability targets.

The systematic collection, integration, and analysis of data are essential for implementing CE strategies. Although the use of big data does not directly drive CE practices, it enables companies to make data-driven decisions and implement measures that contribute to circularity.

4.2.5. Cloud Computing

Cloud computing is primarily used for data sharing, communication, and business operations. The use of cloud applications for data and document sharing contributes to increased efficiency, such as reducing paper consumption.

However, its application in CE practices remains limited.

4.2.6. Blockchain Technology (BC)

BC is viewed as an enabler for ensuring traceability and transparency along the textile value chain. However, only 3 of 10 companies, located in the early value chain processes, currently use blockchain, with one brand manufacturer planning its adoption (Table 5). Specifically, blockchain is employed to track and document the origin of materials, ensuring their authenticity and sustainability credentials. It helps ensure that materials, for instance, originate from organic farming or are free from hazardous chemicals, supporting the reduction in resource consumption and negative environmental impacts. Additionally, blockchain is used to verify the use and application of high-quality materials throughout the value chain, which can positively influence the durability and longevity of final products. At the same time, the companies report that data input on BC platforms is largely manual, raising concerns about the accuracy and reliability of the recorded information. Thus, the potential of the BC to significantly advance CE practices by improving transparency and enabling secure real-time data sharing is only partially utilised.

4.2.7. Robotics

The use of robotics in German T&C manufacturing companies is currently limited to 3 of 10 companies, and within these, to individual process automation tasks, such as packaging or loading and unloading goods. The robotic systems currently deployed are not yet integrated into broader digital ecosystems or circular strategies, and their primary focus is on improving efficiency and productivity in specific sub-processes. Although robotics has not yet been widely adopted for CE purposes, individual process automation solutions can indirectly contribute to circularity by reducing waste and improving efficiency. For example, company G uses laser technology to detect and skip seams during printing, preserving the uncontaminated fabric for recycling.

Company J is beginning to explore the potential of more advanced robotic systems as they invested in robots to optimise production processes, while company E is planning to use robotics to reduce resource consumption: "We are looking to optimise our [logistics] processes with these technologies to make them more efficient, speed up operations [. . .] and reduce resource consumption, such as packaging materials".

Current applications of process automation aim for increased efficiency and productivity in specific sub-processes but only contribute to CE goals to a very limited extent. Nevertheless, future developments could see these systems integrated with CE strategies to reduce waste and improve resource use.

4.2.8. Artificial Intelligence (AI)

AI applications are currently used at two companies (E and G), while two others (H and I) are planning to implement them. The diverse range of application areas highlights the significant potential of this technology. AI-powered camera systems are increasingly used to detect defects. They thus contribute to increasing product quality and reducing waste. Company E, for instance, uses AI-powered systems to monitor production processes and quality: "We are performing real-time measurements so we can immediately intervene the moment a defect is detected, preventing unnecessary meters of poor-quality material from being produced" (company E). And company H is "working on [systems] that can recognise different product formats using image recognition software [. . .] for scanning for defects or the quality of the product" (company H).

In addition to improving production processes, AI is being used to optimise design processes. Company G uses AI to generate print designs, significantly reducing the need for physical samples. This not only speeds up the development process but also leads to reduced resource consumption, waste generation, and environmental impacts.

The integration of AI with other systems, such as production or energy management, could lead to major efficiency gains, as company G suggested: "AI could be used to optimise print designs to minimise energy consumption and reduce ink use". Although not yet implemented, this underscores the potential of AI to facilitate CE strategies effectively.

While AI technologies are still in the early stages of adoption in the T&C industry, their potential to drive circular practices by enhancing quality control, design processes, and resource efficiency seems to be significant.

4.2.9. Internet of Things (IoT)

IoT technologies are used in 4 out of 10 companies, all 4 of which can be assigned to the early stages of the value chain (Table 5). The two brand manufacturers are planning to introduce IoT technologies, but no initiatives are planned in the other processes. In companies where IoT is used, sensors for real-time monitoring and error detection (sometimes in conjunction with AI) are used. Company B, for example, uses IoT for machine monitoring: "All our machines are networked, enabling us to conduct analyses and generate reports".

However, the technology's full potential for CE practices remains largely untapped. While the companies collect data from individual machines, the lack of connectivity between systems and companies limits comprehensive data analysis and real-time decision-making. The potential for IoT to enhance resource efficiency and support CE practices lies in its ability to provide real-time, data-driven insights. For example, IoT sensors could track material use and waste generation, helping companies optimise resource use and reduce waste. Tracer systems, such as mentioned by company A, offer the potential to track materials throughout their life cycle, improving transparency and supporting recycling efforts. Digital labels or RFID sensors fulfil a similar function, e.g., in clothing items. However, these technologies were hardly featured in the interviewee discussions; only the brand manufacturers are planning to introduce digital labels to their products. Company I, for example, sees potential in the switch to QR codes instead of physical labels to provide information about their take-back programme because "it can't be washed away [and directs the consumer directly to the relevant website], where it explains what to do".

The integration of IoT systems into broader CE strategies requires investment in networked systems and data analytics. As regulatory demands for transparency increase, IoT technologies could play a crucial role in enabling real-time monitoring and data sharing for CE practices.

4.2.10. Digital Fabrication

Digital fabrication technologies, such as 3D printing and 3D CAD, are not yet widely used in the T&C manufacturing processes; only 3 of 10 companies currently use them. But their potential to reduce resource use and waste is increasingly recognised. Company J noted that digital modelling could replace physical testing and help significantly reduce material and energy consumption: "I believe that not everything needs to be tested physically. Many aspects can be digitally modeled instead". Company G has already transitioned from wet to digital printing, allowing it to manage the entire production process digitally. This shift has improved efficiency and reduced resource consumption and waste generation.

While most companies are still exploring the potential of digital fabrication technologies, their ability to reduce waste, optimise production processes, and enhance resource efficiency makes them promising tools for advancing CE practices.

4.2.11. Other Digital Systems and Platforms

Other digital systems and platforms, notably the core business information software packages—Enterprise Resource Planning (ERP) and Product Data Management/Product Lifecycle Management (PDM/PLM) applications, for example—play a key role in supporting CE practices by ensuring data flows and enhancing traceability. Four of the ten companies interviewed reported plans to upgrade their ERP systems to support sustainability and CE goals. These platforms are essential for enabling seamless data exchange and documenting product recyclability, which is critical for supporting new business models like rental and repair services.

However, manual processes still dominate in some areas, particularly in data collection for sustainability reports. Companies across all process stages continue to rely on spreadsheets to track data for reporting, highlighting the gap between regulatory demands and the current state of digitalisation.

Online marketplaces for secondary raw materials also offer potential for reusing or repurposing surplus or defective products. Company E noted the importance of such platforms: "There's an online market for secondary raw materials where we can sell defective polyester rolls that might still meet the needs of other buyers". However, their existence currently appears to be limited to specific materials.

4.2.12. Summary

DT deployment to support CE practices in the German T&C manufacturing industry varies significantly across processes and companies. A key trend is that later stages in the value chain adopt more DTs, largely aligned with the narrowing strategy. The applications are focused on improving efficiency, reducing resource consumption and waste, and thus cutting costs, which is highly supported by widely used DTs such as mobile computing, big data, and cloud computing, often operating within, or linked to, the corporate ERP system. These technologies enable data integration, facilitating process optimisation and supporting resource efficiency and environmental management.

Although IoT technologies are partly deployed, the collection and analysis of these data are limited. Data are collected automatically from different IoT devices, but are often not available in centralised systems for filtering and analysis to support informed decision-making. ERP systems, for example, which provide the backbone information processing for many companies, are being modified and developed to provide IoT data integration and analysis functions, but this is not straightforward given the range of IoT devices and the need for specific system configurations.

Social media platforms, which are mainly used for marketing and consumer education, indirectly support the slowing strategy by promoting product longevity. However, more complex technologies such as robotics and AI are less common, although they can contribute to quality assurance, process automation, and informed decision making and thus to cost reduction.

For slowing and closing strategies, technologies like digital tags and platform technologies are used sporadically and the use is focused on later stages, where they facilitate traceability and information sharing with consumers and recyclers, essential for reuse, repair, and recycling.

Digital fabrication holds considerable potential for reducing resource use across all processes, but its application is still limited. As investments in digital technologies grow and regulatory pressures increase, the role of these technologies in CE practices will become increasingly vital.

4.3. What Are the Challenges and Critical Issues for Current and Future CE Transition and Digitalisation in the German T&C Manufacturing Sector? (RQ3)

The interview analysis reveals four clusters of challenges and critical issues relating to CE transition and digitalisation. These are (1) product-related, (2) process-related, (3) organisational, and (4) external issues.

4.3.1. Challenges

Product-related challenges arise from the limited availability and complex processing requirements for alternative materials, such as secondary or recycled fibres and materials, which vary in quality, fibre length, and colour consistency. These inconsistencies often require additional testing and adjustments. Company C, for example, tries to source certified fibres from sustainable production, but "it is still the case that these farms, which perform really well, cannot even supply 5% of our wool", and on the processing of recycled wool: "This is a loss of quality because we simply lose fibre length". Company D observed that "recycled polyester has a different quality standard in each batch, sometimes with color variations", which limit its usability in lighter shades, and therefore lead to quality compromises.

Process-related challenges mainly involve the lack of collaboration and standardised data reporting and transparency across the value chain, which results in inefficient and labour-intensive data management practices. For example, Company B pointed out that while their software evolves continually, all data must be manually entered and maintained, creating inefficiencies. Company C echoed this by stressing the lack of uniform data templates, stating, "the data being requested [by different brands and platforms] is similar [...] but it is not the same. Everyone wants something different", which complicates meeting multiple certification and reporting requirements. Furthermore, implementing changes often requires cooperation among multiple stakeholders across the supply chain. For example, company C sought to adopt reusable transport boxes, which would have required participation from transport companies and downstream partners; however, "our customers don't engage sufficiently, and our external service providers don't cooperate enough". This lack of alignment restricts scalable solutions for enhanced transparency and sustainability in processes. The industry-wide absence of uniform digital integration across platforms and reporting systems intensifies these challenges, underscoring the need for standardised, streamlined digital solutions.

Organisational challenges include limited awareness and internal resistance toward new technologies, often stemming from the separate handling of sustainability and digitalisation functions. This separation impedes integrated CE implementation. Company C specifically noted challenges with a newly implemented ERP system because it has "programmed a huge module for sustainability and traceability [in the old system], which will take years to be implemented [in the new system], because too few questions were asked and in the end it was implemented by IT-people who have no idea about all this stuff".

Furthermore, the SMEs in the industry struggle with limited capacity as regards human and financial resources, which slows the innovation process and hampers their ability to meet market demands and regulatory expectations. For example, company F noted, "It's more time-consuming than I would have thought. So it's not that easy. I wish I had more time and resources and manpower".

External challenges encompass fragmented standards, regulatory demands, and market constraints. The varying requirements across industry standards, certification processes, and regional regulations increase operational complexity. Company I cited the varying regulatory demands across European markets, where "France, for example, always does things differently from Germany", complicating compliance. Additionally, the higher costs of sustainable materials, combined with market resistance to price increases, inhibit broader adoption. As company F, who developed a collection of fabrics made of recycled materials, found, "it didn't gain as much popularity as I would have liked [. . .]. Unfortunately, it's usually one to two euros more expensive per metre of fabric and our customers, especially the German furniture industry, aren't that interested".

4.3.2. Success Factors

To address the challenges discussed above and progress the successful implementation of CE strategies in the German T&C manufacturing industry, three operational areas emerged from the interviews as being of particular importance and having the biggest impact: (1) strengthening collaboration and partnerships; (2) optimising resources and infrastructure; and (3) standardisation and regulatory support.

Strengthening collaboration and partnerships is the most frequently emphasised factor to enable effective transformation. These partnerships are crucial for navigating both organisational and process challenges, as demonstrated by Company A's collaboration with a range of stakeholders, including brands, nonwoven producers, spinners, knitters, and research institutions. Company A emphasises that "having contacts across various levels of the value chain is vital" for product development and innovation, and they actively seek new connections to expand their network. Similarly, company E notes that close communication with supply chain partners is essential, as "suppliers are also continually evolving, more and new recycled materials are being offered [. . .], which opens up new possibilities". Without such collaboration, circularity initiatives would face significant hurdles due to the complexity of the T&C supply chain, which involves multiple actors and processes.

Efficient resource and infrastructure management are also seen as critical in enabling circular processes and minimising environmental impact. For instance, company G is working with suppliers to prepare fabrics in ways that reduce the need for in-house processing, allowing for "a smoother, energy-efficient production". Furthermore, several companies recognise that using local recycling options could significantly cut environmental costs associated with long-distance transport and handling of recycled materials. However, establishing efficient infrastructure often involves external collaborations. As company E states, "collaborative recycling projects and partnerships with local recyclers" provide viable solutions for reducing waste.

Standardisation and regulatory support: The need for standardised metrics and supportive regulatory frameworks is another significant factor for successful CE implementation. Interviewees stress the need for consistent standards across the value chain to enhance traceability and help companies meet sustainability goals effectively. As noted by company C, the current lack of unified metrics complicates compliance and reporting, as "different brands and platforms require various data formats", which results in inefficiency and an increased workload. A cohesive regulatory framework that establishes clear guidelines for material traceability and reporting would alleviate these issues, as would a central platform for sharing standardised sustainability and CE data.

5. Discussion

Previous studies provide a fragmented picture of the current status and necessary future developments across various T&C value chain stages. This fragmentation arises from the diverse perspectives these studies take in addressing circularity within the T&C industry. Most research adopts a product life cycle perspective, focusing in particular on end-products such as textiles and clothing, to explore potential strategies and practices that could facilitate the transformation from a linear to a circular T&C industry [41,80,81]. Similarly, studies examining the use of digital technologies to support this transformation also rely on the product life cycle as a basis, mapping specific technologies to various phases of the cycle [61,65]. In this context, all manufacturing processes are grouped together under the life cycle phase "production", which does not adequately reflect the complexity of the textile value chain. As outlined in Section 2 of this study, the German T&C sector is highly fragmented, producing both intermediate and final products, as well as working in technical and clothing textiles. These processes involve a wide range of stakeholders across different stages of the value chain. Therefore, to better address the research questions, this study took an organisational and process-focused perspective at the micro level, which allowed for the identification of relevant strategies, practices, and suitable DTs that can support and advance them. It is one of the first studies to focus specifically on T&C companies and their CE practices in the context of DT deployment. The results reveal that the adoption of CE strategies varies across the T&C processes, while the degree of digitalisation is relatively low across the processes, with the primary focus being on efficiency optimisation. A number of related themes emerged that merit further discussion.

Firstly, the companies in this study indicated a particular focus on reducing resource consumption, waste, and the consequent environmental impact, which is driven by a need to reduce high energy costs and labour expenses and comply with regulatory demands in Germany. This focus on internal eco-efficiency reflects broader industry trends but does not necessarily align with a full transformation to the CE. This is consistent with the findings of Barreiro-Gen and Lozano [82], who reported that companies often prioritise internal measures rather than collaborating with external stakeholders to achieve wider-ranging holistic circularity goals. Social media, mobile and cloud computing, and internal systems like ERP, PDM/PLM, and integrated management systems are the most widely used technologies across the value chain. The main goal of digitalisation is to improve process efficiency, as well as reducing resource consumption and waste. While these efficiency measures align with CE principles, companies are not implementing them as part of a holistic CE transformation. It is thus unsurprising that DTs are not primarily adopted to support a broader CE transition or sustainability goals, but rather for the more immediate business benefits they offer.

IoT, big data, and AI have significant potential for real-time process monitoring that could support the adoption of CE practices, but most companies are still in the early stages of implementing these technologies. Blockchain and RFID show promise for enhancing traceability and reducing waste, but a lack of standardisation and high manual data management workloads hinder wider adoption. These technologies are not fully integrated into existing management systems, limiting their effectiveness in supporting CE practices. Digital fabrication (DF) technologies, such as 3D printing, 3D design, and digital twins, are also underutilised, despite their potential to significantly support CE practices. These technologies could eliminate the need for physical samples, reduce resource consumption, and automatically collect data for future applications like the DPP [83]. However, research on the potential of DF technologies to progress the CE is still in its infancy. In summary, the overall level of digitalisation in the industry remains low, which aligns with the findings of Schöggl et al. [63]; and even when DTs are implemented, it is often more for reasons of internal efficiencies rather than transitioning to the CE. In that context, however, this study adds qualitative insights into the motivations and challenges behind the adoption of these technologies, and finds a general lack of strategy concerning the CE transition, in which companies integrate CE principles into their corporate strategy to guide appropriate measures and implement suitable technologies.

Secondly, in terms of the slowing strategy, companies are primarily concerned with high-value waste utilisation. For instance, businesses sell by-products to other actors in the industry, but this practice is largely driven by cost-efficiency rather than a genuine shift toward circularity. Manufacturing companies also focus on product durability to differentiate themselves from low-cost imports from Asia, especially since German manufacturers rely on high-quality and long-lasting products to compete. This strategic focus represents a market niche where durability is valued, particularly in technical textiles and high-performance materials for luxury or functional clothing. However, these efforts fall short, as practices such as repair or reuse do not play a significant role for manufacturing companies, even though there are opportunities for extended business models such as via spare parts supply or repair services [84]. While social media is used by brand manufacturers to engage with consumers, promote sustainability efforts, and advertise repair services, its use remains limited. Social media represents an untapped opportunity for manufacturers to engage directly with consumers, for instance, by educating them about repair practices, and contribute to a more repair-friendly culture. As research has shown, consumers often lack the skills and knowledge to repair products [85,86]. Companies could bridge this gap by sharing knowledge and collaborating with local repair communities.

Thirdly, closing strategies are mainly employed by brand manufacturers, where design and material choices are geared towards recyclability. However, there are contradictions within the value chain. While brand manufacturers favour recycled or mono-materials, upstream companies are hesitant to use them due to quality concerns, favouring material mixes instead to ensure the production of high-quality, durable materials. This mirrors a paradox identified by Colucci and Vecchi [84]. Hedrich et al. [87] note similar issues in their study of textile recycling in Europe, but predict that recycling technologies will soon improve, producing higher-quality materials. Companies could engage with these developments and invest in initiatives to drive innovation in this area, which may strengthen their market position as demand for sustainable materials rises with regulations like the EU's Ecodesign for Sustainable Products Regulation (ESPR) [88]. Additionally, business models aimed at extending the use phase of textile products—such as rental services—are not yet profitable, further complicating the CE transition for brands. The reasons are twofold: consumers do not yet fully embrace these business models; and they involve significant manual effort. Digital support could help by creating effective offerings and efficient processes based on extensive data [89].

Fourthly, this study also highlights the significance of early-stage collaboration between companies across the value chain, particularly in circular innovation projects. Schöggl et al. [90] demonstrated the positive impact of such collaborations on CE strategy implementation. However, these efforts remain project-specific, with little evidence of widespread industry transformation. The lack of collaboration across the value chain represents one of the biggest hurdles to scaling circular strategies. Cooperation is essential for developing circular products and processes [90,91], yet innovation remains siloed within individual processes, limiting CE goals for the end product. For incumbent companies, engaging in innovation ecosystems where various stakeholders such as startups, research institutions, or government actors collaborate can be key to fostering successful innovations [92]. In a similar vein, Colucci and Vecchi [84] see significant potential in collaboration between born-circular firms and established companies to drive a radical shift toward

CE, creating a win–win situation for both parties. Business models like repair and resale services also depend on stakeholder cooperation, particularly in terms of decentralised service provision and spare parts supply. While brand manufacturers are key drivers of circular strategies, they cannot achieve these goals without innovation and engagement from upstream and downstream actors. A joint understanding and coordinated efforts across the entire value chain are essential for true CE integration. International processes may impede progress, as studies from Italy [49] suggest local ecosystems are crucial for developing circular and innovative products and business models. More research is needed to explore whether such ecosystems could be established in Germany.

Fifthly, from an organisational perspective, employee and managerial awareness, capabilities, and motivation are critical for advancing digital and CE transformation. The organisational culture plays a crucial role [93], with resistance to change being a common obstacle. However, studies show that this resistance can be overcome by integrating CE into corporate strategies and business practices [94]. Achieving this will require a deeper cultural shift internal to the organisations, making CE a core aspect of the business rather than an external add-on.

Finally, a blueprint for transitioning to circular practices in the German T&C industry can be derived from the research results and the discussion above, which can be customised and applied across the T&C processes studied here (Figure 7). The blueprint revolves around the coordinated adoption of the three CE strategic approaches and related practices, in conjunction with the use of appropriate DTs to enable and support these initiatives.

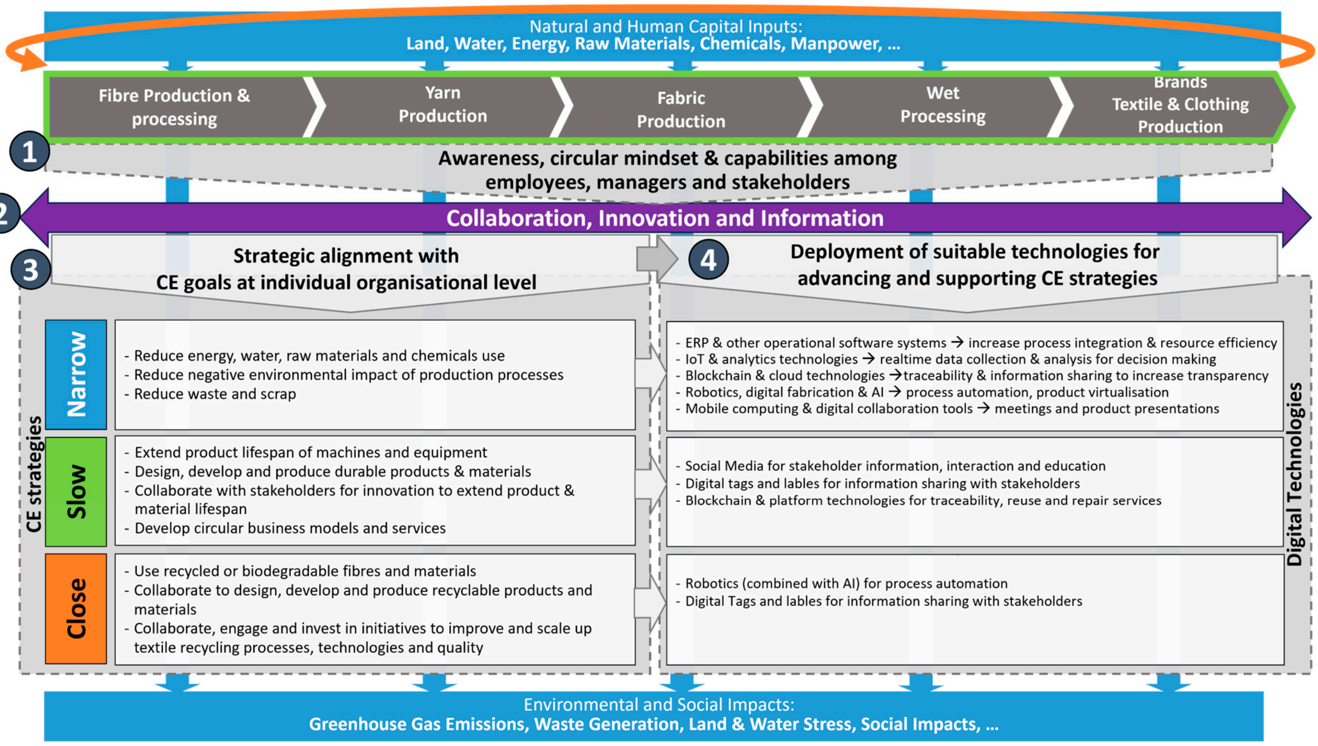

Figure 7. Blueprint for CE strategy development and implementation in T&C manufacturing with appropriate DT deployment.

1. Organisational awareness and capacity building

At the individual organisational level, raising awareness of ecological and social impacts, establishing a mindset for circular thinking, and developing the necessary skills and capabilities among managers, employees, and stakeholders are essential. This includes addressing potential resistance to change, which is common in transitions of this nature. Establishing an organisational culture that values and actively promotes sustainability goals is critical for successful CE implementation. Through training and communication initiatives, organisations can build a foundational understanding of CE principles and practices, creating a workforce that is aligned with circular values.

2. Collaborative networks and ecosystems

Collaboration across the value chain is crucial for developing CE innovations and business models. Strengthening partnerships between organisations within the T&C industry can facilitate knowledge exchange on materials, products, and processes. Establishing regional and innovation ecosystems that also include external stakeholders from other sectors—such as startups, research institutions, and government bodies—can accelerate the creation of circular products and business models. Companies can participate in multiple networks and ecosystems, each dedicated to specific aspects of circularity, to leverage shared resources and drive systemic change in the T&C industry.

3 and 4. Alignment and implementation of strategies, processes, products, and DTs around agreed CE goals

To achieve CE objectives, companies must develop their strategy, processes, and product designs around the principles of narrowing, slowing, and closing resource loops. Each organisation, as well as collaborative initiatives, should work to implement practices associated with these strategies, using digitalisation initiatives to enable and support them.

The narrowing strategy is aimed at minimising resource consumption, waste generation, and the environmental and social impacts associated with manufacturing processes. By leveraging DTs, organisations can optimise their operations to improve efficiency and reduce resource consumption. For example, ERP and other operational software systems can integrate workflows to optimise resource allocation within companies, while IoT devices and analytics provide real-time data on resource consumption and process performance. These insights enable decision-makers to promptly adjust operations to reduce waste. Blockchain and cloud computing further support the narrowing strategy by facilitating seamless data sharing across various stages of the value chain. This integration enhances traceability, allowing companies to monitor and verify resource origins and usage, which is crucial for meeting sustainability standards. Technologies such as robotics, digital fabrication, and AI can also automate processes like quality control and virtual product modelling, minimising physical material usage and ultimately lowering resource requirements. Additionally, mobile computing and collaboration tools help reduce travel by enabling virtual communication, improving cooperation in project-based and operational tasks while reducing the carbon footprint associated with transportation.

The slowing strategy focuses on extending the lifespan and preserving the value of products and materials. This approach aligns with consumer demand for long-lasting, high-quality items and represents a competitive advantage for T&C companies. By engaging stakeholders through social media, companies can educate and encourage consumers to maintain and repair their products, promoting responsible product use. Digital labels and tamper-resistant tags provide reliable product information that is accessible to different stakeholders, aiding in repair, resale, and recycling efforts. Furthermore, blockchain and platform technologies can maintain detailed records of each product's history and condition, facilitating traceability and supporting innovative business models like repair services. This approach not only extends the product life cycle but also strengthens customer trust in the durability and sustainability of companies' offerings.

The closing strategy is essential for enabling effective recycling and end-of-life management, facilitating the development of products that can be reintegrated into production cycles. This strategy encourages companies to design items with recyclable or biodegradable materials, focusing on processes that promote easy recycling at the product's end-of-life stage. Collaborative efforts and investments in recycling methods, technologies, and quality standards are critical for supporting a circular flow of resources. By deploying advanced robotics integrated with AI, companies can improve sorting and separation processes, enhancing productivity and cost efficiency in recycling operations. Digital identifiers, such as tags and labels, further support the closing strategy by aiding reverse flows, for instance, correct disposal and collection, and reprocessing of materials.

As an adaptable roadmap and practical checklist, the blueprint provides a structured approach for companies to strategically adopt and integrate CE principles and DTs across the entire value chain. Through narrowing, slowing, and closing resource loops, the blueprint facilitates a holistic approach that not only enhances operational efficiency but also advances long-term sustainability goals of absolute reduction in resource consumption, as well as negative environmental and social impacts across the value chain. By aligning DTs with CE objectives, companies can transform their practices, creating a more resilient and circular industry. It also recognises the importance of people-related aspects, requiring cultural change and new skills and competencies.

Each company can tailor the framework to specific processes, such as yarn production, textile manufacturing, or garment construction, by selecting appropriate CE practices for narrowing, slowing, and closing resource loops and aligning them with relevant DTs and to meet their strategic goals. The blueprint also highlights how DTs, like IoT and blockchain, can enhance traceability and support compliance with new EU regulations, such as those relating to the DPP. The framework's flexibility enables companies to assess their current status, identify gaps, and outline concrete steps toward transformation. This integrative approach lays the foundation for advancing a circular and digitalised textile sector.

6. Conclusions

This study investigated the relationship between the CE transition and DT deployment in German T&C manufacturing companies. The findings highlight that CE strategies and practices, as well as digitalisation, vary significantly across the value chain. Some key points emerge from the findings, which are briefly discussed below.

It is clear that the focus for many companies remains on internal efficiency measures, driven by economic pressures in the main. While these efforts reduce resource consumption and waste, they are often not aligned with a comprehensive CE transformation. Companies are primarily concerned with improving eco-efficiency within their own processes, rather than pursuing broader collaboration with stakeholders along the value chain, which is essential for achieving circularity. In terms of CE strategies, the slowing strategy is primarily driven by cost-efficiency, with companies focusing on high-value waste utilisation and product durability to differentiate themselves from low-cost imports. While this provides a competitive advantage, practices like repair and reuse are underdeveloped; but there is potential for T&C manufacturers to expand into extended business models, such as repair services and spare parts, to align more closely with CE principles.

The closing strategy, focused on recycling and designing for recyclability, is mainly implemented by brand manufacturers. However, contradictions within the value chain persist, as upstream companies resist using recycled materials due to quality concerns. This reflects broader tensions between sustainability goals and product standards. Advances in recycling technologies, along with regulatory pressure from the EU's ESPR [88], are expected to help overcome these challenges.

DTs, particularly IoT and blockchain, in conjunction with ERP software, are widely adopted to enhance process efficiency. However, their potential to support CE practices remains underutilised. Some of the more advanced technologies, such as big data, AI, and digital fabrication, are still in their infancy in terms of integration into CE strategies. Barriers include a lack of standardisation, manual data management, and limited system integration, which hamper the full utilisation of these technologies for circularity. Collaboration across the value chain remains limited. Although some early-stage projects show promise, a comprehensive transformation toward circularity has not yet emerged. Increased collaboration, especially within circular (innovation) ecosystems that include diverse stakeholders, is crucial to scaling CE strategies and accelerating their adoption. Moving forward, aligning digitalisation with CE goals and fostering greater cooperation across the value chain will be essential for achieving a fully circular T&C manufacturing industry in Germany.

This study has its limitations. It did not encompass all processes of the T&C value chain, with important areas like trade, waste management, and recycling excluded. Future research could encompass these processes to offer a more comprehensive understanding of CE practices and opportunities for collaborative innovations and extending the proposed blueprint accordingly. There were only 10 companies in this study, with two companies per value chain process, which may not accurately represent the industry as a whole. Further research could include quantitative analyses to investigate the variety of actors and processes in the T&C value chain. At the same time, ways to increase the adoption of certain technologies in the industry, notably digital fabrication, could be researched. A further limitation is that this study was conducted solely in Germany, even though the T&C industry is highly globalised. For instance, the analysed brand manufacturers predominantly operate within international networks, rarely collaborating with German manufacturing companies. The findings could be further tested by including companies operating in local supply networks as well as in other regional contexts to validate the blueprint and ensure broader applicability. Expanding the research to different regions could also help to capture the varying dynamics and challenges of CE transition and related DT deployment.

Despite these limitations, the authors believe the research is of value in providing new insights in this field of study and that the blueprint for CE strategy development and implementation put forward here can serve as a starting point for practitioners aiming to implement a systematic CE transformation, and strategically deploy digital technologies to support and enhance this process. The proposed blueprint offers managers a structured and adaptable framework for integrating CE strategies and DTs into their operations. The blueprint's flexibility enables firms to assess current gaps, devise targeted strategies, and foster long-term resilience through collaboration and cultural change. For researchers, the blueprint provides a basis for further development and refinement through additional studies, applying it across diverse regions and contexts to yield new insights. To enhance its effectiveness, the blueprint could be tested, discussed, and extended in further case studies with practitioners, allowing it to be refined in alignment with industry needs. An important next step for expanding the blueprint involves incorporating downstream phases—retail, use, and waste management. Such an expansion would enable companies and stakeholders to devise holistic strategies that engage all relevant actors, promoting a more comprehensive CE transformation. This integrated approach could prove especially valuable for engaging consumers in circular strategies and improving product end-of-life management.

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Appendix A

Table A1. Company CE narrowing practices: Interviewee perspectives.

Theme	Company Code	Statement Examples
Reduce negative environmental impact	A	"We have our own wastewater treatment plant on site".
	B	"We have been recording this consistently since 1997. We can systematically record key indicators, and are actually always up to date in terms of the current input and output; this systematic tracking allows us to establish benchmarks and set improvement goals".
	C	"We make significant investments in photovoltaic systems wherever it is feasible".
	D	"We hold various certifications, including Ökotex for our products, as well as GOTS, GRS, and RWS certifications".
	E	"We have a water treatment system that effectively recovers and processes water for reuse. The system employs various process chemicals, ensuring compliance with ZDHC [Zero Discharge of Hazardous Chemicals] standards, to make the treated water suitable for repeated use".
	F	"20% of our energy consumption is covered by our photovoltaic system [. . .]. We calculate and balance our CO_2 footprint annually (Scope 1, 2, and 3) and fully offset the calculated CO_2 emissions through the support of climate projects".
	G	"Regarding emissions, our digital printing processes and the use of certified inks have virtually eliminated exhaust emissions. This also leads to significantly fewer chemicals on the fabric".
	H	"As a textile finisher, energy consumption—both electricity and heat—is a significant factor. For instance, we require 4 million kilowatt-hours of electricity annually, a quarter of which is generated through on-site solar photovoltaics (PV), a practice we began over 20 years ago and have gradually expanded. However, further expansion of renewable electricity generation currently seems unfeasible. In addition to electricity, we also require 8 million kilowatt-hours of thermal energy, which we generate sustainably using biomass".
	I	"We aim to minimize air freight wherever possible and have set specific air freight targets for each department".
	J	"We are collaborating with other brands and partners at our production sites. This initiative focuses on substituting coal with natural gas or biomass and implementing various energy efficiency measures to further reduce our environmental impact".
Reduce waste and scrap	A	"We reduce waste by integrating quality assurance measures to ensure optimal production outcomes".
	B	"When we notice during production checks or inspections that the product quality is deteriorating, adjustments are made at the cotton stage, including adapting the blend to counteract the issue".
	D	"We have system that analyses and categorises waste into different types, aiming to reduce avoidable waste. This effort spans a wide range, starting from copier paper and extending to various other areas [. . .]. We operate on a made-to-order production basis".
	E	"We aim for real-time error detection to minimise waste, so that as soon as a defect is detected, we can intervene before too much low-quality material is produced".
	F	"We produce almost exclusively on-demand, with everything tailored to customer requirements. We maintain only a small stock program, which we constantly adjust by monitoring which colors perform well and to what extent".
	G	We carefully evaluate where we can reduce waste, particularly since we have to pay for disposal. One significant area of improvement has been the reduction in waste from printing ink, which used to be a major issue. Now, thanks to advancements, ink usage has been minimised, and almost no ink needs to be discarded anymore.
	H	"Production is increasingly aligned with actual sales or near-certain demand. This approach minimises overproduction and eliminates surplus stock that would otherwise need to be reprocessed or discarded later".

Table A1. *Cont.*

Theme	Company Code	Statement Examples
Reduce resource consumption	A	"We operate an on-site gas power plant, which not only generates energy but also produces steam and heat that are directly utilized in production processes, ensuring a very high level of efficiency".
	B	"Between 2008 and 2023, we progressively reduced water usage by 30%. For example, in 2008, 132 L of water were needed per kilogram of yarn, whereas by 2023, this figure had dropped to just 96 L".
	C	"We have modernised our dyeing facility in Germany, equipping it with completely new, fully automated dyeing kettles featuring smaller, individually adjustable batch sizes. This allows for a more efficient dyeing process, significantly reducing water consumption and chemical use [...]".
	D	"There are various ongoing projects aimed at energy savings, as is mandatory for everyone, including us. We are certified in energy management".
	E	"Our process involves an important distinction: the precursor to our final product is a fleece [...]. The edges of this need to be trimmed. Since no solidification has yet occurred, these trimmed edges are collected via suction systems and fed back [...]. This allows us to save material that would otherwise need to be added anew".
	F	"Our electricity, gas, heating oil, and diesel consumption are continuously monitored. Through a variety of measures, we have achieved significant energy savings in recent years. For instance, since 2019, our electricity consumption per meter of produced fabric has been reduced by nearly 19%". "Since 1998, we have been monitoring our water consumption and continuously evaluating necessary measures to conserve this resource [...]. We have achieved significant reductions over the past five years, cutting our annual municipal water consumption by nearly 25% and our annual water consumption for climate control in production by almost 47%". "We are reusing leftover yarns by incorporating them into the production process, such as into the selvedge".
	G	"We reuse water up to four times, capturing it with installed pumps and tanks. For instance, we reuse cooling water in the dyeing process, significantly reducing our energy and water consumption [. . .]. We are already forced to do this for energy reasons - we have had this system for over 20 years now and nobody forced us to do it, [but] we are business people and can do the maths".
	H	"We have implemented a rigorous selection process for dyes, chemicals, and auxiliaries, prioritising those with a very high efficacy spectrum. For example, when working with cellulose and reactive dyes, it is possible to purchase inexpensive reactive dyes with yields of only 60–75%, coupled with an extensive need of water. Our approach focuses on sourcing dyes with the highest possible fixation rates, ensuring that 75–95% of the applied dye remains on the material and not in the water".
	J	"We are working intensively with our suppliers, to establish and evaluate new dyeing and finishing processes and implement process optimisation. Particularly in our production countries, water recovery has become a standard practice due to the limited availability of water. We actively support these initiatives and closely monitor developments, ensuring significant progress is made in this area".

Table A2. Company CE slowing practices: Interviewee perspectives.

Theme	Company Code	Statement Examples
Waste utilisation	A	"Defective goods, as long as they are in acceptable condition and not heavily contaminated, are sold as B-grade products".
	C	"Yes, our main revenue driver when it comes to waste utilisation is selling our waste. We have different types of waste with varying lengths and qualities at multiple stages, and even our combings are of interest to those who need shorter fibers. If we simply sell our waste in bulk, we generate significantly more revenue compared to all our recycling efforts, and it doesn't appear that this will change".
	D	"Waste is collected and sold separately as far as possible".
	E	"We try to separate and collect as much as possible—whether it's household waste, production waste like nonwoven scraps, old wood, or plastic packaging".
	F	"We are currently collaborating on a research project with [university], where we produce round-needled tubular structures from our own waste trimmings. These are intended for use in furniture manufacturing. Since 2018, we have also had our own home collection, offering cushions and small furniture, and we aim to incorporate such circular products into this line".
	H	"Almost nothing goes into general waste; we sort and return all cardboard, films, and yarns used in production".
	I	"We repurpose leftover materials for smaller projects. For example, in our own service factory, we create items like bags from these materials. All of our posters and banners, which are made of textile, are collected from our stores and points of sale, then transformed into bags. These are often used as giveaways and feature interesting designs and images. We are actively working on many projects to reuse waste in this area".
	J	"For our products, we actively engage in upcycling. Items that may be faulty, particularly from our manufacturing process, are repurposed and enhanced to create new products. For example, we produce shopper bags or wallets from cutting scraps. We consistently explore ways to make better use of these materials, ensuring they are transformed into valuable items rather than wasted".
Durable products and materials	B	"We aim to explore niche markets to sustain jobs at our location. Technical textiles, for instance, are significantly more profitable than basic yarns used for producing T-shirts. Our focus is consistently on high-quality products".
	F	"Our fabrics are designed to be washable and easy to care for".
	H	"Our focus is on ensuring our product has the highest possible durability", which applies to both final products and intermediary materials.
	I	"As part of our new brand DNA, longevity has become a core focus for us. This means it is undoubtedly an important topic. We're now introducing extended warranties, which further underscores how crucial this is for us [. . .]".
	J	"Our products have a relatively long lifespan. We're talking about 10 years or more, potentially even up to 20 years, depending on the area of application, intensity of use, and maintenance".
	C	"We have already conducted trials using reusable transport boxes for dye cones".
	F	"We offer training and even provide support to end consumers. For example, if someone has a [product] with our fabric, we have a service hotline where they can ask questions like how to deal with pressure marks on velour, or how to properly clean and maintain the fabric. We also advise on removing stains from materials like marker ink or nail polish. While we don't offer repairs, we do provide a care service to ensure the fabric lasts as long as possible, aligning with our commitment to durability".

Table A2. *Cont.*

Theme	Company Code	Statement Examples
	H	"We strive to reuse everything related to packaging whenever possible. For instance, with cardboard boxes, we have agreements with our customers to return the products in the original boxes, keeping them in circulation for as long as possible. Similarly, stretch films and cores are reused whenever feasible, with efforts to employ reusable cores. For materials like plastic films, we ensure they are sorted by type and returned to the manufacturer for recycling. This approach maximizes the lifecycle of packaging materials and aligns with our sustainability goals".
	I	"We try to repair first—we have a Service Factory, and we're developing strategies to expand our repair offerings".
	J	"We have offered a repair service at our company for as long as the company has existed—around 50 years". "We also provide rental models and second-hand offerings. About a month ago, we officially launched these initiatives, which received some media attention [...]. Our aim is to explore how these models can evolve into viable business opportunities [...]. We are also working on designing future products in specific categories to better align them with rental systems. These products may, for example, be heavier or more modular, allowing easier replacement of components, thereby improving their suitability for rental and extending their overall lifespan".
Extend life-span of machines and equipment	B	"In the past, maintenance intervals were based on rough estimates and experience, such as assuming that a carding set would last around three months. However, with modern testing procedures and technologies, these intervals have been extended significantly".
	G	"Our stretching frame is older than I am, but with proper maintenance, it still makes sense to keep it running".
	H	"We have implemented proactive maintenance, [...], based on this knowledge, components are replaced at appropriate intervals".

Table A3. Company CE closing practices: Interviewee perspectives.

Theme	Company Code	Statement Examples
Recycling of products and materials	B	"Using recycled cotton means less water use in farming, fewer chemicals, and reduced transportation impacts. This makes it a sustainable product, and we aim to maximise its potential, particularly in the premium segment".
	C	"We also have our own 'recycled product' [made from recycled fibres], which sells steadily. However, it always includes a portion of virgin fiber to ensure the material can be processed effectively through our spinning machines".
	E	"In our carbon fiber nonwoven production, the process was set up to incorporate waste from carbon fiber nonwoven production. We purchase these materials and produce our own carbon fiber nonwovens from them. This means that these products are essentially made entirely from recycled materials, qualifying as 100% secondary raw materials".
	F	"We have a recycled collection for two years now. However, it's not textile-to-textile recycling; instead, we rely on PET recycled yarns made from PET bottles. Currently, we are also exploring new options and have sourced a new fiber-to-fiber recycled yarn that we are now testing".
	H	"We purchase certain packaging items, such as cartons and foils from recycled materials".
	I	"We are working on a circularity collection, meaning a collection [...] of mono-component products, meaning they are made of 100% recycled polyester wherever possible". "When we use natural fibers, particularly in the wool sector, we exclusively use recycled wool, such as shredded wool or collected wool, to ensure resource efficiency. We aim to use as little conventional [virgin] wool as possible". "The consumer can visit our website to generate and print a free DHL return label, allowing them to send products back to us at no cost. Currently, we handle this process in-house and do not collaborate with an external partner for returns".
	J	"We strive for, and have already largely achieved, the predominant use of non-fossil raw materials in our products. Currently, approximately 90% of our raw materials consist of recycled, bio-based, or biomass-allocated materials. This shift has significantly reduced our carbon footprint". "We also operate a take-back system, allowing customers to return their old products. Depending on their condition, we either repair the items under our manufacturer's warranty or as a paid service [...]. However, some products, due to their condition, cannot be economically repaired. Currently, we collaborate with 'Fairwertung', which oversees the redistribution of these items. This includes second-hand resale, recycling, or appropriate disposal, depending on the product's viability.
Recyclable products and materials	A	"We explore how our fibers can contribute to making textile products more circular. For instance, we assess the potential to replace synthetic fibers with functionalised viscose fibers, enabling products to be designed for biodegradability or improved recyclability".
	G	"We now stop printing at the seam, which means the fabric remains clean and can be more easily recycled".
	H	"We're already working with designers to use only specific dyes and chemicals, so the product can be recycled later".
	I	"We have guidelines from our recycler on what materials can be used, and we integrate these from the beginning of the design process".

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