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Sustainability, circular economy and digitalisation in the European textile and clothing industry: an applied maturity framework

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The manufacture and sale of textile and clothing (T&C) products have witnessed steady growth in recent decades, with corresponding increases in raw materials consumption, waste generation, and negative environmental impact. Clothing and textiles have typically been produced in linear fashion, and only in recent years has the recycling of finished goods gained traction in the marketplace. Through a review of available literature, the article examines the core issues of sustainability, the circular economy and digitalisation in the T&C industry in Europe and puts forward a framework to assess the maturity of companies operating in this sector as regards these three interrelated themes. The framework is then applied in case study companies in five different European countries– Italy, Germany, Portugal, Bulgaria and Turkiye. The findings suggest the framework is of value in charting T&C company progress in the transition to circular economy practices and enabling digitalisation. In addition, the framework can be seen as a starting point for developing appropriate strategies and actions to progress this transition in a managed and targeted way. The article will be of interest to other researchers in this field of study, and to practitioners in the T&C industry charged with overseeing the move to the circular economy.

KEYWORDS
circular economy, sustainability, digitalisation, digital technologies, textile, clothing, case studies, maturity framework

1 Introduction

Current global patterns of production and consumption are placing increasing pressure on natural resources (United Nations, 2022), whilst, at the same time, global waste generation is expected to continue to rise significantly (Kaza et al., 2018). Without substantial changes, the combined effects of increasing raw material extraction and growing waste streams are likely to intensify environmental degradation, including greenhouse gas emissions, biodiversity loss, and pollution of air, soil, and water systems (OECD, 2019). The textile and clothing (T&C) industry exemplifies these developments. Over the past decades, both the production and consumption of textile products have increased significantly, while product lifespans have shortened, as garments are often discarded after limited use (Gözet and Wilts, 2022). Textile consumption in the EU is associated with substantial environmental pressures and ranks among the most impactful consumption categories in terms of resource use and greenhouse gas emissions (European Commission, 2020). These developments have intensified criticism of the prevailing linear production and consumption model. Only a small proportion of post-consumer textiles is recycled into new fibres, leading to substantial resource losses and environmental impacts (Köhler et al., 2021). The EU textile sector generates approximately 5.4 million tonnes of post-consumer waste annually, with less than 1% currently subject to fibre-to-fibre recycling (Köhler et al., 2021). However, recent analyses indicate that scaling closed-loop recycling is both technically feasible and economically viable: reaching 18–26% fibre-to-fibre recycling by 2030 would require €6–7 billion in capital investment but could generate an annual profit pool of €1.5–2.2 billion and create approximately 15,000 new jobs (Hedrich et al., 2022).

Against this backdrop, the European Union has increasingly promoted the circular economy (CE) as a key approach to decouple economic growth from resource use. The concept seeks to minimise waste and pollution across the entire lifecycle of materials and products (European Commission, n.d.; European Union, n.d.). Rather than following a traditional end-of-life logic, CE principles emphasise strategies such as reducing resource use, reusing products and components, recycling materials, and recovering value throughout the supply chain (Kirchherr et al., 2023). Although the CE concept has existed for several decades, it has gained increasing attention in recent years. It has become a central element of major sustainability initiatives, including the United Nations Sustainable Development Goals (United Nations, 2015) and the European Union's Green Deal (European Commission, 2019). Within this context, digital technologies are increasingly recognised as key enablers for CE implementation by improving data availability, transparency across supply chains, and resource management (Liu et al., 2022; Wynn and Jones, 2022).

Building on these developments, this article addresses the following research questions (RQs):

> *RQ1:* What is the current status of the related themes of sustainability strategies, CE practices, and digital technology deployment?
>
> *RQ2:* Can a framework be developed and applied to assess the maturity of T&C companies as regards these themes in a European context?

Following this brief introduction, Section 2 sets out the two-phase research methodology. Section 3 then directly addresses the two RQs, including the development of a maturity framework that is then applied in 5 detailed case studies. Finally, Section 4 concludes the article, summarising the contribution, pointing out limitations and suggested future areas of research in this field.

2 Research methodology

As noted by Babbie (2021), research can broadly serve exploratory, descriptive, or explanatory purposes. Given that theoretical development regarding sustainability, the CE, and digitalisation remains relatively nascent, this study primarily adopts an exploratory orientation, complemented by elements of a descriptive research design aimed at characterising key aspects of the phenomenon under investigation. The research process was structured into two main phases (Figure 1). In the first phase, a semi-structured literature review was conducted to evaluate the current state of sustainability, CE practices, and digitalisation. This review provided the conceptual foundation for developing an initial maturity framework. The second phase employed a pragmatic case study approach to apply and validate the framework. This empirical stage enabled an exploration of its practical relevance and applicability within the complex and heterogeneous context of the European T&C industry. The two phases of the research design are discussed in greater detail in the following sections.

2.1 Phase 1: Semi-structured literature review and initial framework development

The study adopts a qualitative, inductive approach. To address RQ1, a semi-structured literature review was conducted to assess the current status of sustainability strategies, CE practices, and related digital technology deployment. Literature reviews enable a systematic understanding of the state of research, identification of key themes, and recognition of research gaps (Snyder, 2019; Tranfield et al., 2003). This approach was adopted in accordance with the established guidelines of Snyder (2019) and Turnbull et al. (2023), which are particularly suited to fields characterised by conceptual plurality and cross-disciplinary breadth such as CE and digitalisation.

Peer-reviewed journal articles were identified through a structured search of the Scopus database, complemented by backward snowballing to trace foundational contributions not captured by keyword searches alone. Scopus was selected on the basis of its broad multidisciplinary coverage and its strong overlap with other major databases (Gusenbauer, 2022; Pranckutė, 2021). The following search string was applied to titles, abstracts, and keywords:

(*sustainab* AND "Circular Economy" AND digital**) *AND* (*business OR organi* OR industr**)

The search was restricted to peer-reviewed journal articles and review articles published in English or German, covering the period 2016 to 2025. The initial search yielded 152 records. These articles were assessed against the pre-defined criteria presented in Table 1, which were derived directly from the research question and the search strategy.

The identified records were screened on the basis of title and abstract against the above criteria. Of these, 102 records were excluded as they did not meet one or more inclusion criteria. The remaining 50 articles proceeded to full-text review. Backward snowballing of the reference lists of included studies yielded a further 26 relevant articles meeting all inclusion criteria. The final corpus therefore comprises 76 studies. The selection process is illustrated in Figure 2.

The retained articles were analysed using inductive thematic analysis to identify key patterns relating to the three core themes. The analysis began from an established foundation in the literature and proceeded iteratively, allowing emergent themes to surface through close engagement with the selected studies. Given the exploratory and framework-building purpose of this review, coding was conducted by one author and iteratively discussed with the lead author throughout the analytical process. Emerging codes and category assignments were reviewed jointly in regular sessions until consensus

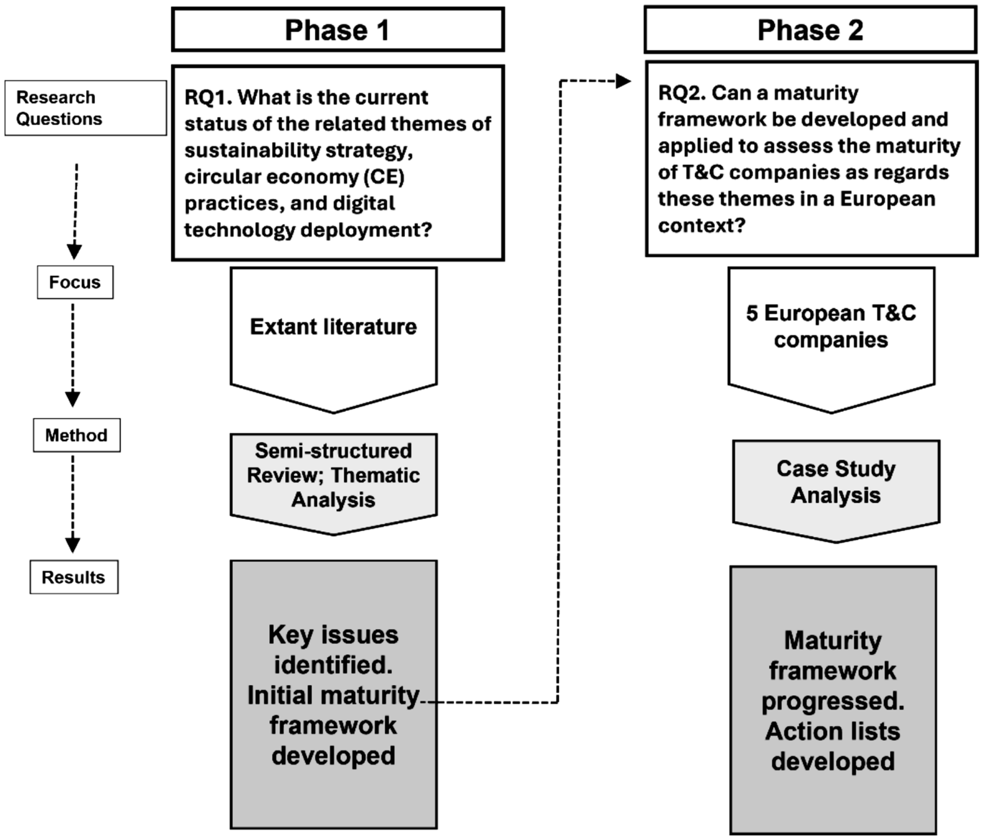

FIGURE 1
The two-phase research process.

TABLE 1 Inclusion and exclusion criteria.

Criterion	Inclusion	Exclusion
Thematic scope	Addresses ≥ 2 of the 3 core themes: sustainability strategies, CE practices, digital technology deployment	Addresses only one theme in isolation, with no substantive connection to the others
Organisational context	Situated at the organisational, business, or industry level	Exclusively macro-level policy analysis or consumer-behaviour focus without organisational dimension
Geographic context	Primarily industrialised country setting	Primarily developing or emerging country context (explicitly excluded via search string)
Implementation relevance	Addresses strategies, practices, drivers, barriers, or implementation of the core themes	Purely conceptual or theoretical, with no implementation or empirical relevance
Document type	Peer-reviewed journal article or review article	Conference papers, book chapters, grey literature, dissertations
Language	English	All other languages

was reached, ensuring analytical consistency and interpretive rigour across the coding framework.

The thematic analysis informed the development of an outline conceptual framework upon which the initial maturity model was based. Jabareen (2009) defines a conceptual framework as "a network, or a plane, of linked concepts that together provide a comprehensive understanding of a phenomenon" (p. 51), and this can play a central role in organising and explaining complex phenomena such as those studied here. Conceptual frameworks do not just describe reality but actively structure how it is interpreted. This is particularly important in interdisciplinary domains such as the CE and dgitalisation, where organisational, technological and regulatory dimensions intersect (Clark and Wallace, 2015). Conceptual frameworks also enhance transparency and rigour, by making explicit the relationships that underpin analysis (Ravitch and Riggan, 2017). Here, this provided the key concepts for the development of the initial maturity framework. Maturity frameworks are widely used as conceptual tools to describe evolutionary stages of organisational capabilities that help companies in systematically assessing and improving organisational practices, processes and technologies, typically defining sequential stages of development that allow organisations to assess their current position and identify pathways for advancement (Poeppelbuss et al., 2011).

The analysis began with familiarisation. The sources were read repeatedly and initial observations, recurring issues, and notable differences across literature sources were recorded. The next stage involved coding the material. Coding was primarily inductive, allowing categories to emerge from the data, while also being informed by the research objectives and sensitising concepts derived from the conceptual framework. This ensured that the analysis remained both empirically grounded and aligned with the purpose of the study (Saunders et al., 2023). The third stage involved developing the initial maturity framework by reviewing, refining, and grouping codes into higher-order categories. These categories were then applied systematically across all relevant sources, and, in a final interpretive stage, broader patterns, barriers, and enabling factors shaping the focal organisational processes were identified. These insights informed the refinement of the initial framework, providing a coherent method for linking qualitative evidence to interpretation and framework development.

2.2 Phase 2: Case study

In Phase 2 of the study, the initial maturity framework for the transition to sustainability, the CE and digitalisation in the T&C industry, developed in Phase 1, was empirically examined through five case study companies from five European countries. The aim of this phase was to apply the framework and assess its practicality based on the insights gained from the five cases. Case studies are widely recognised as a suitable research strategy for investigating complex organisational phenomena within their real-life context and they enable researchers to explore how emerging concepts are applied and operationalised in practice (Eisenhardt, 1989; Yin, 2018). Case study research typically relies on multiple sources of evidence in order to gain in-depth insights into complex organisational phenomena (Eisenhardt, 1989). Original data were collected through a combination of document analysis and semi-structured expert interviews, as detailed in Table 2.

The case study companies were selected through purposive sampling in order to ensure the inclusion of organisations actively engaged in sustainability and CE initiatives, thereby enabling the exploration of diverse organisational approaches and practices across the industry. Five companies from five different countries were selected for the case studies in order to capture diverse organisational contexts within the European T&C industry. The sample

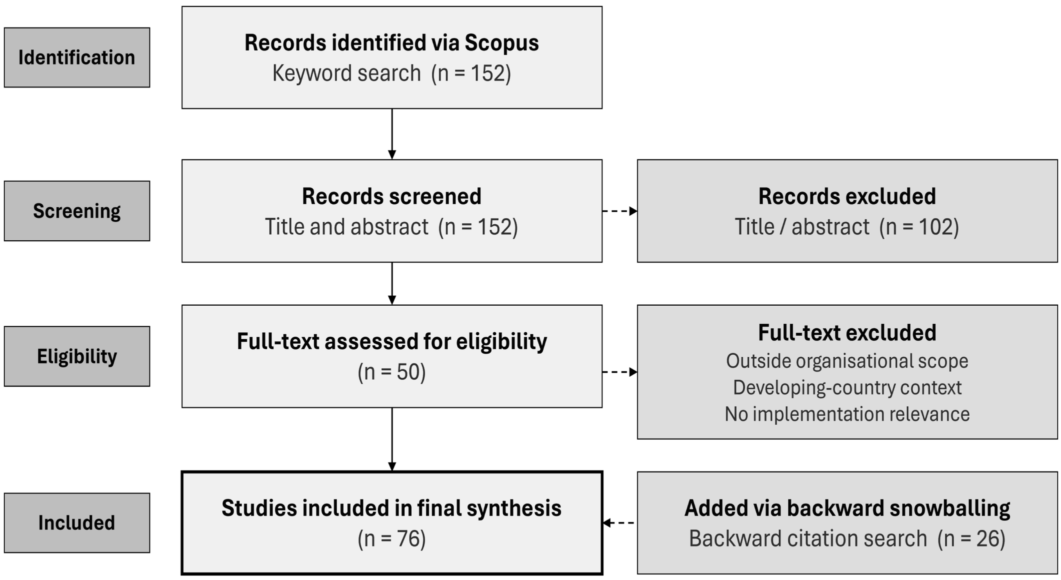

FIGURE 2
Procedure of literature screening and selection.

TABLE 2 Research methods used in the 5 case studies.

Research method/ Case study	Document analysis	Interviews	Other
C1	Company website and sustainability reports	Interview with company CEO	
C2	Company website and publicly available reports	Interview with company CEO	
C3	secondary document analysis: company's website, press interviews (newspapers and magazines), and published results of R&D projects	Interview with the Production Manager	Review of relevant social media channels Direct observation at company
C4	Company website, company reports, other publicly available reports.		Review of social media posts
C5	website and sustainability reports	Interviews with the Operations and Sustainability Director	Site visit to company production units.

includes firms from Italy and Germany, both of which represent leading countries in the European T&C sector in terms of turnover. To reflect additional industry contexts, one company was selected from Portugal, which occupies a mid-range position within the European T&C industry, and one from Bulgaria, representing a country positioned at the lower end of the sector in terms of revenue. In addition, a case from Türkiye was included, as the country hosts the second-largest number of T&C companies in Europe after Italy. This sample enabled the exploration of organisational practices across different economic and structural conditions within the European T&C industry. Table 3 provides an overview of the size of the T&C industry in the respective case study countries, indicating turnover, number of firms, and number of employees.

A brief profile of the five case study companies is presented below. Table 4 provides an overview of these companies, including their size in terms of turnover, number of employees, and industry sub-sector.

2.2.1 Case study C1 (Italy)

Company C1, founded in 2017 and headquartered in Prato, is an emerging apparel venture that designs and produces garments using regenerated materials sourced from post-consumer and industrial textile waste. The company manufactures sweaters, accessories, and home textiles made from recycled cashmere, silk, linen, viscose, denim, and cotton fibers. In 2023, it produced over 24,000 garments composed of approximately 95% recycled fibers, distributed through both online channels and two stores (in Prato and Milan) and a temporary store in Rome. The company's production system relies on local suppliers, with 87% located within 30 kilometers of its headquarters. It uses a pre-sale mechanism for capacity planning and maintains a no-discount policy to protect product value.

C1's organisational model is tightly connected to the Prato textile district, drawing on its historical craftsmanship and technical expertise. The company emphasises transparency and collaboration with its production partners, publicly crediting artisans for their work and maintaining open visibility into each stage of the manufacturing process. This structure reinforces a localised production identity rooted in craftsmanship, regional integration, and controlled business growth within the contemporary fashion sector.

TABLE 3 T&C industry (incl. NACE 13, 14, 15) parameters in countries featured in the research as of 2024.

Country	Turnover (€ million)	Number of companies	Number of employees
Italy	89,322	48,307	458,425
Germany	28,045	8,050	139,250
Portugal	10,780	14,486	158,977
Bulgaria	1,863	4,264	67,196
Türkiye	51,869[1]	100,518	1,165,759

Source: Eurostat (2024) and Turkish Statistical Institute (2024).
[1]The currency conversion was based on an exchange rate of 1 TRY to 0.019 EUR.

2.2.2 Case study C2 (Germany)

C2 is a family-owned textile finishing company founded in 1984 and headquartered in Upper Franconia, Bavaria. With a workforce of 23 employees, the firm operates as a fully integrated textile printing and finishing enterprise within a B2B business model, serving fashion and textile brands. Originally established as a trading company, C2 subsequently transitioned into manufacturing, initially investing in rotary screen-printing technologies. In 2013, rotary printing was completely phased out and replaced by digital printing technologies. As a result, C2 today positions itself as the only German textile printing company operating exclusively with digital production systems.

The company specialises in digitally printed fabrics for womenswear, menswear and other textile applications. Production is carried out exclusively on a made-to-order basis. Over its forty-year history, C2's development has been characterised by continuous investment in process innovation, resource efficiency, and digitalisation, reflecting a long-standing commitment to sustainable development and operational optimisation.

2.2.3 Case study C3 (Portugal)

Company C3, founded in 1993 and headquartered in Covilhã, the main wool city of Portugal, produces premium textiles fabrics with recycled materials and wool using regenerated mate-rials sourced from post-consumer and industrial textile waste. The company has certification from the Responsible Wool Standard (RWS), the Global Re-cycled Standard (GRS) and OEKO TEX. Since 2023, the company has invested in innovation projects to develop best quality of yarns with recycled wool. More diverse products include different combinations of recycled wool and natural wool (without dying process), and the company uses more than 600 tonnes of wool per year for carded production. With the increased demand for materials made from recycled fibres by premium European brands (primarily based in Nordic countries, France, and Germany), the company has invested not only in innovative products but also in the consumption of domestically sourced raw materials. The company has also increased efficiencies in its production processes, through digitalisation, a new

TABLE 4 Overview of country location, turnover, number of employees and industry sub-sector for the case study companies included in the research.

Company code	Country location	Turnover (€ million)	Number of employees	Industry sub-sector
C1	Italy	3.3	25	Fashion brand
C2	Germany	No data	23	Textile printing and finishing
C3	Portugal	25.2	200	Textile wool and blend fabrics
C4	Bulgaria	1.2	41	Clothing production, Fashion brand
C5	Türkiye	18	250	Denim garment manufacturer

wastewater treatment plant with 70% recovery of liquid effluent, and waste reduction.

2.2.4 Case study C4 (Bulgaria)

The company was founded in 1997 and has its headquarters, production base and company store in the city of Smolyan, Bulgaria. It is one of the market leaders in the Bulgarian textile industry. The company originally manufactured women's clothing but subsequently expanded its activities by offering uniforms for bank employees, restaurants and hotels, and for schools, as well as company uniforms in various sectors of the economy. Over the past 10 years, the company has been selling its textile clothing on international markets, and their textile goods are of proven high quality. The company currently employs 41 staff and produces 36,000 textile garments on an annual basis.

2.2.5 Case study C5 (Türkiye)

Company C5 is a denim garment producer that specialises in sustainable and customised denim finishing techniques. The company was established and headquartered in Istanbul in 1985, but production is centred in its 11,000 m^2 facility in Çorlu, Tekirdağ. C5 has an annual turnover of around 18 m. euros and employed 250 workers in 2025. The company adopts sustainable production techniques, especially in the washing and finishing phases of denim garment production. C5 engages circularity-oriented practices by using material and chemical substitution, and appropriate waste and resource management. Moreover, the company has a demand-aligned production capacity rather than volume driven manufacturing. C5 operates with a monthly production capacity of around 150,000 denim garments, with the flexibility to scale output in line with on-demand manufacturing models. The company integrates advanced dry processing technologies and renewable energy sourcing as well as globally recognized sustainability certification into its manufacturing system.

The five case studies were conducted by different authors who had prior relationships with, and knowledge of, the companies studied, and thus there was a degree of subjectivity in assessment and interpretation. To counter this, the lead author acted as an overseer of all five cases and this produced a recalibration of some of the cases against the maturity framework following the initial assessments by individual authors.

3 Results

3.1 Introduction

This section presents the results of the study and is structured in three parts. Following this brief introduction, Section 3.2 reports the findings from the literature review and addresses RQ1. Building on these findings, an initial maturity framework is put forward that serves as an analytical framework for examining organisational practices related to sustainability, the CE, and digital technologies. Section 3.3 then presents the results of the case study analysis, in which the proposed maturity framework is empirically applied and assessed based on insights from the five case study companies.

3.2 Addressing RQ1: What is the current status of the related themes of sustainability strategies, CE practices, and digital technology deployment?

3.2.1 Sustainability strategies

Sustainability has gained increasing importance in corporate contexts, with many firms recognising the need to address environmental and social challenges. Sustainability is commonly defined through the combination and interplay of three dimensions: economic, environmental, and social (Amini and Bienstock, 2014; Dyllick and Hockerts, 2002; Pazienza et al., 2022). Accordingly, a sustainable company is one that is economically successful in terms of financial performance while minimising the negative impacts of its business activities on environmental and social systems. Elkington (1998) conceptualised this as the Tripple Bottom Line. In this view, sustainability is to be embedded in corporate strategy and business models (Bocken et al., 2014; Geissdoerfer, Vladimirova et al., 2018; Schaltegger et al., 2016), products (Hallstedt et al., 2010; Hynds et al., 2014; Maxwell and Van Der Vorst, 2003) as well as processes and supply chains (Eccles et al., 2014; Seuring et al., 2022; Seuring and Müller, 2008). The United Nations Sustainable Development Goals (SDGs) provide companies with a strategic framework that guides sustainability strategies, innovation and business model development, as well as operational decision-making (Agrawal et al., 2022; Berrone et al., 2023; Rosati et al., 2023).

The external policy environment increasingly shapes how companies develop sustainability strategies. While regulatory compliance creates a baseline for corporate action, incentive-based instruments, such as tax relief for circular business model investments and extended producer responsibility schemes with fee modulation, tend to elicit more proactive organisational responses than punitive approaches alone, as they reduce the financial barriers that particularly constrain SMEs in capital-intensive transitions (Munonye, 2025; Svatikova et al., 2025).

3.2.2 Circular economy practices

The CE has emerged as a key concept for operationalising corporate sustainability, aiming to decouple economic growth from resource consumption (Geissdoerfer et al., 2017; Kirchherr et al., 2023). It promotes the retention of material value through strategies such as reducing, reusing, repairing, remanufacturing, and recycling (Ghisellini et al., 2016; Kirchherr et al., 2017; Reike et al., 2018).

Four main themes characterise the current state of CE adoption. Firstly, product design and material innovation are increasingly recognised as central levers for advancing circularity. Early circular design approaches focused primarily on preserving product integrity and enabling multiple use cycles through durability, repairability, and upgradability, while emphasising full recyclability at end-of-life to retain material value within the economic (Bocken et al., 2016; Den Hollander et al., 2017). More recent contributions adopt a broader perspective by integrating CE economy principles with sustainability considerations, combining resource preservation with the minimisation of environmental impacts across the product lifecycle (Aguiar and Jugend, 2022; Sassanelli et al., 2020). This integrated approach, referred to as sustainable circular product design, is increasingly viewed as essential for aligning product development with CE objectives while simultaneously addressing environmental and economic performance requirements. Literature focusing specifically on the

T&C industry suggests that companies increasingly consider circular design principles, such as using recyclable or natural, recycled or mono-materials, designing for durability, and reducing material complexity (Abdelmeguid et al., 2024; Brydges et al., 2023; De Aguiar Hugo et al., 2021; Dissanayake and Weerasinghe, 2022).

Secondly, business model innovation is widely recognised as a key mechanism for advancing sustainability and CE transitions. Business models define how organisations create, deliver, and capture value, and therefore play a critical role in commercialising sustainable products and technologies (Magretta, 2002; Teece, 2007). Sustainable business models extend conventional approaches by integrating environmental and social considerations into value creation and delivery, while generating long-term economic value for a broader set of stakeholders (Bocken et al., 2014; Geissdoerfer, Vladimirova et al., 2018; Schaltegger et al., 2016). In parallel, circular business models aim to narrow, slow and close resource flows through strategies such as product-service systems, lifecycle extension, and resource recovery (Bocken et al., 2016; Geissdoerfer et al., 2020; Lüdeke–Freund et al., 2019; Pieroni et al., 2019). Despite their growing prominence in the literature, empirical evidence suggests that companies often prioritise incremental adaptations to existing business models rather than implementing more transformative circular innovations (Kirchherr and Hartley, 2025; Stumpf et al., 2021), highlighting the ongoing challenges associated with business model transformation.

Third, supply chain and production processes are widely recognised as critical enablers of sustainability and CE transitions. Since companies typically operate within complex inter-organisational networks, implementing circular products and business models requires coordinated practices across procurement, production, and distribution activities (Amir et al., 2022; Geissdoerfer, Morioka et al., 2018; Zhang et al., 2021). In this context, sustainable and circular supply chain management extends conventional time- and cost-efficiency-oriented supply chain logic by integrating environmental and social objectives with strategies to narrow, slow, and close resource flows across forward and reverse networks (Batista et al., 2018; Farooque et al., 2019; Seuring et al., 2022; Seuring and Müller, 2008). This integrated perspective highlights the importance of collaboration across supply chain partners, alignment of internal production processes, and the use of digital technologies to enhance traceability and lifecycle management (Geissdoerfer, Morioka et al., 2018; Montag, 2023; Wu et al., 2025). Literature focusing specifically on the T&C industry indicates that the transformation of supply chain and production processes is particularly challenging due to highly fragmented, decentralised, and globally dispersed supply chains. Existing studies highlight persistent deficits in data sharing, traceability, and cross-organisational coordination, which hinder the development of circular materials, products, and processes (Abdelmeguid et al., 2022; Colucci and Vecchi, 2021; Saccani et al., 2023). To address these barriers, research increasingly emphasises the role of digital technologies, such as blockchain and specialised traceability systems, alongside stronger stakeholder integration to establish closed-loop supply chains (De Felice et al., 2025; Dissanayake and Weerasinghe, 2022; Gazzola et al., 2025).

3.2.3 Digital technology deployment

Digital technologies are increasingly recognised as key enablers of sustainability and CE initiatives, as they support data capture, analysis, and communication across complex organisational and supply chain contexts (Bressanelli et al., 2022; Bühler et al., 2025; Cagno et al., 2021; Kristoffersen et al., 2020; Wynn and Jones, 2022). Nine categories of digital technologies can be identified as particularly relevant to sustainability and CE transitions in the T&C industry (Wiegand and Wynn, 2024). Table 5 provides a structured overview of these technologies, their potential contributions to circular and sustainable practices, and their respective fields of action.

A nuanced perspective on these enabling effects is warranted. A recent report by the European Environment Agency (Manshoven et al., 2025) shows that digital technologies in the European T&C industry are predominantly adopted for efficiency and cost reduction rather than for sustainability or circularity objectives, and that implementation remains limited, particularly among SMEs. Moreover, efficiency gains carry the risk of rebound effects and the environmental footprint of digital infrastructure itself, including energy and water consumption associated with data centres and AI applications. These findings suggest that the relationship between digitalisation and CE advancement is contingent on deliberate strategic alignment rather than there being an automatic connection between the two concepts and related in-company initiatives.

In this context, the Digital Product Passport (DPP) has emerged as a strategically significant instrument for operationalising the connection between digital technology deployment and CE objectives. Defined as a centralised digital data system that aggregates key product-related information across the entire lifecycle, encompassing material composition, environmental data, supply chain provenance, and end-of-life instructions – the DPP is designed to enhance traceability, supply chain transparency, and regulatory compliance (Psarommatis and May, 2024; Zhang and Seuring, 2024). As a key regulatory element of the EU's Circular Economy Action Plan and the Ecodesign for Sustainable Products Regulation (ESPR), its implementation is expected to take effect from 2027 (European Commission, 2024). For the T&C industry specifically, the DPP holds particular transformative potential: by consolidating disparate data into a unified system accessible to companies, suppliers, regulators, and consumers, it addresses the persistent deficits in traceability and inter-organisational data sharing that characterise the sector (Carvalho et al., 2025).

3.2.4 Initial maturity framework

From the above assessment of the relevant literature, an initial maturity framework was developed, based on three change dimension: Organisation, Product and Process. Additionally, digital technology deployment is recognised as a key cross-cutting enabler of sustainability and CE initiatives, rather than a parallel dimension. Prior research suggests that these developments occur incrementally (Kirchherr and Hartley, 2025), with companies moving from limited awareness and isolated initiatives toward more integrated and systemic approaches. In addition, particularly in the T&C industry recent empirical studies (e.g., Wynn and Wiegand, 2025) indicate considerable heterogeneity across firms in the implementation of sustainability strategies, circular practices, and digitalisation.

To ensure construct clarity and prevent conceptual overlap between dimensions, each of the three substantive dimensions is operationalised according to a distinct analytical domain. This structure draws on Geissdoerfer et al. (2018), who explicitly distinguish between the business model logic through which circular value is created and captured, and the supply chain and operational processes through which that logic is executed – a distinction that directly maps onto the boundary between the Organisation and Process dimensions proposed here. Accordingly, the Organisation dimension captures strategic intent and value architecture, encompassing corporate

TABLE 5 Digital technologies and their potential role for leveraging the transition to sustainability and the CE. Adapted from Wiegand and Wynn (2024), licensed under CC BY 4.0.

DT	Potential role for advancing circularity in the T&C Industry	References
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 lifecycle to optimise process and resource efficiency and supporting new service-oriented business models • Can enhance traceability and identification of products or components, thereby enabling and improving sustainable and circular business models as well as automation and optimisation of collection, sorting, and recycling processes and providing data for a DPP	Bressanelli et al. (2022); Chauhan et al. (2022); De Felice et al. (2025); Dissanayake and Weerasinghe (2022); Franco (2017); Hassan et al. (2024); Lopes de Sousa Jabbour et al. (2018); Perotti et al. (2024); Saccani et al. (2023)
Social media	• Provides new avenues to reach consumers in order to inform, and educate them about products, services, innovations and developments, to influence consumer behaviour regarding circular activities and involve them into co-creation processes	Abdelmeguid et al. (2024); Antikainen et al. (2018); Chauhan et al. (2022); Colucci and Vecchi (2021)
Mobile applications	• Offers diverse organisational opportunities to reduce resource consumption and enhance operational efficiency through monitoring & controlling applications, reducing employee travel activities or replacing paper-based processes by digital ones • Provide the opportunity to extend product lifecycles, for instance, through reselling platforms or to support new business models like rental, leasing or repairing	Hassan et al. (2024); Huynh (2022); Wynn and Jones (2022)
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-related KPIs. • Enables 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 integration and dissemination into management systems as well as supporting strategic and operational decision-making.	Alves et al. (2022); Han et al. (2023); Hassan et al. (2024); Kristoffersen et al. (2020); Laskurain-Iturbe et al. (2021); Lopes De Sousa Jabbour et al. (2022)
Cloud computing	• Provides the basis for networking systems and thereby ensures greater data and information availability and transparency, which enables data-driven decision-making and new business model development • Enables platforms for secure data storage and exchange between supply chain partners and other stakeholders and can contribute to reduced energy consumption and the reduction of physical goods in various locations	Bressanelli et al. (2022); Cagno et al. (2021); Gazzola et al. (2025); Neri et al. (2023)
Blockchain (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 • Offers various functions such as traceability of product and material data, recording and secure and trustworthy exchange of data between parties, and, within Smart Contract applications, efficient support for procurement management	Abbate et al. (2023); Alves et al. (2022); Hassan et al. (2024); Huynh (2022); Rusch et al. (2023); Upadhyay et al. (2021)
Process automation and robotics	• Ability of machines and systems to operate autonomously, to interact with each other and to cooperate with humans, e.g., in production or logistics processes • Could support circular strategies by leveraging AI systems to undertake autonomous waste sorting or disassembly processes.	Cagno et al. (2021); Chauhan et al. (2022); De Felice et al. (2025); Dissanayake and Weerasinghe (2022); Hassan et al. (2024); Lopes De Sousa Jabbour et al. (2022)
Artificial intelligence (AI)	• Is based on the development of machines and systems applying machine learning techniques and processing unstructured data such as natural language or images • Algorithms are used in a sustainability/CE context by helping with prediction, decision-making, resource optimisation and pattern recognition	Chauhan et al. (2022); De Felice et al. (2025); Dissanayake and Weerasinghe (2022); Hassan et al. (2024); Laskurain-Iturbe et al. (2021); Neri et al. (2024); Schöggl et al. (2023)
Digital fabrication (DF)	• Refers to processes where computer-controlled modelling, simulation and control tools are used to manufacture physical objects directly from design data • Often supported by computer-aided design (CAD/CAM) tools, which can be directly transferred to manufacturing machines and systems such as 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 • 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 and providing stakeholders with information on ingredients, manufacturing, disassembly, or repair requirements throughout the product lifecycle	Bressanelli et al. (2022); Chauhan et al. (2022); Colucci and Vecchi (2021); Dissanayake and Weerasinghe (2022); Hassan et al. (2024); Huynh (2022); Lopes De Sousa Jabbour et al. (2022); Neri et al. (2023); Schöggl et al. (2023)

strategy, governance, and business model design; the Process dimension captures operational execution and inter-organisational coordination, including production processes, resource flows, and supply chain partnerships such as reverse logistics and collaborative CE projects. The Product dimension captures material design and lifecycle management decisions.

These three domains are analytically distinct but empirically interdependent: a circular business model (Organisation) typically requires corresponding changes in product design (Product) and in operational processes and supply chain relationships (Process). The dimensions are therefore not independent causal variables but complementary lenses through which the same organisational transition is assessed from different angles (Figure 3).

The framework deliberately focuses on environmental and CE issues; social sustainability aspects, such as labour rights, working conditions, and living wages, fall outside the scope of the present study and are identified as a direction for future research. Furthermore, a framework's maturity levels must be understood against the backdrop of the EU textile system's current circular reality. Köhler et al. (2021) quantify that only 38% of textiles placed on the market are separately collected across reporting countries with stark variations between the countries and sorting is still predominantly manual. These system-level baselines provide the empirical context against which organisational maturity levels should be calibrated: for example, a company classified at "advanced" process maturity is nevertheless operating within a system where the upstream and downstream infrastructure for closed-loop recycling is likely to be severely restricted.

Drawing on these insights, the proposed initial maturity framework conceptualises four stages of development - static, basic, intermediate, and advanced - across the three key organisational dimensions noted above: Organisation, Product, and Process, complemented by digital technology deployment operationalised as a cross-cutting enabling layer. In early stages, organisations focus primarily on regulatory compliance and isolated efficiency improvements. More advanced stages are characterised by strategic alignment of business models with sustainability and CE principles (Organisation), circular design and lifecycle management of products (Product), and the systemic alignment of supply chain processes with CE objectives (Process), with digital technologies enabling transparency, traceability, and circular value creation across all three.

3.3 Addressing RQ2: Can a maturity framework be developed and applied to assess the maturity of T&C companies as regards these themes in a European context?

This section assesses the five companies from different European countries against the initial maturity model derived from the literature. Data is garnered from a range of sources by the respective authors (see Table 1) and presented as a descriptive narrative.

3.3.1 Case study findings

3.3.1.1 Case Study C1 (by Filippo Visintin and Guilherme Horner Bussolo)

C1, a Prato-based SME founded in 2017, operates as a native-circular company that designs and produces garments and accessories entirely from regenerated materials. Its production model is deeply rooted in the local textile ecosystem, relying on a tightly connected network of suppliers performing spinning, weaving, packaging, and labelling within short geographical proximity. This district-based configuration enables continuous coordination, high-quality standards, and minimized environmental and logistical impacts.

The company displays advanced maturity in the *organisational dimension* as sustainability and circular principles are fully institutionalised rather than add-on initiatives. The company maintains a formal code of conduct, ethical guidelines, and sustainability policy that define behavioural expectations for all partners. These policies are publicly available and aligned with recognised international standards, such as the ILO (International Labour Organization) principles and the Common Framework for Responsible Purchasing Practices. Moreover, sustainability is not delegated to a single department but pervades governance, purchasing, and marketing. Supplier relationships are structured through stable contracts and mutual visibility. This alignment between the company's stated values and operational practices demonstrates a high level of organisational integration, where sustainability principles are embedded in day-to-day management rather than treated as separate initiatives.

As regards the *product dimension*, C1 meets many of the characteristics of the advanced level through deliberate design strategies that prioritise product longevity, multiple life cycles, and regenerative recycling. Building on its use of regenerated materials, the company designs garments with durable constructions, timeless aesthetics, and high-quality yarns that maintain integrity over repeated uses. C1 also provides extensive transparency and traceability of product-related environmental and social impacts. Through its digital platform, each product includes detailed information on fibre composition, production origin, and certified environmental indicators based on Life Cycle Assessment (LCA) data. Customers can view quantified metrics on resource savings and emission reductions, while the disclosure of artisan and workshop information adds visibility to the social dimension of production. In addition, the company operates structured repair and take-back programmes that close the product loop in practice. Through its online Used Garments Take-Back Service, customers can return worn items either by post or at partner collection points. The garments are then sorted by fiber type, such as wool, cashmere, cotton, or denim and directed to specialised recycling facilities within the Prato district. Materials suitable for regeneration are mechanically processed into new yarns, which are subsequently reintroduced into the company's production cycle. This process not only diverts textiles from waste but also ensures material continuity between past and future collections, translating the company's circular design principles into a measurable recovery system.

The free repair service extends product lifespan by restoring worn items, while the used-garment collection initiative enables recovered materials to be reprocessed into new fibres. These services embed repair and recycling into the product system rather than treating them as add-on activities. Collectively, these mechanisms illustrate that C1's product strategy aligns with the defining traits of the advanced level, durability by design, verified transparency, and active material regeneration throughout the product life cycle.

In terms of the *process dimension*, C1 exhibits advanced maturity through its deliberate control of production volumes and alignment with actual market demand. Instead of following conventional fast-fashion dynamics, the company coordinates production through pre-sale mechanisms that enable capacity planning based on verified

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Change dimension/ maturity level	Definition		
	Organisation	**Product**	**Process**
Static	Lack of overarching awareness of sustainability and CE principles. Sustainability and CE are not integrated into the strategy or structure. No targeted development of sustainability and CE skills in the organisation. The business model remains predominantly linear. Efforts to reduce resource consumption or waste/emission generation are driven largely by cost-saving and marketing motives rather than genuine environmental concerns.	Materials and products are not designed with sustainability or circularity in mind. No transparency or traceability of product-related environmental and social impacts. No product or material-related repair or recycling activities.	The focus is primarily on compliance with environmental and social regulations, with no significant efforts to reduce energy, water, materials or chemicals consumption within internal and/or supply chain processes. No CE-related cooperation or collaboration with external partners.
Digital technology deployment	Digitalisation occurs on an *ad hoc* basis, without strategic objectives. They are used internally within the company or individual processes. There is no overarching digital strategy. Technologies deployed would typically be the early digital techs – social media and mobile apps, with limited use of the Cloud to host some of the company's systems		
Basic	Emerging awareness of sustainability and CE principles. Simple sustainability and CE activities are initiated sporadically and without a strategic framework e.g., certain SDGs are pursued, but without linking to corporate objectives. Organisational unit for sustainability/CE being developed with the relevant knowledge and skills. Efforts to reduce emissions and waste are evident, but they operate within the confines of a linear business model. Data and fact-based communication of sustainability and CE activities to strengthen the company's image.	Pilot projects to explore alternative products or services. But activities are limited and often isolated e.g., use of more sustainable materials and packaging or sustainability certification for individual materials, products or product lines. The emphasis remains on incremental improvements rather than a shift towards full circularity.	The reduction of material, energy, water and chemicals use in internal processes (e.g., through ISO management certifications) and the minimisation of scope 1 and 2 emissions are being pursued but no CE-related cooperation or collaboration with external partners.
Digital technology deployment	Digital technologies are deployed function by function for process improvements and efficiency gains. Change is incremental and the business model is not radically altered. IoT is typically used on the shop floor and elsewhere for data capture, and analytics applications are used for data analysis and reporting.		
Intermediate	Full awareness of sustainability and CE principles with a strategic alignment and specific objectives based on the SDGs, although implementation is still in its infancy. Exploratory monitoring of sustainability and CE indicators and derivation of measures. Organisational unit for Sustainability/CE established, building knowledge and skills across the organisation. Efforts to reduce emissions and waste are evident, but they operate within the confines of a linear business model. Data and fact-based public communication of sustainability and CE activities to strengthen the company's image.	Materials and products are designed with a focus on product and material durability, upgradability, and eco-design. Products, materials and services are developed with the intent of closing, slowing, or regenerating resource loops. Product and materials traceability is implemented and transparent life cycle assessments or certifications for all materials, products and services are provided e.g., GRS, Cradle2Cradle, GOTS, Green Bottom.	The reduction of material, energy, water and chemicals consumption in supply chain processes and the minimisation of scope 1, 2 and 3 emissions are actively pursued. Joint CE-related projects and innovations with external partners e.g., for reverse logistics, recycling or repair/ reuse activities.
Digital technology deployment	The use of digital technologies is aligned with overall business strategy goals. Digitalisation is addressed at corporate level either as part of the IT strategy or as a separate digital strategy. Integration of digital technologies with existing information systems is prioritised. Data quality and cybersecurity are recognised as key corporate issues allied to digitalisation. AI, Robotics, digital twin, digital fabrication may all be used in various process areas.		
Advanced	Sustainability and CE principles are fully embedded in corporate strategy, governance, and business model design. Systematic monitoring of sustainability and CE indicators and derivation of measures. The business model is oriented towards value creation through maximising resource use and minimising waste e.g., through product-service-systems or sharing / renting models. Sustainability and CE knowledge and skills are rooted throughout the company and are constantly being developed strategically through training and education for both internal and external partners. Data- and fact-based, transparent public communication of sustainability and CE activities, as well as targeted information and involvement of stakeholders (e.g., consumers) on life cycle extension and recovery.	Materials and products are fully designed for longevity, multiple uses and regenerative recycling. Full transparency and traceability of product-related environmental and social impacts through LCA or certifications for all materials, products and services are provided. Product or material-related repair, refurbishment or remanufacture activities.	All processes along the value chain are aligned with CE principles and focus on minimising resources and waste. Production on demand is being pursued. Optimisation and localisation of value and logistics processes in cooperation with all relevant partners, with the aim of closed material cycles. Joint CE-related innovation projects with supply chain and value chain partners, aimed at closing material loops through integrated reverse logistics, recycling, and remanufacturing processes.
Digital technology deployment	Digital technologies are seen as a key lever to enable significant business change, possibly involving transitioning to a new business model. Digital technologies may now be deployed within the company's products and services, as well as supporting internal processes. Digitalisation follows a cross-company and cross-process approach and supports inter-company transactions and communication across the extended supply chain. Advanced technology deployment, including blockchain and digital fabrication, allows participation in digital platforms and ecosystems. The Digital Product Passport (DPP) is implemented as a strategic instrument for product lifecycle transparency and inter-organisational data sharing. Digitalisation is also actively governed with respect to its own environmental footprint; the energy and water intensity of digital infrastructure is monitored, and efficiency gains are systematically directed towards circular objectives rather than increased production volumes.		

FIGURE 3
The initial maturity model.

orders. This system, combined with a no-discount policy and the rejection of mass-marketing campaigns, allows for stable and predictable production cycles, reduces waste, and preserves value throughout the supply chain. The operational structure supports a steady workload for artisans, balances supply and demand, and minimizes the environmental and financial risks associated with overproduction. Such process discipline reflects a high degree of integration between sustainability objectives and operational planning, consistent with the process-level criteria of the advanced maturity stage.

Digital technology supports and strengthens C1's circular model by improving transparency, traceability, and data management across its production and distribution systems. The company operates a well-developed e-commerce platform that serves as both a commercial interface and a communication channel for environmental information. Product-level data are linked to traceability tools that disclose material composition, origin, and certified environmental indicators, allowing customers to access evidence of environmental performance directly. C1 has also implemented a DPP system and is piloting blockchain-based applications to ensure data accuracy and regulatory readiness for forthcoming EU requirements such as the Ecodesign for Sustainable Products Regulation and EPR schemes. Despite not relying on heavy industrial automation, such as robotic manufacturing, C1 benefits from robust back-end digital process automation. In particular, the company leverages integrated systems to streamline data flows, automate order management, control inventory efficiently, and coordinate seamlessly across multiple sales channels. In addition, in collaboration with the Swedish startup Papertale, the company is also planning a blockchain traceability project to facilitate the tracking of garments' journeys, including how a donated piece is reused or recycled (Table 6).

However, unlike many firms transitioning from linear to circular models, digital technologies in C1 have not triggered a radical business-model shift. Rather, they serve to consolidate and scale an already circular business. As a native-circular enterprise, the firm uses technology as a mechanism for deepening its existing model, strengthening transparency, traceability, and communication rather than transforming its core business logic. Thanks to the Open Supply Hub platform, the company transparently displays a map of all its suppliers and sub-suppliers on its website, thereby promoting social responsibility across the supply chain. This distinction highlights an important nuance in interpreting the stage of digital maturity: for circular-born SMEs, digitalisation represents the evolution and integration of capabilities rather than a transformation of purpose. In this sense, C1 embodies a form of digital maturity characterised by capability intensification, ecosystem integration, and preparedness for data-driven collaboration, rather than by disruptive technological change. However, whilst C1 is technologically well advanced, its use of digital technologies is relatively limited, and C1 is most appropriately classified as being at intermediate level.

C1's *next developmental steps* should focus on achieving stronger integration across organisational, product, process, and digital dimensions. While the company already operates at an advanced level of circular and sustainability performance, its digital tools currently serve mainly as instruments of transparency and toward regulatory readiness. Moving forward, these tools could be strategically leveraged to support continuous learning and decision-making. The real opportunity for C1 lies not in simplifying data entry but in enhancing supplier participation and data interoperability ensuring that all partners can feed accurate, standardised data into the DPP ecosystem in line with emerging EU interoperability standards under the ESPR and EPR frameworks.

Strengthening this capability would allow the company to maintain the inclusiveness of its local supply network while ensuring full compliance with future traceability requirements. Targeted support for smaller workshops, such as technical onboarding and digital training, would help harmonise data quality without imposing disproportionate administrative burdens. Extending the DPP infrastructure to capture repair and reuse histories would also allow the company to move from static transparency toward dynamic lifecycle monitoring, generating real-time insights into durability, recovery rates, and material recirculation. Establishing a small cross-functional coordination team to align digital, sustainability, and operational functions would ensure that technological developments directly contribute to circular

TABLE 6 Overview of C1's deployment status across the digital technologies.

DT	Application at C1
IoT	None
Social media	C1 produces and shares a range of relevant, consistent, and valuable content, such as text, images, videos, and blog posts, focused on sustainable fashion to engage and connect with its customers. This content is distributed through the company's website and across multiple social media platforms.
Mobile applications	The company has not developed a dedicated mobile app; however, its website is designed to be easily accessible and fully usable on mobile devices.
Analytics/big data	ERP implemented to unify its operational processes and provide the basis for analytics applications in due course. Early adopter of the Digital Product Passport in the fashion industry, with more than 50% of its products already covered.
Cloud computing	Not used.
Blockchain	The company is experimenting with blockchain-based traceability projects, particularly for managing garments collected through its take-back programs
Process automation	Despite limited industrial automation, C1 relies on robust digital tools to automate data flows, order management, inventory control, and multi-channel coordination.
AI	Not used.
Digital fabrication	Not used.

performance and regulatory readiness. Through these actions, C1 would strengthen the coherence of its advanced maturity across organisation, product, and process dimensions, and could further exploit the benefits of full digitalisation as the integrative backbone of its circular management system.

3.3.1.2 Case study C2 (by Tina Wiegand and Martin Wynn)

C2 is a family-owned, fully integrated textile finishing company headquartered in Upper Franconia, Bavaria, employing 23 staff and operating exclusively in a business-to-business (B2B) context for fashion and textile brands. Having transitioned from rotary screen printing to fully digital production in 2013, the company combines long-standing textile expertise with a pronounced orientation toward sustainability, technological innovation and operational efficiency.

In the *organisational dimension*, sustainability considerations are deeply embedded in management decision-making processes. Environmental and resource protection are described as long-standing corporate objectives that derive primarily from economic rationality and technological problem-solving capabilities rather than from regulatory pressure. This orientation is reflected in the absence of a formally articulated sustainability strategy, ESG reporting structures, or a designated sustainability officer. There are no codified supplier guidelines, audit systems, or explicit references to the SDGs. Instead, both strategic and operational approaches are shaped by the normative values and sustainability mindset of the managing directors.

C2 is certified according to STANDARD 100 by OEKO-TEX® and uses GOTS-approved printing inks sourced from European suppliers. Investments in resource-efficient technologies, such as a proprietary closed-loop water recycling system and the strategic conversion of the entire production process to digital printing, demonstrate a proactive approach to environmental management. Strategic decisions are taken centrally by the management team but are embedded in a strong culture of innovation and employee involvement. Improvement proposals and engagement from staff of all departments are actively encouraged and financially rewarded, and regular training ensures continuous capability development.

Despite this pronounced sustainability orientation, CE principles are not systematically integrated into corporate strategy. The business model remains linear, as a Tier 1/2 B2B supplier without take-back schemes or service-based components, and there are no measurable sustainability targets, such as Scope 1–3 emission goals. At the *organisational level*, C2 can therefore be classified as basic: sustainability is strategically acknowledged and operationally implemented, yet circularity is neither fully institutionalised nor systematically measured.

As for the *product dimension*, C2 demonstrates several sustainability-related characteristics. The company primarily processes natural fibres such as viscose and cotton, complemented by selected recycled qualities. Most base fabrics are sourced from German suppliers, thereby reducing transport distances and associated emissions while enabling closer relationships and lower social and environmental supply chain risks. All fabrics and printing processes are OEKO-TEX certified, and inks comply with GOTS requirements. Product durability is enhanced through high-quality finishing processes and colourfast digital printing technologies that minimise fading and distortion.

However, design-for-circularity principles remain limited. There are no structured take-back systems, repair services, life cycle assessments, or formal design-for-disassembly concepts. The company's position within the value chain restricts its influence on end-of-life processes. At the same time, the exclusive reliance on on-demand production significantly reduces overproduction and inventory build-up, representing a key lever for circular value creation in the fashion industry. The transition to digital printing eliminates approximately 20–30 metre set-up losses typical in rotary printing, substantially reduces residual inks, and lowers water and chemical consumption. Overall, the *product dimension* can be classified as basic. Whilst material selection and durability are comparatively advanced, systemic loop-closing mechanisms are absent.

The most pronounced sustainability measures are evident in the *process dimension*. C2 operates a sophisticated internal water circulation system in which wastewater from rinsing processes is captured, stored, and reused multiple times. Cooling water from steaming operations is also recirculated, reducing both freshwater consumption and energy demand. The shift to digital printing has led to substantial reductions in water use, chemical input, colour waste, energy consumption, and pre-production textile waste. Laser-based seam detection prevents the printing of seams, thereby avoiding contaminated fabric remnants and improving recyclability. Energy optimisation is achieved through bundled production cycles that minimise heating processes, as well as through a newly constructed administrative building powered by geothermal energy and photovoltaic systems.

Nevertheless, reverse logistics systems, structured recycling partnerships, and cross-company circular collaborations have not yet been established. While there is strong managerial interest in platform-based solutions for textile waste valorisation, systemic inter-organisational loop-closing mechanisms are currently lacking. The *process level* can therefore also be classified as intermediate, characterised by advanced resource efficiency but without closed material cycles beyond organisational boundaries.

As regards *digital technology deployment,* digitalisation constitutes the most advanced and strategically distinctive aspect of C2's development. Digital fabrication is the defining technology of C2's entire business model and the primary driver of its sustainability performance. Following a gradual transition that began in the mid-2000s, the company fully abandoned rotary screen printing in 2013 and has since operated exclusively with digital textile printing technologies. This makes C2 the only textile printing company in Germany to operate on a purely digital production basis. The shift to digital printing eliminates the approximately 20–30 metre set-up waste typical of rotary processes, substantially reduces residual inks, and significantly lowers both water and chemical consumption. Laser-based seam detection prevents the printing of seams, avoiding contaminated fabric remnants and improving downstream recyclability. The company maintains a professional, continuously updated machine park that enables reliable production capacity, short lead times, and high output quality across a range of fabric substrates. An in-house design department operates with digital design software, enabling the development of proprietary dessins as well as the processing of customer-supplied design data. Digitally designed products are transferred directly to production systems, realising the full CAD-to-manufacturing integration that characterises advanced digital fabrication. Virtual design iterations reduce the need for physical samples, contributing to resource efficiency across the product development process.

Artificial Intelligence (AI) is actively deployed in the design process. AI-assisted design tools are used to generate and develop dessins and colour concepts, which has eliminated the need for purchasing external international dessin licences and significantly reduced related travel. This application illustrates how AI can support CE and sustainability objectives indirectly by reducing resource consumption associated with design workflows and enabling a more self-sufficient, locally anchored design capability.

Analytics and Big Data capabilities are embedded in C2's ERP and production software infrastructure. Real-time validation mechanisms cross-check incoming order data against material specifications, preventing inconsistent material-dessin combinations and thereby reducing mis-production and associated waste. The ERP system generates data flows across the entire order-to-delivery process, supporting production planning, capacity management, and quality assurance. While advanced analytics applications for sustainability KPI monitoring or CE-specific performance indicators are not yet systematically implemented, the data infrastructure in place constitutes a sound foundation for such developments.

Cloud computing underpins the digital integration of C2's internal value chain. The company's IT architecture connects order management, production control, and delivery tracking through networked systems accessible across the organisation. An in-house IT specialist and active collaboration with machine and software developers ensure ongoing system maintenance and integration, as well as the incorporation of emerging sustainability-related technical requirements into the production infrastructure.

Process automation is inherent to C2's digital printing operations. The computer-controlled digital printing machines execute production processes with a high degree of automation, including automated colour management, substrate handling, and post-processing steps such as steaming and washing. Laser-based seam detection represents a further layer of automated quality control integrated into the production workflow. These automated systems operate continuously and are regularly upgraded in collaboration with machine manufacturers, ensuring that C2's production environment reflects current technological standards.

Mobile applications contribute to operational efficiency at C2 primarily through the digitalisation of administrative and communication workflows. Paperless accounting and order processing, digital customer communication, and the company's web-based presence, including a digital fabric sample gallery through which customers can browse current collections and initiate orders, reduce paper-based processes and support flexible, location-independent business interactions. Social Media is used by C2 for business communication and brand positioning, including the presentation of current developments, documentation of customer and partner collaborations, and the communication of the company's sustainability credentials and regional identity. While not a primary operational tool, social media channels support C2's market presence and reinforce its positioning as a sustainable, digitally advanced textile manufacturer.

IoT and Blockchain applications are currently not deployed at C2. Given the company's B2B business model and its position as a Tier 1/2 supplier without direct consumer interfaces or take-back schemes, these technologies are of limited immediate relevance to its current operations. Table 7 provides a structured overview of C2's deployment status across these technologies. In sum, C2's digital maturity can be classified as advanced, even though some of the digital technologies have had limited impact to date. Nevertheless, digitalisation at C2 has been not merely operational but transformative: the complete transition to digital fabrication has fundamentally reshaped the company's competitive positioning, enabled fully on-demand production, and generated substantial sustainability benefits across water, chemical, energy, and waste dimensions. The integrated deployment of Digital Fabrication, AI, Analytics, cloud computing, and process automation, coordinated through a coherent ERP architecture, justifies this classification. At the same time, the absence of inter-organisational digital connectivity, IoT-based traceability, and structured sustainability data management indicates that the full potential of C2's digital capabilities to support CE-related objectives has yet to be realised.

Next steps: A maturity gap is thus evident: digital technologies can be assessed as advanced, whereas circularity across organisational, product, and process dimensions remains at a basic to intermediate level. This asymmetry opens significant development potential. Existing digital capabilities could support material traceability, digital waste sorting, preparation for Digital Product Passport requirements, structured circular data management, and enhanced supplier transparency. To align digital and circular maturity levels, the introduction of measurable circular KPIs, digital traceability of production waste, the development of regional recycling partnerships, preparation for emerging ESPR and DPP requirements, and deeper digital supplier integration would represent logical next steps.

In addition, closer cooperation with fashion and textile brands as C2's direct customers appears critical. Given its upstream position in the value chain, the company's capacity to influence eco-design parameters or DPP implementation remains limited unless such requirements are jointly defined and operationalised. Strengthened

TABLE 7 Overview of C2's deployment status across the digital technologies.

DT	Application at C2
IoT	Individual printing and finishing machines with ERP integration but without interconnected data exchange
Social media	Only used for brand communication
Mobile applications	Paperless processes, online fabric gallery
Analytics/big data	ERP-based real-time validation, production planning
Cloud computing	Networked IT architecture, ERP integration
Blockchain	Not applied
Process automation	Automated printing processes, laser control
AI	Design process: Dessin generation, replacing external dessin purchases
Digital fabrication	Core of the business model: fully digital textile printing, CAD/design, laser seam detection. A central component of CE transition.

collaboration could enable the co-development of eco-design specifications, harmonised material data structures, and interoperable information flows, thereby embedding circularity requirements more systematically across the value chain. With its flexible governance structure and high digital competence, C2 is well positioned to assume an active role in such collaborative circular innovation processes and to progress toward advanced circularity in the medium to long term.

3.3.1.3 Case study C3 (by Madalena Pereira)

C3, an SME based in Covilhã, Portugal, operates as a circular transition company, designing and producing woolen fabrics and blends in a mid-to-high-end range, increasingly using recycled materials. The production model is partly linked to the local textile ecosystem, but also to national wool production, consuming 500–600 tons of national wool annually. Its textile structure is vertically integrated in the carding area, linked to farmers who supply the natural wool fiber, which is subsequently washed, processed, and spun in the region. Design, weaving, dyeing, finishing, packaging, and labeling are all carried out in-house at C3. This relationship with local industry helps reduce environmental and logistical impact; however, the production of high-quality product lines using wool from Australia increases logistical impacts.

The *organisational dimension* demonstrates intermediate maturity in some aspects and advanced maturity in others, but overall intermediate is the appropriate classification. Sustainability and CE principles are not fully embedded in the organisational strategy and operations, due to limitations regarding the source of high-quality virgin raw materials. Company production exceeds 2.5 million meters of fabric with minimal inventory in the warehouse. Production is based solely on customer orders and does not generate surpluses, and dead stock (e.g., damaged stock) is re-utilised in various forms via, for example, small retailers and fashion schools. In the production of carded textiles, the principles of sustainability and circularity are fully institutionalized. C3 has a code of conduct and a plan for preventing corruption risks and is audited in the social component (ICS) to improve working conditions throughout the global supply chain. Sustainability practices are implemented in different departments, and customer relationships are long-lasting, except during market fluctuations caused by severe economic cycles, climate change, and geopolitical instability.

Furthermore, sustainability is not delegated to a single department, but permeates governance, purchasing, and marketing. Supplier relationships are structured through stable contracts and mutual visibility. This alignment between the company's stated values and operational practices demonstrates a high level of organizational integration, where sustainability principles are incorporated into daily management, rather than being treated as separate initiatives with GRS and RWS company certification.

In the *product dimension*, C3 has a high level of implemented certifications; in addition to Global Recycling Standard (GRS) and Responsible Wool Standard (RWS), it is licensed by the Woolmark Company, OEKO-TEX Standard 100, and accredited by the Lycra Company, and has high quality control policies in a certified laboratory. The lack of certification for Portuguese wool to guarantee its value, and the transparency of its good practices, are cited as weaknesses. The company's premium-range clients increasingly require practices at the advanced stage. C3 has also begun sharing its data with its clients, allowing for transparency and traceability of the environmental and social impacts related to its products. Currently, a project is underway for the digital sharing of quantifiable metrics, suggesting that the company is transitioning from an intermediate to an advanced stage. Textile waste is collected and treated within the company, or by regional partners, then reintroduced into the production process or used in other applications. The separation of different materials remains a negative factor due to the various mixtures on the market that operate with blends containing elastane and polyester. Overall, the company can be viewed as being at an intermediate level as regards maturity in the product dimension.

In terms of the *process dimension*, C3 also demonstrates an intermediate level of maturity. The reduction of material, energy, water, and chemical consumption in supply chain processes and the minimization of scope 1, 2, and 3 emissions are actively pursued. CE and innovation projects are being actively pursued, both internally and with various partners in scientific and technological fields, aiming, for example, to reduce water consumption and recover approximately 60% of water usage. The development of innovative products using recycled wool, blended with virgin fibers, resulted in value-added products for premium brands, for which internal processes were developed and adapted for the industrial-scale production of these new products (associated with R&D projects such as the Bioeconomy of Textiles and Giatex for wastewater treatment). Internal quality control in a cerified in-house laboratory at every stage of the process ensures high levels of quality, guaranteeing a longer product lifespan. All chemicals used in the process were produced in the EU, comply with Regulation (EC) No 1907/2006 (REACH) and Regulation (EC) No 1272/2008 (CLP), ensuring the protection of human health and the environment, and minimising the carbon footprint. All waste generated in the various existing processes is separated and treated in order to be reprocessed. In terms of energy, the installation of solar panels contributes to a reduction in energy consumption and new measures have been implemented, with energy audits being carried out regularly.

The use of *digital technology* remains at the basic stage (Table 8). Digitalisation is largely pursued function by function, for process improvements and efficiency gains. The dyeing and finishing process sections are being transformed to obtain real-time consumption values through the implementation of digital technologies and robotics throughout the process. All collections are developed with digital systems, but change is incremental, and the business model is not radically altered.

Table 8 provides a structured overview of C3's deployment status across all nine technology categories. Overall, the company is adequately supported by in-house information systems, but the use of digital technologies is limited. Many technologies are being assessed or piloted, but embedding within the company processes is at a relatively early stage. In sum, C3's digital maturity can be classified as basic, but moving toward the intermediate stage.

Next steps: In the organisational dimension, C3's evolution to the advanced maturity level requires the systematic integration of sustainability and CE principles into organisational strategy and operations, supported by quantifiable goals aligned with international benchmarks. In addition, strengthening coordination along the value chain is required, particularly upstream with regard to valuing domestically sourced wool, through the development of certification mechanisms that ensure quality and traceability. Evolving communication and public transparency of data from the company's CE initiatives is also crucial. Strengthening partnerships with clients, academic institutions, and research centers can also contribute to increased

TABLE 8 Overview of C3's deployment status across the digital technologies.

DT	Application at C3
IoT	Emerging/pilot deployment, chiefly associated with the GIATEX project: intelligent monitoring systems, sensors, and real-time data collection supporting decision-making in water management, effluents, dyeing, and finishing. Full plant-wide integration is under way.
Social media	Primarily institutional and B2B use, corporate communication, product presentation, trade-fair participation, sustainable positioning, and brand-image reinforcement. It does not constitute an operational circularity tool.
Mobile applications	No proprietary mobile application, for either clients or internal use; digital interaction takes place essentially through the website and conventional digital channels.
Analytics/big data	Real-time consumption values are being captured in the dyeing and finishing sections; a project for the digital sharing of quantified environmental metrics with clients is under way.
Cloud computing	Information systems support production, management, and quality control, but a dedicated cloud architecture is still under development.
Blockchain	Not yet implemented; identified as a future opportunity for traceability, recycled-content verification, and Digital Product Passport (DPP) readiness.
Process automation	Digital control and robotics are being introduced across the dyeing and finishing line to obtain real-time consumption values.
AI	AI systems are at an early learning/adoption stage, with prospective application to production planning and operational-performance optimisation.
Digital fabrication	Collections are developed using digital design systems; adoption is incremental rather than transformative of the business model.

organisational resilience and the promotion of collaborative innovation with customised training for employees in sustainability, circularity, and digitalisation.

As regards the product dimension, it is recommended to adopt eco-design strategies oriented toward recyclability, prioritizing single-fiber materials that are easy to separate, or investing in new synthetic fibers that replace biodegradable polyester and elastane, knowing that these fibers are fundamental in blends with wool fibers to provide properties of resistance, durability, and comfort. The increasing incorporation of certified recycled fibers could reinforce the company's sustainable positioning and others CE certifications. Additionally, the digitisation of environmental data sharing with clients is a critical vector for increasing transparency and traceability. The exploitation of circular models, including repair and upcycling practices with downstream partners and clients, could contribute to extending the product lifecycle.

In terms of processes, to progress to an advanced stage, all processes must be aligned with CE principles. C3 must achieve "zero waste" levels, continue improving environmental performance through the implementation of closed-loop water reuse systems, and optimise energy consumption. Strengthening R&D activities, particularly in the areas of bioeconomy and wastewater treatment, could drive the adoption of innovative solutions with less environmental impact. The valorisation of textile waste should evolve toward higher value-added applications and increased market share. It is also relevant to promote industrial symbiosis practices at the regional level, upstream with national wool producers and downstream with waste treatment companies.

The digital dimension constitutes a central strategic vector for the evolution of C3. An inte-grated approach to digitalisation is recommended, supported by real-time monitoring systems of resource flows. The use of data analysis tools and artificial intelligence could support the optimization of production planning and operational performance. At the same time, the development of digital traceability solutions, such as digital product passports, will be fundamental to reinforcing transparency and ensuring alignment with emerging regulatory demands, and share in online platforms. Strengthening digital technologies and integrating them into all processes is a priority for the transition to a new business model.

3.3.1.4 Case study C4 (by Radoslav Radev)

C4, located in the city of Smolyan, Bulgaria, produces women's clothing and various types of uniforms for schools, hotels and restaurants, bank employees and other business sectors. In its activities, C4 strives to respect the principles of sustainability and the CE by reducing harmful emissions and textile waste that pollute the environment, creating sustainable products, using recycled materials and incorporating them into textile goods.

Assessing the *organisation dimension,* the company lies at the intermediate level. There are still some steps to be completed related to the principles of sustainability and environmental efficiency in their integration into the company's business strategy and related operations. The monitoring of sustainability and CE indicators needs to be further developed, which will help to implement corrective actions. The company now has a business model that is oriented toward minimising waste, recycling it and maximising the use of resources in the context of sustainability and the CE. Knowledge and skills regarding sustainability and CE practices need to be more deeply rooted in company culture and its employee training, which will continuously help to develop the sustainable strategy and prosperity of the company. More transparent and detailed information should be made available, for example, on the company website, and in the media, regarding the company's policies on sustainability and the CE. This will enable transparent public communication of sustainability and eco-efficiency activities based on data and facts, as well as targeted information and the participation of stakeholders in product life cycle extension.

As regards the *product dimension*, C4 is again at intermediate level. The company's textile goods are designed with textile materials with a focus on the durability of textile products with the possibility of increased quality through eco-design. The company has implemented a machine for recycling textile waste (cuttings when cutting textile garments), which aims to close, slow down and regenerate resource cycles. Textile waste can be used to produce wadding for work clothes, pillows, etc., with recycled renewed textile materials being part of various textile products.

The implementation of the recycling machine is aimed at optimizing the production process and increasing the resource efficiency and quality of textile products. In addition, the implementation of waste-free production technology, based on the effective management of input raw materials and textile waste, is in line with sustainable policies for the production and creation of textile products and the principles of the CE.

In terms of the *process dimension*, C4 creates value for textile products, in accordance with the principles of ecological production with a focus on minimising resources and textile waste. The majority of C4's activities are related to the production of various textile products at the customer's request in accordance with international standards for the quality of goods. In this way, targeted control of textile production volumes is carried out in accordance with real market demand, which is of vital importance for the implementation of economic, environmental and social efficiencies while complying with the principles of sustainability and the CE.

The company does not deploy typical fast fashion production methods. Rather the company allows for good coordination and management of production through pre-sale mechanisms, facilitating optimal planning of production capacity based on orders placed by companies. This enables stable and predictable production cycles, which reduces textile waste while preserving value throughout the supply chain. Process improvements balance supply and demand and minimising environmental and financial risks associated with overproduction, which is a prerequisite for minimising environmental pollution. The high degree of integration with external partners underpins effective production planning, yet the company has not yet implemented systematic digital integration and has only recently implemented a recycling machine. This suggests the company is at the intermediate level of maturity as regards the process dimension.

Digital technologies have the potential to significantly impact sustainability and CE in the company, but the company's current use of digital technologies is limited to specific technologies, and thus the overall profile lacks consistency (Table 9). For example, through the use of social media (Facebook, Instagram) and the company website, C4 creates and shares text content, images, videos and various publications with its consumers and business partners. This material encompasses the company's textile clothing, production methods, new technology deployment, partnerships details, and brand communication. The website features an online gallery of textile clothing, which is a prerequisite for paperless processes when choosing clothing. It is well-designed, easy to use and is accessible via mobile devices.

In-house, C4 has a basic networked IT architecture that supports CAD/CAM systems, digitally assisted manufacturing processes and the exchange of information between computers and production equipment. The network supports the exchange of data between the various systems and machines in the textile clothing production process. Many of the shop floor processes are automated using a range of machines and applications including the Kuris cutting robot, the Durkopp Adler fillet machine, Veit ironing equipment, Durkopp Adler and Juki straightening machines, as well as specialized machines for a number of other operations. As regards digital fabrication, the company uses the Gemini CAD/CAM system for digital design aspects of textile clothing, such as cutting processes and size calculation. However, the company has not yet implemented IoT, analytics/big data, blockchain or AI applications, which positions the company at the basic level as regards digitalisation maturity.

Next steps: The company must continue to respect and develop the principles of sustainability by further reducing harmful emissions and textile waste that pollute the environment, creating sustainable products, using recycled materials and incorporating them into textiles, which will enable the company to be competitive in the European market. The company can complete a full transition to an advanced maturity level by integrating the principles of sustainability and environmental efficiency more fully into organisational strategy and related operations. Sustainability and CE indicators can be used to monitor and assess the adoption and implementation progress. Periodic training of company employees is also needed to acquire and develop knowledge and skills in the context of sustainability and the circular business model.

In terms of the product dimension, with the implementation of advanced technologies, the company has the potential to move to the advanced level, as the textile goods now being produced are long-lasting, with some of them being composed of recycled materials, providing an advantage in the national and international markets. The digital product passport will be introduced for company products, and the company must continue to create value for textile products, with a focus on minimising resources and textile waste.

As regards digitalistion, in 2025, the company entered into a grant agreement with the Ministry of Innovation and Growth to fund a project to increase processing efficiencies in the company. This project is

TABLE 9 Overview of C4's deployment status across the digital technologies.

DT	Application at C4
IoT	Not applied
Social media	C4 uses the company's website and social media (Facebook, Instagram) to develop communication with its consumers and business partners by providing relevant information about textile clothing, production, new technologies
Mobile applications	C4 has a website with an online textile clothing gallery that can be used on mobile devices, which is a prerequisite for paperless processes when choosing textile clothing.
Analytics/big data	Not applied
Cloud computing	Networked IT architecture on premises but Cloud is not used.
Blockchain	Not applied
Process automation	Automated processes in C4 are fabric cutting, sewing activities, ironing and finishing activities.
AI	Not applied
Digital fabrication	C4 has a system that is used for digital design of textile clothing

expected to help increase the productivity of sewing processes by implementing automated sewing equipment with digitalized functions, further eliminating manual operations and increasing the speed of production in key operations. In addition, it is expected to increase the durability of the produced textile clothes, reduce textile waste in the production process and reduce the amount of textile raw materials used by implementing specialized sewing equipment to optimise use of resources. The company recently opened a new high-tech production department for cutting, equipped with automated robots and other tools noted above. The company's use of social media could be more active to reach more consumers as part of company communication strategy, and in terms of the website, a more modern interface could be offered with a greater emphasis on sustainability and the CE practices now pursued by the company. The continued deployment of digital technologies can further the optimisation and integration of the organisation, its processes and textile products. The company has the opportunity to position itself as green and sustainable, with a circular business model, which would be an indicator of differentiation to consumers, manufacturers, traders, competitors, and government agencies.

3.3.1.5 Case study C5 (by Semra Ocak and Ayşen Erdinçler)

C5, founded in 1985, operates as a Türkiye-based denim and woven garment producer, headquartered in Istanbul. The company manufactures the products at its facility in Çorlu, Tekirdağ. C5 embraces operational efficiency, quality control, research and development, on-demand production, and responsible manufacturing. The monthly production capacity is 150,000 garments, with flexibility to scale according to the project requirements. The company has transitioned from a traditional denim garment manufacturer to a producer that prioritizes sustainability and circularity, notably in the past 15 years. The company produces women's and men's denim garments by using circular and environmentally sustainable techniques, supplying fabrics from highly environmentally conscious manufacturers, and implementing sustainability principles. In 2020, C5 revised its strategic approach by committing to a circular production model by 2030, structured around six core circular economy pillars: Reduce, Reuse, Recycle, Rethink, Renew and Regenerate.

The company's activities focus mostly on denim washing, finishing, and customised production processes, positioning C5 downstream in the denim value chain, where environmental impacts regarding water, chemical and energy use are particularly important. The implementation of advanced dry-processing and laser-based applications enables resource-efficient finishing and facilitates small-batch and personalised production. C5 prioritizes on-demand, limited-volume production for specific brands, allowing for enhanced monitoring processes over quality, resource use and environmental impacts. C5 has operated in the apparel manufacturing industry for several years, while ensuring international standards and sustainability criteria. The company's website, social media, and client-facing channels are used to keep the public informed about circular practices. The new campaigns and collaborations are systematically announced through these media, emphasising traceability and circularity. Furthermore, eco-design, cleaner production, and circularity training programs for employees are implemented.

As regards the *organisational dimension*, sustainability is embedded in strategic decision-making through frameworks for chemical use, energy sourcing, textile waste management, and certification processes, and overall maturity is adjudged to be at the advanced level. C5's organisational approach demonstrates an advanced maturity level in sustainability and CE adoption. The company has internationally recognised standards such as GOTS (Global Organic Textile Standard), LEED (Leadership in Energy and Environmental Design), Social & Labor Convergence, Higg Index, ISO 14001 and 50,001, GRS (Global Recycled Standard), Organic 100 Content Standard. C5 also operates in accordance with ZDHC (The Zero Discharge of Hazardous Chemicals) Level 3 chemical management criteria, Sedex (Supplier Ethical Data Exchange), and ICS (Initiative for Compliance and Sustainability) platforms. Apart from these auditing mechanisms, the company has been regularly conducting Performance InCheck assessments to monitor chemical usage in its manufacturing facility since 2022. These reports evaluate the compliance of input chemicals with the ZDHC Manufacturing Restricted Substances List (MRLS)[1] and Chemical to Zero Program standards, offering a systematic and standardised overview of the chemical inventory used during a certain period.

C5 uses EIM (Environmental Information Management) reporting to systematically monitor chemical, water, energy and worker impact, supporting both process optimisation and circularity initiatives. These characteristics promote transparency and ongoing improvement in input chemicals and materials, putting C5 among one of the Türkiye's leading examples of environmentally responsible denim garment manufacturers. C5 also demonstrates a structured approach to sustainability and CE adoption by collaboration with platforms such as Textile Exchange, Denim Deal, Circulose, Transformers Foundation, and Conscious Fashion + Lifestyle Network.

The company does not confine sustainability to a single standalone department: responsibility is integrated across production, design and resource management systems. This reflects an awareness of life cycle based environmental impacts, particularly regarding highest CO_2 emissions in textiles occur upstream – from agricultural practices to fabric production – while downstream (e.g., washing and finishing) stages of denim jeans offer better potential for environmental impact mitigation.

The company's approach to chemical use relies not only on international standards, but also an innovative approach which has been applied to production recipes. For instance, the conventional processes using potassium permanganate ($KMnO_4$) are explicitly separated from the sustainable alternatives in internal formulations, where the organic bleaching agents are applied to give the denim jeans a fading effect. Organisational commitments are further strengthened by lowering carbon intensity by using 100% renewable energy in the facility.

From *the product dimension* perspective, C5 integrates sustainability and CE principles into production processes through material selection. Denim garments are produced using organic and certified materials as well as fabrics containing recycled fibre and recyclable materials. Since C5 operates a Business-to-Business (B2B) model, it does not currently implement take-back, repair or recycling systems for post-consumer garment wastes. The monitoring and collection of post-consumer textile waste fall outside of the

1 Available online at: https://mrsl.roadmaptozero.com/.

company's operational scope, this being the responsibility of the downstream actors such as brands and retailers. However, C5 implements proactive corrective and reprocessing repair practices to prevent products from being downgraded to second quality. For instance, when a finished garment does not fully meet the client's demand because, for example, of deviations in colour tone or finishing effects, the additional controls are applied to achieve the required model before the product is released for sale. This also helps to minimize material loss.

Pre-consumer textile wastes, generated during the cutting and finishing stages are collected and sent to an external recycling facility through a recycling company, where wastes are mechanically processed back into fibres and ultimately reused in denim fabric production. Additionally, plastic and paper wastes are separately collected and sent to a licenced recycling facility. C5's proactive corrective and reprocessing repair practices and waste management practices generally indicate an advanced level maturity in the product dimension. These practices are implemented in accordance with the CE principles embedded in material selection, finishing technologies, and the waste management systems. They also include initiatives for slowing material loop, reducing raw material use, and recycling pre-consumer textile wastes. Overall, this warrants a rating of advanced maturity in the product dimension, even though post-consumer wastes remain outside C5's operational scope and governance boundary due to its B2B model characteristics.

In *the process dimension*, the finishing process to give jeans faded and worn effects is done through technologies that aim to reduce chemical and water dependency. In the finishing process, the use of recyclable, sustainable stones and ozone technologies instead of pumice stone, having limited number of reuses, is a noteworthy process innovation reducing the solid waste generation. Reducing the use of resources and slowing the material loops directly supports CE principles.

The company demonstrates a high degree of environmental optimisation by using the dry-process technologies and digital integration. Digital pattern making, incorporating laser technologies for cutting, bleaching and marking operations, reduce the consumption of water and chemicals. However, some manual processes, such as sanding for specific aesthetic effects are still used in production, and their negative effects on the environment are managed through limiting the production with these manual processes and applying an appropriate waste management system. Key sustainability indicators such as water and energy consumption, chemical inputs, and textile wastes are monitored at varying degrees. Wastewater generated during wet processes is treated with chemical treatment, biological treatment and membrane filtration. C5 ensures that the sludge produced during operations is sent to a recycling facility to be used as a raw material and energy input in cement production, since it has a high calorific value. Instead of disposal, this method allows material recovery through industrial symbiosis channels.

Chemical compliance and material standards play a major role in motivating suppliers. In this context, buyer-driven requirements, approved chemical lists, using recyclable accessories in jeans, shirts and jackets and production recipes are used to meet sustainability requirements. Production is carried out in line with customer orders, following an on-demand manufacturing approach rather than stock-based production. This model allows for the production of confirmed orders, ensuring that production levels remain aligned with actual market demand. C5 also incorporates circular and lower-impact material options in production. By integrating such materials into its design and production phase, C5 enables customers to make more sustainable choices without compromising flexibility, quality and design purposes. Overall, the integration of digital design, dry finishing technologies, controlled chemical and resource use, and renewable energy puts C5 at advanced maturity level in the process dimension.

Digitalisation plays a central role in production planning, coordination and environmental data management. C5 uses an Enterprise Resource Planning (ERP) system to digitally manage all production processes and operational steps. An agreement with their ERP systems provider was established to improve supply chain traceability and production planning across production processes. While the detailed system configurations are not publicly available, digital integration supports production control and process optimisation, while enabling closer coordination between orders and manufacturing activities. Digital reporting tools further strengthen monitoring environmental performance of the production processes. While no full product-level life cycle assessment is conducted, greenhouse gas emissions are calculated and reported in collaboration with a private company partnership, offering structured data on climate-related impacts at organisational and process levels (Table 10).

Digital fabrication constitutes the most operationally embedded form of digital technology at C5. Digitally control laser technologies, ozone applications, and dry processing techniques automate denim finishing processes, enabling precision manufacturing while reducing water and chemical consumption. Additionally, C5 collaborates with an external partner to explore the implementation of Artificial Intelligence (AI) within production and supply chain. This initiative is currently at an exploratory stage, aiming to gradually integrate AI-driven solutions across the supply chain, with an emphasis on resource conservation, process optimization, and predictive decision-making. The company has also initiated a pilot project for the Digital Product Passport (DPP) to achieve product traceability and lifecycle transparency across the denim value chain. Beyond production technologies, digital tools mainly support coordination and communication functions. Social media platforms and corporate communication channels are used to communicate sustainability initiatives and circular economy practices. Digital tools are systemically deployed to support production coordination, environmental reporting, and process traceability. This indicates an intermediate level for digitalisation at the company, as early-stage initiatives are underway to explore AI integration across the supply chain.

Next steps: Based on the most recent evaluation of its organisational, product, process, and digitalisation pathways, C5 demonstrates a strong strategic foundation in sustainable and circular denim production. However, circular performance could be further strengthened by exploring higher-value applications for pre-consumer waste valorisation and by deepening collaboration with recycling and upcycling partners. Although denim is inherently durable, intensive finishing effects may reduce garment longevity. C5 could enhance product lifespan through modular design approaches supported by innovative materials and finishing techniques. In parallel, advancing digitalisation initiatives—such as expanding the use of ERP systems, Digital Product Passports (DPP), and AI-driven optimisation—would support improved traceability and sustainability performance. To move closer to full circularity, the introduction of

TABLE 10 Overview of C5's deployment status across the digital technologies.

DT	Application at C5
IoT	IoT are not explicitly deployed for product lifecycle tracking or circularity related operations.
Social media	C5 uses social media and corporate communication channels primarily for communication and stakeholder engagement. The company's website and social media channels communicate sustainable initiatives, circular production practices and strategies, responsible production practices, collaborations and environmental commitments.
Mobile applications	No dedicated mobile applications supporting circular business models or customer interaction was identified.
Analytics/big data	Enterprise Resource Planning (ERP) system is used to digitally manage production processes and operational coordination. Digital reporting tools and Environmental Impact Measurement (EIM) systems enable systematic monitoring of water, chemical, energy and working conditions impacts to support process optimisation and environmental performance assessment.
Cloud computing	No explicit cloud computing infrastructure or cloud-based circular applications were reported. Digital coordination relies primarily on ERP and internal reporting systems.
Blockchain	Not applied. Traceability and transparency are ensured through certification schemes, auditing platforms, and reporting mechanisms rather than blockchain-based systems.
Process automation	Laser-based production technologies are applied in cutting and finishing processes to support precision manufacturing and resource-efficient production operations.
AI	AI integration is currently under exploration in collaboration with an external partner; no implemented AI-based optimisation or decision-making systems were identified.
Digital fabrication	Digital pattern making and advanced laser technologies support customised and made-to-measure denim production, enabling flexible order management and reduce resource consumption.

post-consumer take-back, repair, or refurbishment schemes, implemented in partnership with retail actors, could complement the company's current B2B operating model. Moreover, extending existing monitoring practices to include life-cycle-based environmental indicators would strengthen transparency, support strategic decision-making, and align reporting with emerging EU regulatory expectations.

3.3.2 Synthesis

The five case studies used the framework to assess the level of maturity in the respective companies and generate an action list to progress toward sustainability, CE and digitalisation alignment (Table 11). This suggests the initial framework is a workable model for assessing maturity in sustainability, CE and digitalisation in the European T&C industry. Although this is not a systematic empirical evaluation, it served as a valid workable model for cross-country comparisons and assessment.

This synthesis provides additional insights. Firstly, the companies studied have progressed at different rates in the three dimensions of Organisation, Product, and Process (Figure 4), reflecting the variations in corporate strategy for sustainability and the CE. The case examples suggest that only at the advanced level of maturity do the three dimensions move toward alignment as more comprehensive and integrated corporate strategies are developed and implemented, and digitalisation is advanced to a similar level as a key change enabler across the three dimensions. However, until the advanced level is reached, digitalisation lags behind these change dimensions, suggesting it has not been used as the instigator of the transition to the CE, but rather digital technology deployment has been driven by evolving business requirements.

Nevertheless, although digital technologies may not directly progress CE implementation, they positively affect inter-organisational collaboration, which in turn can advance adoption of sustainability and CE practices. Digital technologies can indirectly support individual CE strategies by reducing resource-intensive processes or negative environmental impacts, but these effects often remain isolated and fail to be connected or coordinated with overall sustainability objectives. In contrast, practices and examples where holistic approaches involving multiple stakeholders are pursued tend to deliver greater overall success. This resonates with the concept of a "twin transition," encompassing the combination and coordination of the green transition, driven by "the need to reach the aims of climate neutrality and sustainability" and "the digital transition, [which] is an on-going process of technology-driven change" (Muench et al., 2022, p. 9).

Secondly, consideration of the "twin transition" provides a further analytical perspective. Drawing on the synthesis of findings in Table 11 and the literature detailed in section 3.2, the mapping of progress toward sustainability and CE practices against digitalisation supports the identification of four company profiles (Figure 5). The level of maturity across the three change dimensions (Organisation, Product and Process) is averaged out and taken as the overall level of maturity for sustainability and the CE. "Beginners" have not adopted holistic sustainability strategies and CE practices nor have they progressed digitalisation to any significant degree. These companies tend to provide general, sometimes opaque or unverifiable information in their sustainability reports or refer to future-oriented objectives. Their digitalisation efforts suggest isolated measures aimed more at intra-organisational efficiency than inter-organisational cooperation and collaboration or the pursuit of sustainability strategies. They are lagging behind general developments, remain anchored in their linear business models and are inadequately prepared for upcoming regulatory requirements like the DPP or reporting obligations under CSRD and CSDDD, as well as changing consumer patterns. None of the five companies studied here falls within this definition.

In contrast, "Transformers" are the companies that have clear sustainability strategies aligned with widely recognised

TABLE 11 Synthesis of case study assessment using maturity framework.

Case study	Organisation	Product	Process	Digitalisation	Next steps
C1 (Italy)	Advanced: fully institutionalised principles and policies; alignment with international standards; organisational integration.	Advanced: deliberate design strategies; extensive transparency and traceability; structured repair and take-back programmes.	Advanced: Capacity planning reduces waste; process discipline.	Intermediate: Technologically advanced with ecommerce platform and data-driven collaboration. However, deployment of digital technologies remains relatively limited at present.	Stronger overall integration; leverage digitalisation benefits; extend DPP infrastructure.
C2 (Germany)	Basic: No systematic embedding into corporate strategy.	Basic: Some sustainability characteristics, but evidence of circularity principles is limited; Digital printing is a positive.	Intermediate: Strong water management, plus a range of benefits from digital printing; but systemic inter-organisational loop-closing mechanisms are lacking.	Advanced: Value chain integration via standard IS plus digital technology benefits (paperless accounting, a reduction in physical sampling, fully on-demand manufacturing, and substantial cost savings).	Exploit potential of digitalisation for material traceability, digital waste sorting, preparation for Digital Product Passport, data management, and supplier transparency; closer cooperation with main customers.
C3 (Portugal)	Intermediate: Limited embedding of sustainability and CE principles in overall strategy but evidenced in areas of production; sustainability permeates governance, purchasing, and marketing.	Intermediate: Overall strong certification and quality control, but not for Portuguese wool; client data sharing is a positive and textile waste is treated and recycled;	Intermediate: Material, energy, water and chemical reduction measures; CE and innovation projects, both internally and with various partners in scientific and technological fields; certified internal quality control.	Basic: Functional approach for efficiency gains and process improvements, but active support and enablement of sustainability and CE practices is limited.	Full embedding of sustainability and CE principles into strategy and operations; stronger upstream coordination of policy measures; adopt eco-design strategies in product development; increase transparency via digital data sharing with clients.
C4 (Bulgaria)	Intermediate: Key principles largely integrated into strategy and operations; waste reduction and recycling initiatives, but more embedding in culture and awareness needed.	Intermediate: Eco-design principles in evidence; textile waste is recycled and reused in company products; waste-free production technology implemented.	Intermediate: Textile production volumes are tightly controlled to avoid waste; optimised production planning based on customer orders; advanced process integration with external partners.	Basic: Government funded project for automated seeing equipment with digitalised functions; robotics now used for cutting; social media and website for communications.	Greater focus on emissions and waste reduction; more embedding in organisational strategy and operations; training to improve awareness and progress culture change. Introduce DPP; exploit social media more.
C5 (Türkiye)	Advanced: sustainability embedded in strategic decision-making; adheres to internationally recognised standards; integration across production, design and resource management systems.	Advanced: materials selection integrates sustainability and CE principles; proactive corrective and reprocessing repair practices; pre-consumer textile wastes are collected and recycled.	Advanced: finishing process technologies aim to reduce chemical and water dependency; digital pattern making reduces water and chemicals consumption.	Intermediate: ERP used to digitally manage all production processes and operational steps; digital reporting tools monitor environmental performance of the pro-duction processes; AI being trialled across supply chain; DPP being piloted.	Explore higher-value applications for pre-consumer waste valorisation; greater collaboration with recycling and upcycling partners; modular design approaches, innovative materials and finishing techniques; post-consumer take-back, repair, or refurbishment schemes; progress DPP and AI initiatives.

sustainability goals, such as the SDGs, and implement comprehensive measures and practices to minimise resource use and waste generation in line with CE principles. They also collaborate with relevant stakeholders and report transparently and verifiably on their progress toward these goals. Companies C1 (Italy) and C5 (Turkiye) fall into this group, although both companies could make more progress in their digitalisation initiatives to move closer to a balanced twin transition.

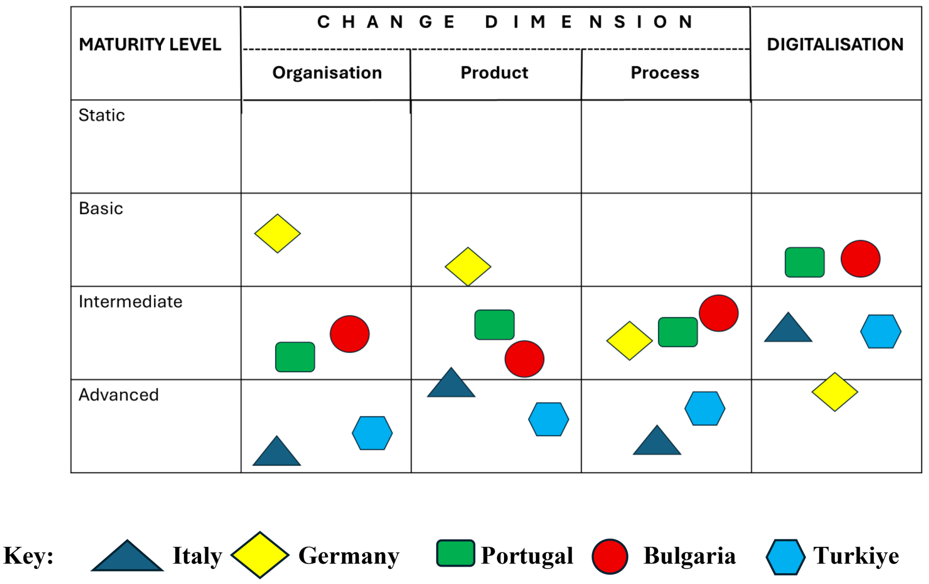

FIGURE 4
Levels of maturity of the five case study companies.

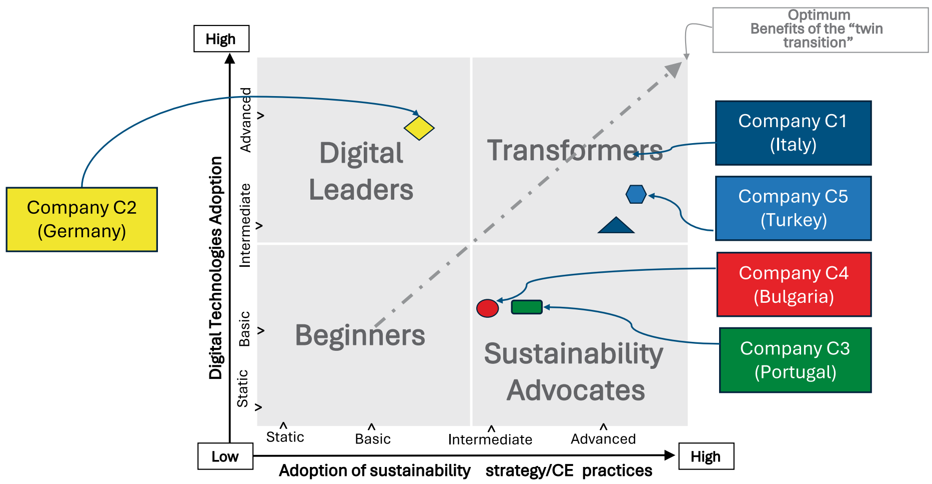

FIGURE 5
Sustainability/CE and digitalisation: company profiles for T&C companies.

Two other groups can be identified. "Digital Leaders" have a strong focus on digitalisation, emphasising efficiency and productivity gains. While sustainability benefits may occur as a byproduct, these companies lack a comprehensive sustainability and CE strategy or, at best, have a highly fragmented one. Here, C2 (Germany) is in this grouping, but overall this group is likely to be relatively small in the European T&C industry, as digitally advanced companies will usually have, even if only in outline, sustainability and CE strategies in place. More likely, digitalisation may lag behind progress in sustainability and CE strategy development, as is the case with four of the five companies studied here. In this context, the European Monitor of Industrial Ecosystems (EMI) concluded: "SMEs in the textiles industrial ecosystem have been less engaged in digital technologies than in the green transition" (Izsak and Moreno, 2024, p. 8).

"Sustainability Advocates" are companies that have clear sustainability goals and extensive, holistic CE practices, which they report on comprehensively, transparently, and verifiably. However, in terms of digitalisation, they follow a strategy that deviates from the general trend by emphasising craftsmanship, individualisation, and direct customer interaction over innovation, automation, and digital collaboration. While they do use digital technologies, such as online shops, websites, or social media channels, these are more focused on communication rather than supporting operational processes. C3 (Portugal) and C4 (Bulgaria) can be seen as examples of this grouping.

T&C companies can use this profiling, in combination with the maturity model, to locate their current positioning and plan appropriate strategies and measures for moving forward. The findings suggest an alignment of maturity levels across the three change dimensions in the maturity model is likely to provide the best basis for implementing sustainability and CE principles, and that digital technology deployment should be brought to the same level of maturity to instigate and support change initiatives which are integrated and strategically embedded throughout the value chain, and which harnesses the full potential of digitalisation.

4 Concluding remarks

This article investigated the current status of sustainability strategies, CE practices, and digital technology deployment in the European T&C industry and provided a framework for assessing company maturity against inter-related change dimensions. The maturity framework can be used by practitioners to assess company maturity in these interrelated change dimensions and develop an action plan for their alignment and progression. As regards contribution to theory, Kristoffersen et al. (2020) pointed out that "research is presently in a pre-paradigmatic stage, as frameworks that support linking DTs and the CE have started to appear only recently, and no dominant framework has emerged as yet" (p.243). The authors put forward a "digital-enabled circular strategies framework" (p. 252) that includes a classification of digital technologies supporting circular strategies related to corporate strategy. Since then, other authors have suggested related definitions and frameworks. Bressanelli et al. (2022), for example, in developing a "smart circular economy paradigm," examined the role of digital technologies in the circular economy product life-cycle, and put forward an agenda for future research. The maturity framework set out and applied in this article can be seen within this context as an exploratory study that attempts to further explain the relationships and dependencies of digitalisation, sustainability and the CE, specifically in the context of the T&C industry.

Overall, the findings present a mixed picture. Despite the advanced level of maturity displayed in the Italian and Turkiye cases, digitalisation efforts in the European T&C industry in general appear fragmented, and there seems to be a lack of alignment or integration with sustainability and CE strategies. As highlighted in the German and Bulgarian cases, companies often fail to connect digitalisation with their sustainability and CE initiatives, and this may lead to missed opportunities or increased costs. Integrated, holistic approaches involving multiple functions are required to deliver greater overall success. Inter-organisational collaboration is a key factor which can be made more effective and efficient through digital technology deployment.

This study clearly has its limitations. Although the case studies featured in this article provide a considerable amount of detail, they cannot fully capture all the regional differences and specificities of the European T&C industry, and generalisation should be treated with caution. While general trends regarding the progress of sustainable and circular practices, as well as the adoption of digital technologies, were discerned from the literature analysis, the diversity in company size, value chain stages, and regional contexts limit the generalisability of the findings across Europe and beyond. The application of the maturity framework in five case study companies does not represent a validation of this framework, but nevertheless, the authors believe that the study provides a valuable piece of comparative work that can provide the basis for further research in a number of areas.

Although the study is framed around the triple bottom line, the framework operationalises sustainability primarily through its environmental-related CE dimensions. Given the T&C industry's well-documented history of labour exploitation, the explicit incorporation of social sustainability indicators into the maturity framework is a possible direction for future research. While the advanced maturity level acknowledges stakeholder and consumer involvement in lifecycle extension and recovery, the framework does not provide an analytical mechanism to systematically assess how companies educate, incentivise, or co-create with consumers as part of their circular transition. This represents a deliberate scoping decision, as the framework is designed to assess firm-level organisational, product, process, and digital capabilities. Future research could extend the framework by incorporating consumer engagement strategies and their relationship to circular maturity, drawing for instance on typologies of consumer involvement in circular textile transition (Vidal-Ayuso et al., 2026).

Future research studies could also include parallel analyses of digital technology deployment in support of sustainability and circularity in the T&C industry, as little detailed information is publicly available on how companies are integrating digital technologies into their sustainability strategies and CE practices. This could provide insights into the optimal combination of digital technologies and CE practices in the industry's various functions. It is also evident that collaboration and partnerships are critical in engendering the transition to sustainability and the CE, and that digital technologies play a major role in building trust and ensuring real-time and transparent information flows, and this area could also be profitably researched. For example, studies could focus on identifying the barriers and challenges to successful digitally enabled and supported partnerships, as well as the key factors that contribute to their success. The maturity framework put forward here could be tested in other T&C company environments, both within Europe and in other environments, including in upstream operations in developing countries. Such wider application and amendment of the framework could lead in due course to a more grounded validation, rather than the illustrative examples featured here.

Furthermore, the emergence of the DPP as a mandatory EU regulatory instrument represents a particularly timely focus for future research: longitudinal studies tracking T&C company responses to DPP implementation requirements would provide valuable evidence on the relationship between regulatory pressure, digital maturity, and CE transition, complementing the framework-based assessment approach adopted in the present study.

The role of consumers, including their consumption patterns, knowledge, and skills related to sustainability and CE, and especially, the role of digital technologies in engaging consumers in sustainable and circular consumption patterns, represents another critical area for research. Understanding these factors could provide valuable insights into how to effectively engage consumers in the transition to a sustainable and circular T&C industry. Future research could also examine how different policy instrument designs shape the rate and depth of circular transition in the T&C sector. Comparative analysis of incentive-based instruments, such as subsidies for circular product design, tax credits for recycled material use, and green public procurement criteria, versus compliance-focused regulatory approaches, would help identify the most effective levers for accelerating the transition across different firm sizes and institutional contexts (Svatikova et al., 2025).

In addition, the framework does not operationalise technical material regeneration processes, and thus emerging approaches such as electrospinning of cellulosic waste streams may inform future refinements of the process dimension's advanced-level criteria (Suen et al., 2023). Such research initiatives could be complemented by comprehensive quantitative studies to shed more light on the state of the European T&C industry, particularly in terms of regional differences and company sizes in the twin transition to sustainability and digitalisation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MW: Validation, Data curation, Conceptualization, Visualization, Project administration, Formal analysis, Investigation, Writing – review & editing, Methodology, Supervision, Writing – original draft. TW: Formal analysis, Writing – original draft, Methodology, Visualization, Data curation, Investigation, Validation, Conceptualization, Writing – review & editing. RR: Data curation, Writing – original draft, Investigation, Validation, Formal analysis. FV: Investigation, Data curation, Formal analysis, Validation, Writing – original draft. GH: Writing – original draft, Formal analysis, Investigation, Data curation, Validation. MP: Data curation, Writing – original draft, Investigation, Formal analysis, Validation. SO: Formal analysis, Validation, Data curation, Investigation, Writing – original draft. AE: Investigation, Writing – original draft, Formal analysis, Data curation, Validation.

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