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Transformative supply chains: the enabling role of digital technologies

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ABSTRACT

To remain competitive in turbulent business environments and address increasing regulatory pressures, modern supply chains should undertake transformations towards circularity and resilience. Despite the relevance of the topic, how enabling transformative changes as those increasingly observed in reality is a topic still not fully understood. We fill this research gap by developing a novel social-ecological model of the supply chain that investigates the enabling role of digital technologies in supply chain transformations. The model first offers a conceptualization of transformative supply chains as social-ecological systems capable of transforming towards new configurations, more consistent with internal pressures and external challenges, through the supply chain transformative capabilities. Then, how digital technologies influence these dynamic capabilities is argued. The conceptual model is investigated through a multiple case study approach in Made-in Italy sectors. We analyze eight case studies involving large, medium, and small companies, which confirm theoretical argumentations. Specific propositions linking the digital technologies with supply chain transformative capabilities are finally formulated, and theoretical and managerial implications discussed.

1. Introduction

Nowadays, global challenges foster traditional supply chains (SCs) to profoundly modify their configurations to remain competitive. For example, the geopolitical crises, frequent shortages, and increased natural disasters characterizing current business environments forced companies to modify their SCs to become more resilient to disruptions. Resilient SCs are in fact proven to "*evolve over time*" (Carvalho et al., 2012; Yu et al., 2019), "*survive, adapt, and grow*" (Pettit et al., 2010), and "*navigate [...] to secure more desirable [...]*" performance (Wieland, 2021). At the same time, the climate changes, severe biodiversity losses, fast-running degradation of natural resources, coupled with increased governmental pressures for sustainable economies force companies to make their SCs more sustainable and aligned with Circular Economy (CE) principles (Massari and Giannoccaro, 2023). The latter in fact aim at decoupling economic growth from environmental degradation (Govindan et al., 2020; Nandi et al., 2021; Yu et al., 2021) by reducing virgin raw material and energy consumption directly from the product's design phase, replacing product's ownership with its associated sharable service, and extending products' value for as long as feasible (De Angelis et al., 2018; Farooque et al., 2019; Fraccascia et al., 2019; Genovese et al., 2017; Masi et al., 2017). These transformations towards resilient and circular configurations occur worldwide and are spread across industries. In the fashion industry, for instance, retailers are currently moving from off-shore to near- or on-shore on-demand supplier networks producing a broader range of products in smaller numbers. The same actors are strengthening regional sourcing to reduce time-to-market for highly fashionable, time-sensitive items (Berg et al., 2017) as is the case of H&M that recently announced plans to adopt Inditex's strategy to source about 50% of garments from Europe and neighboring countries (Stratton, 2018). Further evidence characterizes the fashion industry where the focal company engages with new stakeholders, such as textile recycling companies, garment repairers, clothing take-back actors, remanufacturers, and even the final customer, to effectively collect used products and resell them on second-hand markets (Henninger et al., 2021; Machado et al., 2019). In the furniture industry, manufactures established industrial symbiosis relationships with external manufacturers operating in carpentry or agricultural sectors so as to use their by-products e.g., wood residues, wooden pallets, offcuts, packaging boxes (Oliveira et al., 2018), as secondary raw materials replacing virgin ones.

To fully understand these phenomena, a holistic approach like that provided by social-ecological system (SES) theory is required. This has been proven suitable to investigate the "*open*" and "*transformative*"

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nature of modern SCs (Gualandris et al., 2024; Wieland and Durach, 2021; Wieland, 2021 Wieland et al., 2023) and to conceptualize them by means of social and ecological components strongly interconnected with each other and with the external environment (Wieland, 2021; Nacchiero et al., 2024). Compared to the adaptive entities in ecological systems, the newly observed components lead the system throughout profound transformations more radical than those driven by co-evolutionary and co-adaptation processes. The transformative SC has thus emerged as a new holistic paradigm for studying modern competitive SCs. The few studies on this topic have posed attention on their configurations by highlighting the structural elements of social-ecological SCs i.e., the "*dancing*" and "*interconnected*" components (Wieland, 2021) and multi-level relationships that SCs have with external SESs (Wieland and Durach, 2021), and relating these elements to the emergence of social-ecological resilience (Wieland et al., 2023) and regenerative performance (Gualandris et al., 2024). The factors enabling SC transformations, instead, still remain not fully understood. In this regard, we argue that digital technologies (DTs) may be beneficial.

The combined use of DTs for large amount of data collection-sharing-analysis, including Internet of Things, Cloud Computing, Blockchain, Big Data Analytics, and Artificial Intelligence, may help manufacturers to better monitor their processes and products (Ben-Daya et al., 2019; Garrido-Hidalgo et al., 2019), forecast market changes (Maheshwari et al., 2021), provide them with new insights on the consumers' purchase decisions of e.g., second-hand products (Mishra et al., 2017; Montecchi et al., 2019), and strengthen their collaboration with key SC stakeholders (Lohmer et al., 2020). Digital Twin help to simulate the structures and performance (Liu et al., 2021) of novel SC configurations, while revealing precious insights into their effects and vulnerabilities. SC partners are thus able to experiment different scenarios and strategies by using the virtual models of this technology. Autonomous Robotic Systems can easily detect defects, disturbances, and deviation from efficiency standards along production lines (Kamble et al., 2018; Koh et al., 2019), while aiding in the control and optimization of innovative solutions within transforming SC configurations. Additive Manufacturing and Cloud Manufacturing technologies may support manufacturers pursuing co-creation and joint production processes through the development of digital networks of shared resources and capabilities (Gupta et al., 2019; Yu et al., 2015).

To investigate the enabling role of DTs for SC transformations, we develop a social-ecological model. In particular, we conceptualize the transformative SC as "*a social-ecological system capable of transforming towards new configurations more consistent with internal pressures and external challenges*." Going beyond past studies, which adopt a dynamic capability (DC) view to understand how SCs evolve on and adapt to rapidly changing environments (Aslam et al., 2018; Beske, 2012; Defee and Fugate, 2010; Eckstein et al., 2015; Hong et al., 2018), we consider that transformative SCs are instead endowed with *triggering, envisioning, navigating*, and *stabilizing* capabilities. These refer to a specific class of DCs (Nacchiero et al., 2024) that can enable transformations towards new configurations embracing circularity and resilience. We argue that DTs, by affecting the above supply chain transformative capabilities (SCTCs), play an important role for resilient and circular transformations. To explore the framework developed, we designed a multiple case-study analysis by carrying out semi-structured interviews with Italian companies operating in Made-in-Italy sectors. The results confirm the significant and positive role of SCTCs on the SC transformation towards circularity and resilience and underscore the enabling role of DTs.

The rest of the paper is organized as follows. Section 2 presents the literature background concerning the DC theory and the DCs enabling circularity and resilience in SCs. In Section 3, the novel conceptual framework on SCTCs is presented. Section 4 describes the research methodology, while in Section 5 we present the results. In Section 6, implications and limitations are finally provided.

2. Literature background

2.1. Supply chain dynamic capabilities

DCs have been introduced to explain how firms "*integrate, build, and reconfigure internal and external competences to address rapidly changing environments*" (Teece et al., 1997). DCs correspond to a subset of organizational capabilities that operate to purposefully create, extend, or modify the resource base of an organization, to respond to changing market circumstances (Helfat, 1997; Helfat et al., 2007; Winter, 2003). DCs refer to a set of capabilities including sensing, seizing, and reconfiguring capabilities (Teece, 2007), adaptive, absorptive, and innovative capabilities (Wang and Ahmed, 2007), sensing, learning, integrating, and coordinating capabilities (Pavlou and El Sawy, 2011).

The concept of DCs, defined at the level of the firm, has been also extended to the SC level, leading to the construct of supply chain dynamic capabilities (SCDCs). The latter refer to the abilities of the whole SC to handle turbulent and changing environments (Masteika and Čepinskis, 2015) as well as internal complex relationships (Beske, 2012). A long list of SCDCs have been proven to be useful for improving firm's operational performance (Eckstein et al., 2015; Defee and Fugate, 2010), triggering SC ambidexterity (Aslam et al., 2018), and enabling sustainable SC management practices (Beske, 2012; Hong et al., 2018). Specific SCDCs are also found to enable processes for SC reconfiguration and adaptation towards resilience and circularity. Christopher and Peck (2004) identified 4 categories of SCDCs useful for resilience, including SC reengineering, collaboration, agility, and SC risk management culture. Pettit et al. (2010) identified 14 different capability factors (such as flexibility, efficiency, visibility, adaptability, anticipation, and recovery) and 71 sub-factors, for improving resilience. They highlighted the critical linkages between these capabilities and the SC vulnerability to environmental turbulence, external pressures, and disruptions. Ali et al. (2017) classified 5 core SC resilience capabilities, based on the distinctive phases of pre-, during-, and post-disruptions: ability to anticipate, adapt, respond, recover, and learn. Ali and Gölgeci (2019) identified 22 capabilities and grouped them according to the resilience classes of preparedness, resistance, and rebound. Redundancy, information sharing, SC innovation, co-opetition, robustness, agility, adaptation, and SC redesign emerged as relevant capabilities. Chowdhury and Quaddus (2017) identified the proactive features, reactive features, and design qualities that a resilient SC should possess to sense, seize, and transform resources while facing with environmental changes. Yu et al. (2019) presented a novel DC framework to clarify how companies foster resilience in response to SC dynamism and disruptions. Their findings revealed a significant positive influence of SC dynamism on both SC disruption orientation and SC resilience. According to Shin and Park (2021), companies quickly and better adapt to market uncertainties, evolving customer needs, and unexpected disruptive events when endowed with effective capabilities such as flexibility, agility, efficiency, visibility, and collaboration. According to Stadtfeld and Gruchmann (2024), SC resilience requires specific DCs, to be considered as bundles of practices beyond risk management, enabling organizations to proactively prepare for, effectively counter, and efficiently recuperate from disruptions. In a similar vein, scholars have also investigated the SCDCs specific for circular SCs. Key findings demonstrate that *sensing, seizing* and *reconfiguring* capabilities (Coppola et al., 2023; De Angelis et al., 2023; Elf et al., 2022; Sandberg and Hultberg, 2021; Santa-Maria et al., 2022) are effective for handling incremental improvements of current business models (Prieto-Sandoval et al., 2019), adapting existing business models to CE and sustainability principles (De Angelis et al., 2023; Santa-Maria et al., 2022), implementing CE strategies (Khan et al., 2020, 2021), reconfiguring internal resources and technologies and adjusting product stewardship strategies so as to prevent pollution and lower the environmental impact of products (Coppola et al., 2023). A specific set of dynamic learning capabilities, explored by Ritola et al. (2022), is required to successfully handle the multiple phases of evolutionary patterns towards CE such as the detection of problems and opportunities, the generation of new ideas and solutions, and finally their implementation.

Literature have recently investigated the organizational, structural, and technological factors enabling SCDCs. They include aspects such as knowledge creation and integration, experiential learning, organizational restructuring, employee well-being, and technology exploitation (Khan et al., 2020; Elf et al., 2022; Neri et al., 2023; Ritola et al., 2022; Sandberg and Hultberg, 2021; Sandberg and Hultberg, 2021; Santa-Maria et al., 2022). However, these studies mainly focus on the DCs for SC reconfiguration and adaptation, with limited attention on those for SC transformations (Nikookar et al., 2024). This represents a relevant gap of the literature we intend to fill. In this regard, the role of DTs as enabling factors of SCDCs merits further and more specific investigation, as we discuss in Section 2.2.

2.2. Digital technologies enabling supply chain dynamic capabilities

DTs encompass a wide range of technological systems, including Internet of Things (IoT), Big Data Analytics (BDA), Artificial Intelligence (AI), Autonomous Guided Vehicles (AGV), Autonomous Robotic Systems (ARS), Additive Manufacturing (AM), Digital Twin Simulation (DTS), Augmented Reality (AR), Virtual Reality (VR), Cloud Computing (CC), Blockchain (BC), and Cybersecurity (CS) (Ivanov et al., 2019; Oliveira-Dias et al., 2022; Massari et al., 2023; Centobelli et al., 2022). They represent key elements of modern SCs (Rosa et al., 2020), useful for real-time collection, sharing, and analysis of a vast amount of data, the automation of SC processes (Ivanov et al., 2018; Liu et al., 2022), and the security of the entire SC (Oliveira-Dias et al., 2022).

DTs play a fundamental role in enabling SCDCs. For example, DTs foster SC resilience. When BDA is adopted, an increase in the level of SC flexibility and adaptation can be observed (Iftikhar et al., 2021). DTS technology, by increasing visibility and facilitating supply network monitoring, can positively affect SC reaction and adaptation to unexpected changes (Ivanov and Dolgui, 2021). DTs strengthen the development of the so-called digital capabilities i.e., *digital agility* and *digital adaptability*, by permitting focal companies to "*sense, seize and transform*" in a turbulent environment and support the reconfiguration of internal resources and structures to quickly respond to disruptions (Dubey et al., 2023). Similarly, BC technology enables the development of *sensing, seizing,* and *maintaining* capabilities, including visibility, supplier redundancy, collaboration, agility, automation, contingency planning, and risk mitigation (Pattanayak et al., 2023), thus leading the entire SC into a more decentralized, responsive, and trusted ecosystem, characterized by higher resilience performance.

DTs are also critical with regard to DCs for SC circularity. They enhance sensing, seizing, and reconfiguring DCs, which in turn are required for the implementation of CE strategies such as reducing energy consumption, taking back end-of-life products, and green logistic. The simultaneous use of BDA, AI, IoT, CC, and other DTs positively affect the development of corporate CE capabilities with the mediation role played by SC collaboration, SC risk management, and SC integration DCs (Yuan and Pan, 2023). BC permits SC firms to *sense* customer requirements on circular products, *seize* circular business models, and *reconfigure* organizational structures to enhance circular resource flows (Quayson et al., 2023). Furthermore, by enabling information sharing, collaboration, and traceability, BC positively impacts transparency, reverse logistics, secondary material availability, and circular thinking within circular SCs (Meier et al., 2023). IoT is considered an antecedent "*in promoting sustainable activities and thus promoting CE practices such as remanufacturing, reusing and recycling*" (Al-Khatib, 2023).

Similarly to the foregoing studies, we argue that DTs can also play a relevant role by affecting DCs supporting SC transformations towards resilient and circular systems. We investigate this issue by adopting the theory of SESs to conceptualize SCs as transformative systems and to identify the specific class of SCDCs supporting transformations. Then, we advance how DTs affect them. The conceptual framework under investigation is presented in Section 3.

3. The theoretical framework

3.1. The transformative supply chain: a social-ecological model

SESs are open and dynamic systems made up of social and ecological components strongly intertwined (Preiser et al., 2021; Villasante et al., 2022). SESs, like other complex adaptive systems, are characterized by relational constitution, adaptability, dynamism, radical openness, complex causality, and emergence (Preiser et al., 2018). Their behaviors and performance emerge *from the bottom*, influenced by the strong interactions and feedback within and between the system's components and the external environment (Biggs et al., 2015; Preiser et al., 2018). Any change in a SES propagates across time- and space-scales leading to non-predictable cascading effects (Biggs et al., 2015; Rocha et al., 2018). In presence of changing conditions generated either by the system itself or by external forces, the dynamic and non-linear interactions allow the SESs' components to radically transform (Olsson et al., 2014) by intentionally searching, selecting, and adopting new and radically different configurations (Reyers et al., 2018). In fact, transformation covers multiple phases and occurs through the internal feedback loops, which can either dampen or amplify system changes across scales (Rocha et al., 2018). It is thus distinct from adaptation enveloping through single-scale adjustments and changes on SC structures and activities in response to external and internal drivers (Moore et al., 2014; Nelson et al., 2007).

Recently, scholars have applied the SES perspective to study SCs and explore new SC management principles (Gualandris et al., 2024; Nikookar et al., 2024; Statsenko et al., 2024; Wieland, 2021; Wieland and Durach, 2021; Wieland et al., 2023). According to Wieland (2021), SCs are made up of "*dancing*", "*interconnected*", and "*organic*" components intricately connected with the external environment. Wieland and Durach (2021) argued that modern SCs are intricately connected to other SESs operating at different levels, including the political economy and the global ecosystem. Nacchiero et al. (2024) defined social-ecological SCs as "*open, interconnected, and dynamic systems consisting of social and ecological subsystems fully integrated with each other and with the external environment*". This interconnection makes it impractical to manage the system in the manner one would manage a closed, engineering-related system. Gualandris et al. (2024) in fact introduced a novel set of organizational principles i.e., *proportionality, reciprocity,* and *poly-rhythmicity,* useful to manage *regenerative* SCs i.e., inter-organizational networks able to sense the surrounding systems and align their own internal structures and dynamics with those of external systems to enhance strength, resilience, and life sustainability. The transformative nature of modern SCs emerged also from the recent studies on social-ecological resilience (Nikookar et al., 2024; Wieland et al., 2023; Mirzabeiki and Aitken, 2023). In this regard, Nikookar et al. (2024) identified a new set of SC antifragility capabilities such as SC mindfulness, SC transformative learning, SC plasticity, SC bricolage, and SC collaboration, proven effective for post-disruption growth.

In line with the studies above, we define the transformative SCs as "*social-ecological systems capable of transforming towards new configurations more consistent with internal pressures and external challenges*." The internal feedback, driven by non-linear relationships among the system's components, and the changes in the external environment trigger the entire ecosystem's transformation towards new configurations embracing circularity and/or resilience. The transformative pathway towards circularity requires the focal firm changing the current configuration of its SC to collect end-of-life resources and recover value from. This not only affects how resources flow within the ecosystem, but it also inherently implies the need to engage more strongly with end customers and to involve CE stakeholders to partner with, such as reverse logistic and other service providers carrying out repair/remanufacture/

reconditioning operations on used products (Abideen et al., 2021; Bai and Sarkis, 2018; Kellens et al., 2017), waste management companies responsible for recycling processes (Aarikka-Stenroos et al., 2022; Del Giudice et al., 2020; Hazen et al., 2020; Leising et al., 2018), potential re-users of components and parts (Centobelli et al., 2022; De Giovanni, 2022; Sharma et al., 2020), and symbiotic partners for by-product exchange (Batista et al., 2018; Herczeg et al., 2018; Leising et al., 2018; Luthra et al., 2022). The transformative pathway towards resilience requires moving towards reshoring or nearshoring of manufacturing systems, relying on collaborative production networks, purchasing critical materials from local sources, developing flexible and reconfigurable services (Fernàndez-Miguel et al., 2022), and adopting dynamic mass production models relying on shared sourcing and inventory capacities (Liu et al., 2020).

To successfully achieve multi-level and cross-scale transformative changes, the SCTCs should be developed and/or improved. *Triggering* capability involves the ability to analyze the current SC vulnerabilities i.e., identifying internal inefficiencies, losses, and bottlenecks, and to scan the external environment i.e., identifying emerging opportunities associated with new market trends, new customer behaviours, but also those deriving from governmental pressures, social-economic crises, geopolitical conflicts, and technological revolutions. Conceiving new SC configurations and experiment them on small scales requires *envisioning* capability. This involves the ability to explore new solutions by internal R&D efforts, exploit innovative proposals coming from external partners and auditing organizations, and experiment alternative SC configurations. Additionally, it includes the ability to evaluate the feasibility of a limited set of innovative configurations through pilot tests. *Navigating* capability is defined as the ability to recognize the best-performing SC configurations and adopt them widely. This allows SC partners to share all relevant information and agree perfectly on the transformative path to undertake and implement the selected configuration widely within the SC, bringing it to the *large-scale*. *Stabilizing* capability corresponds to the ability to institutionalize the new SC configurations. In this regard, SC partners are required to consolidate the established relationships and standardize new processes and routines characterizing the implemented SC configurations. Stabilizing also involves the ability to deal with resistance to change for whom it is necessary to engage with new stakeholders from different sectors, and strengthen cross-scale relationships with key stakeholders, e.g., customers, non-profit organizations, government entities.

We argue the above SCTCs enable the transformations of social-ecological SCs towards resilient and circular SCs. In line with the studies on digitally enabled DCs presented in Section 2.3., we argue that DTs can also enable the development of SCTCs, which in turn are important for circular and resilient transitions. Fig. 1 shows the conceptual framework under investigation.

3.2. The enabling role of digital technologies on supply chain transformative capabilities

In this Section, based on the literature, we argue how DTs affect the triggering, envisioning, navigating, and stabilizing capabilities characterizing the SCs.

3.2.1. The effects on triggering capability

Triggering capability involves the abilities to identify inefficiencies, value losses, and process' bottlenecks within the current SC configuration, and to analyze new opportunities arising from the external environment scanning including those related to evolving market trends and new customer behaviours, but also those related to governmental pressures, social-economic crises, geopolitical conflicts, and technological revolutions.

In this regard, literature reports numerous cases of how DTs can be adopted to analyze SC operations, track and trace products and resources, as well as promote the triggering-related self-analysis by identifying inefficiencies, losses, and bottlenecks across the entire SC. For example, IoT technology, by enabling the integration of "physical objects" and their connection in digital networked spaces, allows firms to collect in real-time process-related information and continuously monitor process status over time, to acquire material- and product-related information (e.g., quantity, quality, position, temperature) and track them throughout the forward and reverse value chain processes (Ben-Daya et al., 2019; Garrido-Hidalgo et al., 2019). Radio Frequency Identification (RFID) provides real-time identification, real-time material flow and tracing, helping to increase data quality (Ivanov, 2018). The adoption of IoT increases the visibility along the entire SC, ensuring the tracking of raw materials, semi-finished, finished products, stocked materials, assets, and even by-products and waste. IoT-driven visibility, enhanced via real-time monitoring and information transparency (Tsang et al., 2018), makes possible to trace the origin of SC disruptions, observe disruption propagation (Ivanov et al., 2018). Similarly, BC technology results to be particularly significant for the analysis of SC operations since it enhances visibility, traceability, and fostering transparency across SCs. In a BC-based SC ecosystem, transactions are subjected to validation through the consensus of all partners involved, remaining constantly visible to them (Antonopoulos, 2014; Hastig and Sodhi, 2020). The adoption of DTs is very useful to identify and manage SC risks. Firms adopting BDA and AI technologies have improved their abilities in SC risk resilience capability (Singh and Singh, 2019), risk mitigation abilities through a timely identification of operational and SC risks (Choi et al., 2018), disruptions (Dubey et al., 2020), and economic frauds (Lee et al., 2021), and a more accurate evaluation of their impacts (Ivanov et al., 2018). AI algorithms also help organizations to prioritize risks based on their impacts (Bechtsis et al., 2022), quickly and automatically build business continuity plans to speed up recovery (Dubey et al., 2022), devise risk management strategies (Ivanov, 2018), and finally mitigate uncertainty (Bechtsis et al., 2022). BC-based SCs better deal with uncertain environments through the use of decentralized intelligent systems able to quickly detect information frauds and cyber threats (Dashottar and Srivastava, 2021; Riesco et al., 2020), and the increased products' traceability and provenance knowledge reducing the consumers' perceived risk on purchasing second-hand products decisions (Montecchi et al., 2019).

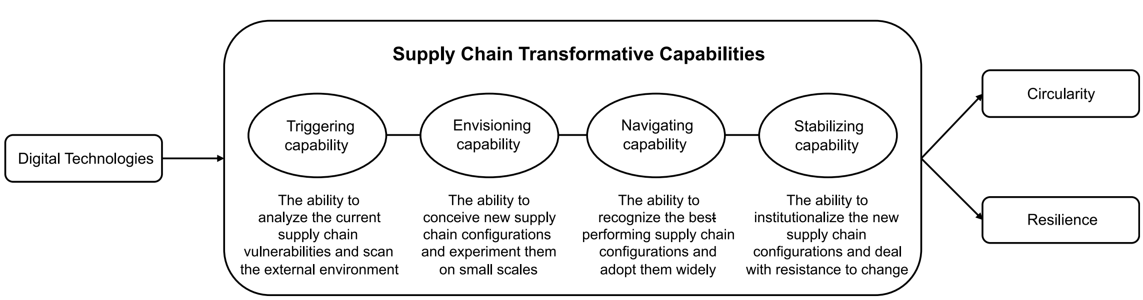


Fig. 1. The literature-based conceptual framework under investigation.

Furthermore, DTs are valuable tools scanning the external environment to analysing and predicting market demand and consumer behaviours. For example, Maheshwari et al. (2021) emphasized the adoption of BDA by organizations to anticipate emerging transformative trends amidst volatile market conditions. By examining historical variations in production lead times and logistics provider performance, Korolov (2018) applied AI-based machine learning (ML) algorithms to improve delivery date forecasts. Feng et al. (2022) highlighted how the use of BDA and ML can be very useful for simulating and predicting consumer behaviors for sustainable products useful in the design phase. Similarly, BDA techniques such as the topic sentiment mining, are used to perform cluster analysis on consumer data collected from Twitter so as to identify subtle trends in consumer purchasing behaviours and develop more efficient, customer-focused, and sustainable SCs (Mishra et al., 2017).

3.2.2. The effects on envisioning capability

Envisioning capability concerns the ability to conceive new SC configurations, experiment them on small scales, and evaluate their feasibility. Digital Twin is rapidly evolving within modern SCs, driving their radical transformations (Liu et al., 2021). Its adoption becomes strategic to support innovation activities within SCs by creating digital prototypes to perform virtually product and process design, validation, and market testing (Lo et al., 2021). As stated by Zheng et al. (2019), DTS could enhance value co-creation processes, since it can be used to create digital space with collecting prototypes and end-users' data for product innovation. While IoT technology facilitates the collection, envisioning, and evaluation of innovative ideas or objects from outbound individuals by providing unique identities and interconnected networks in cyberspace, DTS enables their virtual representation, aiding in effectively modifying their attributes (e.g., shape and materials) through virtual monetization mechanisms (Rahmanzadeh et al., 2023). AM may also play an essential role on envisioning capability. AM is extensively used for rapidly producing and testing conceptual and functional prototypes (Mellor et al., 2014), complex assemblies (Luomaranta and Martinsuo, 2020), and highly customized and innovative products (Candi and Beltagui, 2019). 3D printing is replacing expensive and time-consuming production, enabling SC designers to iterate through multiple different trials at a low cost and so improving product design and innovation. In the automotive industry, where electrification is a prominent trend, AM offers the opportunity to develop lighter parts for electric vehicles, essential for improving battery life and overall vehicle performance (Prashar et al., 2023). By enabling the visualization of envisioned solutions on a smaller more manageable scale (e.g., niche market products, and capsule collections), AM allows SC firms to assess feasibility, identify potential challenges, and refine strategies before scaling up to a global SC level.

3.2.3. The effects on navigating capability

Navigating capability concerns the ability to recognize the best-performing SC configurations and adopt them widely. This phase is inherently complex as it requires SC partners to develop trust-based collaborative relationships. DTs thus can play an enabling role to support the navigating capability as they promote collaboration. Through BC-based smart contracts, firms can rapidly build trustful relationships, as well as automatically monitor and strengthen the level of trust in existing relationships (Lohmer et al., 2020). The decentralized, open, and cryptographic nature of BC technology (Choi et al., 2020), ensures automated information sharing, thus increasing information sharing and reducing the possibility of SC partners missing important communication. The same technology provides manufacturing companies with a secure access to collaborative production networks, thus using shared resources instead of relying on excessive inventory levels (Wang et al., 2021). Information sharing is also increased by collecting data through the use of IoT devices (Li et al., 2020). CC and cloud manufacturing technologies are also important for developing a collaboration-based approach among SC partners. Cloud manufacturing service platforms provide virtual portals that facilitate the creation of a shared network of resources and capabilities (Gupta et al., 2019; Yu et al., 2015). The combined adoption of cloud manufacturing and AM promotes co-creation and open design strategies while stimulating creativity and resource sharing essential for navigating. According to Beltagui et al. (2020), digital platforms, like 3D Hubs, democratize access to manufacturing capabilities, empowering consumers to become active participants in the innovation-oriented processes within SCs. CC-based 3D printing tools provide manufacturers with access to online digital design services without the need for acquiring the technology on their own (Xie et al., 2019). BDA and AI are useful for improving the collaboration with customers and suppliers (Ivanov, 2018) and relevant SC partners (Mandal, 2019). These technologies are also essential for implementing the best-tested configuration in a controlled and efficient way i.e., improving the performance of existing operational tasks (Hopkins, 2021), without incurring in excessive costs (Belhadi et al., 2019), reducing future SC inefficiencies (Abdel-Basset et al., 2018), waste, and emission production (Raut et al., 2019). SC firms leverage AI-powered technologies to efficiently design processes, eliminate waste, implement real-time monitoring for error-free production, and facilitate lower process cycle times, all crucial in accelerating transformation and bringing new products to market faster (Dash et al., 2019). Raut et al. (2019) focused on the effects of BDA-enabled green SC practices, suggesting their relevant role in reducing carbon dioxide emissions, improving sustainable development collaboration, and increasing consumer green satisfaction. SC process optimization comes also from the adoption of ARS that are considered versatile assets capable of adapting to evolving production requirements and dynamic market demands. ARS provide unmatched flexibility and agility, enabling SCs to remain responsive in the face of transformative change, whether it is involving scaling production volumes, accommodating changes in product specifications, or integrating other new technologies into manufacturing processes (Kamble et al., 2018; Koh et al., 2019). For example, the use of Intelligent Autonomous Vehicles reduces shipping and fuel costs, minimizes the occurrence of accidents, and decreases CO_2 emissions (Bonnefon et al., 2016; Heard et al., 2018).

3.2.4. The effects on stabilizing capability

Stabilizing capability concerns the ability to institutionalize the new SC configurations, through the standardization of new relationships, processes and routines, and deal with resistance to change through a stronger stakeholder engagement. CC-based platforms are considered essential to integrate new stakeholders (Gregori and Holzmann, 2020) and strengthen customer relationships (Matzembacher et al., 2020). According to Shee et al. (2018), a CC-based SC enables supplier-to-customer integration via a timely information sharing and a higher level of information backbone. Digital platforms increase the effectiveness of information-, knowledge-, and resource-sharing, necessary for stakeholder engagement (Ridley-Duff and Bull, 2021; Tajvidi and Tajvidi, 2021). Customer engagement is crucial to stabilize an innovative SC configuration. Technologies for digital communication help in this regard by enabling the SC to reach wide audiences (Kao and Luarn, 2020).

In doing so, the social media-related DTs also bolster the stabilizing-related marketing aspect, crucial for SC firms to externally communicate their transformative goals, e.g., sustainability, circularity, resilience, and the achieved post-transformation configuration. While Calder et al. (2009) highlighted the positive impact of engagement through online media on advertising effectiveness and user awareness, Gummerus et al. (2012) emphasized the necessity of entertaining content and opportunities for socialization e.g., within Facebook communities, to ensure long-term engagement behaviors. As suggested by Jahn and Kunz (2012), fan pages can serve as excellent tools for companies to foster positive customer-brand relationships. Through these platforms, SC firms can fully engage, integrate, and immerse their end-users in a vibrant and active community where they can share contents on current topics and raise awareness about new paradigms. The use of digital objects such as digital tags and QR codes can increase customer engagement and cultural awareness (Sunny et al., 2020) by efficiently communicating details about the materials used, resource consumption, CO_2 emissions, and quality of repair, as well as emphasizing aspects like material circularity or social and environmental sustainability performance. It was found that Twitter is extensively utilized for stakeholder participation, business promotion, and contract provision. In line with these findings, it has been widely demonstrated that BDA facilitated more accurate sales opportunity identification, better targeted marketing (Belhadi et al., 2019; Hazen et al., 2014; Wang et al., 2016). Furthermore, branding and communication strategies are essential to promote innovative configuration to customers. For instance, a SC that transformed itself towards an innovative circular configuration should motivate customers to buy a circular product. DTs may help in this regard. Vogels et al. (2018) studied the role of food-waste mobile apps, e.g., reminder and food-storage ones, in guiding consumer behaviors towards a more sustainable direction. They found that consumers often lacked motivation to use these apps, feeling that the costs, in terms of time or energy, outweighed the benefits. In recent decades, a range of food-sharing apps and web platforms were created to increase the reuse of surplus food e.g., from households, restaurants, retail, and other sources, while contributing to sustainable and circular SC practices (Bolwig et al., 2021; Michelini et al., 2018). Urdea et al. (2021) revealed that DT-based experiential marketing contributes to establish sustainable long-term customer relationships by providing several advantages for companies, e.g., attractiveness, brand engagement, loyalty, and customers, e.g., satisfaction, confidence, personalization. VR can provide unprecedented experiential shopping value to impact positively on consumers' approach intentions and mindset, thereby contributing to the stabilization of downstream SC stages. Exploring the advanced Nike VR store, Jiang et al. (2019) stated that "fashion retailers can create a fantasy-like store environment that does not exist in the real world and can effectively communicate emotional fashion information with vibrant and fantastic 3D images and sounds" by using VR technology. However, they found that mere technological advancement alone is not enough to positively influence customers. Customers need to perceive high vividness and interactivity to exhibit stronger approach intentions. Moreover, they discovered that such positive influences are serially mediated by perceived telepresence and experiential shopping value. In their research, Hilken et al. (2022) illustrated how the combined use of AR and VR can positively impact purchase intentions and brand attitudes. Interestingly, they found that this effect is contingent upon the sequence of deployment, with AR preceding VR.

4. Methodology

To pursue our research aim, we adopted the grounded theory methodology, as proposed by Strauss and Corbin (1998), since this is proven suitable to explore under-researched phenomena occurring within SCs (Wieland et al., 2024), such as the transformative processes we intend to address in this study. The methodology prescribes developing a literature-based conceptual framework (see Section 3), and then exploring this through the analysis of multiple case studies (Eisenhardt, 1989). In the following sections, we describe case study selection (Section 4.1.), data collection (Section 4.2.), and data analysis processes (Section 4.3.).

4.1. Sample selection

As samples, we searched for Italian companies operating in Made-in-Italy sectors that have recently transformed their SCs. Recent studies have in fact shown that Italian companies are strongly committed to CE principles and synergically implement CE strategies on the level of SCs (Ghisellini and Ulgiati, 2020; Mura et al., 2020). Italy is also ranked first among the main EU countries, based on the degree of resource use in production and consumption, waste management, and second raw materials among other indicators (Circular Economy Network, ENEA, 2020). Italian companies received also financial support by Italian government through the National Plan for Recovery and Resilience, to initiate, govern, and complete their SC transformations towards resilience and circularity (Minelle et al., 2022). We focused on Made in Italy sectors, given their relevance for Italian economy, and selected fashion and furniture industries, since they are addressing severe challenges to remain competitive in the current competitive environment. We selected most-representative samples through secondary data sources, such as the sustainability reports of Made-in-Italy sectors (Symbola, 2020, 2021), recently proven to be effective to report circularity issues (Massari and Giannoccaro, 2024) as well as reported actions to pursue resilience. We selected ten firms and checked for the availability of practitioners playing prominent roles, such as CEO, Logistics Manager, Sustainability Manager, Marketing Manager, to be involved in semi-structured interviews. We received confirmation from eight practitioners, each representative for a different company, hereafter anonymized as A, B, C, D, E, F, G, and H. Table 1 reports additional information of the final samples.

4.2. Data collection

We developed the case-study protocol according to Yin (2009). First, a questionnaire was developed to conduct semi-structured interviews (see Appendix A). In line with our research purpose, we formulated multiple questions that aim at exploring two specific topics: (1) the SC transformations towards circularity and resilience, and (2) the influence played by DTs on the SCTCs. Primary data were collected by carrying out 8 semi-structured interviews that were registered through Microsoft Teams platform (see Appendix A for the entire questionnaire).

4.3. Data analysis

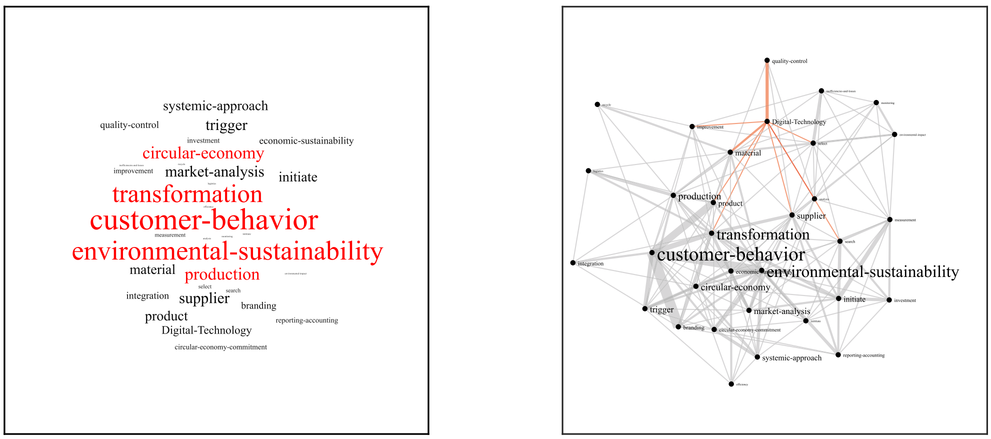
Collected data were then analyzed by employing a systematic and structured approach (Gibbs, 2007). First, all the interviews recorded were transcribed by using the AI-based tool NVivo Transcription, an automated transcription software ensuring a high-level of accuracy (90%). The transcribed notes were then checked by all the authors to avoid mistakes and repetitions. Second, a two-step manual coding (open and axial) was performed to extract keywords and concepts (Corbin and Strauss, 2007) and categorize them in terms of SCTCs, DTs, and CE/resilience performance. All the authors independently performed the coding activity and then converge on the codified concepts (Santa-Maria et al., 2022). The codified concepts were analyzed to uncover main concepts associated with each SCTC and the DTs and to explore the relatedness among them.

5. Results

We now analyze the keywords used by practitioners to explain the distinctive phases that characterize SC transformations. The word-clouds shown in Figs. 2a–5a report the keywords relevant for SC transformations as cited ≥ 3 times by practitioners (the larger the word, the higher the frequency of citation). The co-occurrence networks shown in Fig. 2b–5b visualize the relatedness among previous keywords (the thicker the edge between two keywords, the higher the frequency of co-citation). In line with our conceptual framework (see Section 3.1.), "transformation" (total number of citation equal to 35) envelops through a "systemic approach" (8) consisting of four distinctive phases. Both "environmental sustainability" (17) and "economic sustainability" (6) "trigger" (9) focal companies to "initiate" (8) their transformation by "monitoring" (3) current "inefficiencies and losses" (3), "reporting-accounting" (5) them, carrying out "market analysis" (9) and understanding "customer behavior" (20). In this regard, the keyword "Digital

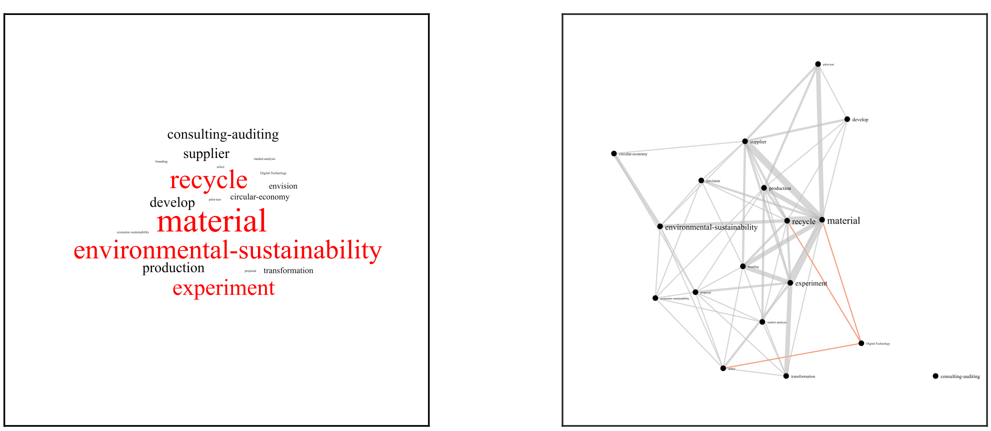
Table 1
Additional information of the samples.

Company	Industry	Product	Company's role	Size	Role of respondent
A	Fashion	Clothing, accessories, footwear, perfumes, jewellery, home items, travel goods	Manufacturer	Large	Supply chain and logistics Manager
B	Furniture	Kitchens, bathrooms, sofas and seating, cabinets and shelving units	Manufacturer	Large	Quality and Environment Manager
C	Fashion	Fabrics	Supplier	Large	Sustainability Manager
D	Fashion	Yarns	Supplier	Medium	Chief Executive Officer
E	Fashion	Outerwear, accessories	Manufacturer	Small	Sustainability Manager
F	Fashion	Fabrics	Supplier	Small	Marketing Manager
G	Fashion	Yarns	Supplier	Large	Marketing Manager
H	Furniture	Design and furniture items	Manufacturer	Micro	Chief Executive Officer



(a) (b)

Fig. 2. The word-cloud (on the left) showing the keywords frequently used (cited ≥ 3 times) in relation to triggering capability, and the co-occurrence network (on the right) showing the relatedness among previous keywords.



(a) (b)

Fig. 3. The word-cloud (on the left) showing the keywords frequently used (cited ≥ 3 times) in relation to envisioning capability, and the co-occurrence network (on the right) showing the relatedness among previous keywords.

Technology" is mentioned multiple times (7) and, specifically, it is cited together with other keywords like "analysis" (total number of co-citation equal to 1) and "quality-control" (3). To "envision" (4) an alternative "proposal" (3) of current SC configuration and to "experiment" this (7) requires conducting "pilot test[s]" (3) on i.e., newly designed "material [s]" (10). The keyword "Digital Technology" is mentioned multiple times (3) and, specifically, it is cited together with other keywords like "material" (1) and "recycle" (1). To "develop" (3) the selected proposal requires not only economic "investment[s]" (6) but also building "partnership[s]" (13) with "supplier" (15), favoring "information-sharing" (12), and implementing strategies for "market-penetration" (11). The keyword "Digital Technology" is mentioned multiple times (8) and, specifically, it is cited together with other keywords like "product" (2), "efficiency" (2), and "production" (1). We note that also "information-sharing" is mentioned different times (12) and, specifically, together with "market-penetration" (4), "partnership" (3), "production" (3), "supplier" (2), and "material" (2). Finally, to "stabilize" (7) requires the "consolidation" (4) and "standardization" (6) of transformative changes through "branding" (9), "trustworthy relationship[s]" (7), "information-sharing" (5) and "communication" (4). The keywords "Digital Technology" and "IoT" are frequently mentioned (5 and 4 times, respectively) and, specifically, they are cited together with the keyword

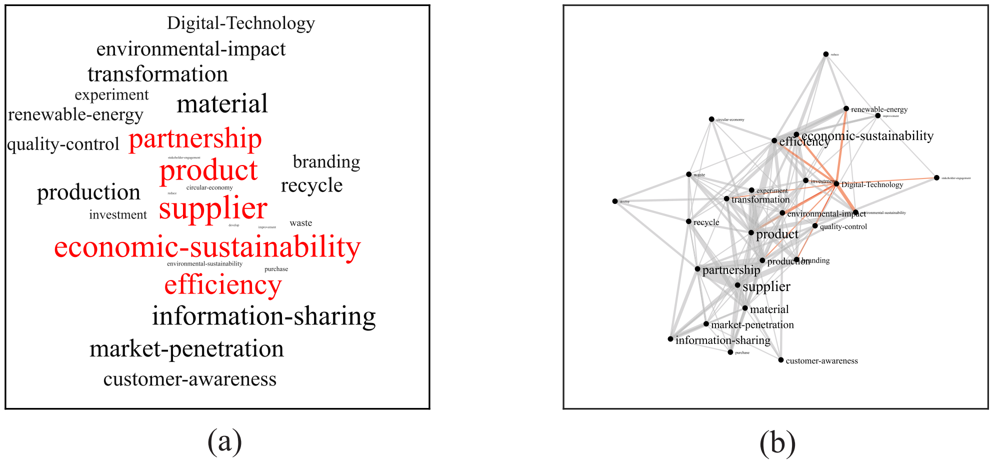


Fig. 4. The word-cloud (on the left) showing the keywords frequently used (cited ≥ 3 times) in relation to navigating capability, and the co-occurrence network (on the right) showing the relatedness among previous keywords.

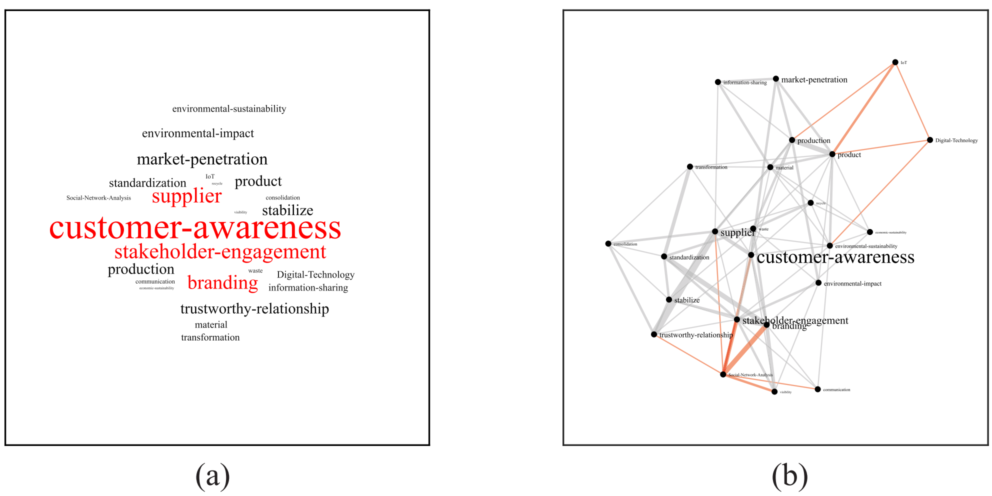


Fig. 5. The word-cloud (on the left) showing the keywords frequently used (cited ≥ 3 times) in relation to stabilizing capability, and the co-occurrence network (on the right) showing the relatedness among previous keywords.

"product" (1 and 2 times, respectively). We note that also "social-network-analysis" is cited frequently (4) and, specifically, together with other keywords such as "stakeholder engagement" (3), "visibility" (2), "customer awareness" (2), and "communication" (1).

The qualitative findings explained in the next sections illustrate how more in details how important triggering, envisioning, navigating and stabilizing capabilities are for SC transformations, and the enabling role played by DTs on each of the above capabilities.

5.1. The supply chain transformative capabilities

5.1.1. Triggering capability

According to practitioners, successful SC transformations require holistic and systemic approaches. In this regard, the analysis of our case studies shows that common and distinct factors drive focal companies to transform their supply chains into more circular and resilient systems. A common denominator is the pursuit of higher competitive advantage (Companies A, B, C, D, E, F). In other cases, companies transform their SCs to respond to specific needs i.e., to align linear SC configurations with the owner's long-term sustainability vision (Company G) or to meet fast-growing customers' sensitivity for sustainable and circular products (Company D). To achieve this, companies have to re-think material and product -handling problems as well as the corresponding manufacturing processes. As emphasized by practitioners, several solutions can be implemented. Reducing the consumption of natural resources (energy, natural gas and water) by replacing them with self-produced and renewable ones (Companies A, B, F), reducing the consumption of virgin fabrics by replacing them with those purchased from certified sustainable suppliers (Companies D, E, F), eliminating single-use plastic packaging (Company A), minimizing the production of industrial wastes (Company A) and releasing less harmful chemical substances (Companies C, E) are in fact all effective ways to produce economic advantages, reduce environmental impact of supply chain operations, and decouple manufacturing processes from vulnerable global sources. In this regard, practitioners explain the importance of carrying out internal assessments to evaluate energy and material consumption along the entire product life-cycle, carefully monitor resource-intensive processes and locate major inefficiencies (Company D), revise risk management and business continuity plans to address ESG risks other than only financial risks, and legal and regulatory risks (Company A), define and adopt qualitative and quantitative indicators for circularity performance measurements (Companies E, F), and finally pinpoint opportunities for improvements and transformations (Companies F, D). According to some practitioners, sustainability reporting activities help companies to disclose in a systematic way current and past transformative changes and formalize further efforts to pursue in the future (Companies A, C).

Alongside internal evaluations, our case studies reveal the importance of conducting comprehensive analyses also on the external environment. The analysis of emerging regulations, directives and norms permit companies to transform accordingly and hence to become more legally compliant with them (Companies G, H). The analysis of commodity markets helps companies quickly identify new strategic suppliers and better select those complying with multiple environmental criteria (Company E). Market analyses allow companies to collect and interpret a large amount of data and signals from consumers to anticipate demand changes, uncover shifts in consumer preferences and effectively respond to them (Company D), from supply chain partners to recognize material supply shortages (Company B) and other potential disruptions (Company H) and better prepare for them.

5.1.2. Envisioning capability

The driving factors push focal companies to envision alternative SC configurations that enhance circularity and resilience. In this regard, our empirical findings show that novel configurations for resilient SCs, decoupling supply chain competitiveness from economic instabilities and global supply markets' vulnerabilities, emerge when focal companies' managers, in their attempt to enhance internal strategies and processes, take into consideration and explore in details innovations led by newcomers, competitive firms, and leading multinational corporations (Company H). More circular and sustainable SC configurations are instead co-envisioned by internal departments (especially R&D and CSR) and raw material suppliers (Companies A, G) or recommended by external consulting firms that had previously observed and monitored the focal company's internal processes (Company D). Our findings also show that SC configurations relying on technologies and assets from local recyclers and resources from national consortia and suppliers, thus securing resilience and circularity, arise from a combination of internal R&D efforts and the observation of external companies such as competing manufacturers (Company B).

The envisioned solutions, despite representing promising innovations, do not always guarantee a corresponding success in the market. To become successful, a series of preliminary trials and validation tests are required to check the feasibility of the proposed solutions. More specifically, practitioners refer to various laboratory experiments to test thermo-mechanical properties of recycled wood (Company B) as well as the durability and recyclability of new wool textiles (Company F), which in turn are required to certify circular products. More structured activities refer to complex pilot projects such as those carried out in collaboration with non-profit organizations to increase the reuse of second-hand products by means of donations and charity initiatives (Company E), or those developed to evaluate the efficacy of emerging technologies like wool fiber tracer systems (Company C).

The implementation of successful initiatives preliminary occurs at a local scale i.e., such as limited capsules collections and fashion trials (Companies A, B, D, E, and F), before being scaled up at higher levels i.e., typically the whole SC (Company E). Only one practitioner has referred to their implementation across all fashion collections directly (Company C). Most-promising solutions are patented as is the case of sustainable nylon yarns made up of by-products (Company G), recycled polyester fibers used to reproduce lightweight and breathable jackets' fillings without neglecting thermal insulation capacity (Company E), special fibers able to decompose into biomass and biogas much faster than other synthetic fibers thanks to, and a new polyamide yarn manufactured with pyrolysis oil derived from discarded or used tires (Company G).

5.1.3. Navigating capabilities

The envisioned configurations are then implemented throughout the SC. To this aim, SC partners have to navigate the selected transformative change. Practitioners revealed that SC firms need to embrace a collaborative district-based logic and develop partnerships (Company G) required to create value for the entire network they belong to (Company A). Closer collaborations among SC partners (Company H), stronger collaborations with upstream suppliers (Company C) and downstream logistic providers (Company E) should go beyond commercial purposes and should pursue mutual contamination of know-how and resources (Company H) by leveraging the mechanisms of information-sharing. Such a collaborative approach facilitates the collective adoption of new configurations by all SC firms and hence enables to *scale-up* best-tested SC configurations. In this regard, however, practitioners also stressed the importance of adapting all SC processes to pursue high resource efficiency targets. To this aim, some companies adopted specific standards and requirements (Company B), other ones replaced carbon-based energy sources with environment-friendly ones (Company C).

5.1.4. Stabilizing capability

Finally, practitioners emphasized the need to stabilize transformations, that is to consolidate changes and turn them into new organizational routines (Company A). This is achieved when customers are fully conscious of "what" they are purchasing from the company and hence are able to recognize the value of circular products that means understanding what the company actually does to recover value from by-products and wastes, to transform them into circular products and then to provide post-sale services to further prolong product life cycle (Company F). On the contrary, when circular products are not yet fully accepted by customers, it becomes crucial to reiterate or even strengthen communication with customers to better emphasize products' circularity through transparent information on their composition and on the consecutive processes required to maintain their value for as long as feasible (Company G). To overcome resistance from end-customers, it is crucial to spread CE culture among them and highlight how their behaviors produce environmental, economic, and social benefits. In this regard, initiatives like the development of internal academies, learning courses and educational projects on circularity topics (Company C), or the strategic engagement with non-profit organizations that, through their diversified network, foster consumer acceptance of circular products (Company D) are considered important by practitioners. These initiatives lead to a greater involvement and openness of the entire SC towards key external stakeholders (Company E). Table B1 (see Appendix B) reports the relevant quotes on SCTCs.

5.2. The digital technologies enabling the supply chain transformative capabilities

5.2.1. Digital technologies enabling triggering capability

Our analysis revealed that DTs play a relevant role to enable triggering capability. For example, BDA and AI, by facilitating the collection and processing of vast amounts of data, are particularly relevant for identifying inefficiencies of manufacturing processes. BDA and AI have been successfully integrated within human-based quality control tasks for enhancing and streamlining quality control processes. This is particularly useful in textile industry, where distinguishing between "*very difficult-to-see defects,*" small imperfections, and what instead are the "*style*" features, is a complex task that requires iterative execution when manually performed (Company C). BC technology helps manufacturing companies validate certifications and compliance documents required to certify product's circularity and sustainability. This technology enables the traceability and validation of raw materials characteristics, confirming that a specific material originates from a facility specializing in material recycling (Company A). BC-based immutable records make easy and secure to trace products' history from origin to end consumer, identifying where vulnerabilities, such as tampering and delays, occur. BC technology has been successfully installed on *standalone* digital applications and *ad-hoc* software, and hence used to trace the provenance of wool fibres and yarns to underpin the sustainability of final fabrics (Company C) and to fully control each single phase of production processes, from raw material sourcing to spinning, from coning to warping, from weaving to finishing (Company F). *End-to-end* visibility, enhanced through the combined use of BC and cloud-based digital platforms, ensure that SC firms access real-time information about products' status, goods' location, and then integrate this with complementary data like internal quality tests, so as to promptly identify process' bottlenecks and understand organization's own strengths and weaknesses (Company F). Furthermore, the combined adoption of CC, BDA and AI technologies help companies gathering information about consumers' behaviours, their interactions with their own retailers or even with other brands (Company A). The combined use of BC, IoT, and CS technologies helps to quickly identify and address other kinds of vulnerabilities, such as frauds and counterfeiting. The authenticity of products is easily verified through the use of RFID tags registered on secure BCs, whilst intellectual property is protected through the use of real-time monitoring systems that contrast the sale of non-fungible tokens (Company A). Other CS technologies such as intrusion detection systems protect SC data and systems from cyber threats, so enhancing the security of SC operations (Company A). Based on the findings above, we formulate the following two propositions.

P1. AI, BDA, BC, CC, CS, and IoT technologies, by enabling the ability to analyze current supply chain vulnerabilities, positively affect the development of triggering capability.

P2. AI, BDA, and CC technologies, by enabling the ability to scan the external environment, positively affect the development of triggering capability.

5.2.2. Digital technologies enabling envisioning capability

AM technology plays a relevant role in this regard. It allows for a rapid creation of customized prototypes characterized by complex geometries that cannot be reproduced otherwise. The low cost of prototypes allows for multiple product design tests. When there is the need to create a prototype, e.g., regarding handles or other furniture products, 3D and digital printing technologies are effective tools, supporting internal R&D efforts during new product design and development (Company B). This is crucial to explore new SC models at small-scales before their scale-up. For example, AM has been successfully adopted to produce 3D printed furniture out from recycled materials (Company H) and hence can become crucial in the construction of 3D printed houses. In so doing, AM can also reduce supply risks by creating the opportunity to replace missing materials with the 3D printed ones (Company H). AM technology permits to envision alternative configurations for retailers' facilities, maintaining the complex architecture of high fashion stores. It also enables the production of new garment and accessory prototypes using physically accurate textiles, including leathers, in an increasingly sustainable way (Company A). Based on the findings above, we formulate the following two propositions.

P3. AM technology, by enabling the ability to conceive new supply chain configurations and experiment them on small scales, positively affects the development of envisioning capability.

5.2.3. Digital technologies enabling navigating capability

AI technologies are crucial to enable the development of advanced decision-making tools for guiding managers towards the selection of optimal decisions. This is fundamental for selecting best-performing SC configurations and management strategies. AI applications permit to gather, collect, and study information more effectively and immediately to acquire new knowledge and hence are important for multiple purposes (Company B). Product Lifecycle Management systems exploit the potential of IoT and AI technologies to identify and execute optimal product design, production, planning, and disposal strategies, so as ensuring resource efficiency and helping the company promptly respond to the forthcoming European regulations on sustainability claims (Company A). Ad-hoc software solutions leveraging CC and BDA technologies ensure real-time monitoring of sales and distribution processes (Company E) and hence support what-if scenario analyses that in turn is critical for recognizing best-performing SC configurations.

DTs, by enabling process automation on large-scale, significantly influence the efficiency of SC operations. The adoption of cloud-based digital servers supports the creation of digital fabric models and the storing of detailed information, including article code and colour and technical features about every fabric and garment entering and/or leaving the company (Company F). The digital archive thus permits the buyer and/or the stylist to search for the desired fabric directly through the server, without the need of receiving the corresponding physical fabric sample. This eliminates the need for extensive production of sample materials and reduces the environmental impact (e.g., 85% reduction in CO_2 emissions) of express shipments (Company F).

The adoption of IoT-based factory management software systems ensures to remotely plan downtime on machines and/or stop them when necessary, thus avoiding excessive energy consumption and reducing the need for manual control operations (Company D). BC-based technologies help companies to record, collect and monitor data on textile recycling processes that are useful especially for detecting errors occurring during the manufacturing cycles, and hence ensuring minimal deviations from quality standards, among recycled textile yarns (Company G). SC data management software exploits AI, BDA, and IoT technologies to provide a systemic view of SC functions including procurement, production, inventory, logistics, and sales. This facilitates data collection, integration, and the corresponding information-sharing among key SC partners (Company F), so improving their collaborative relationships. Through a transportation management software, companies increase suppliers' visibility thus enabling them to adapt and align more effectively with internal logistics. This approach prioritizes the development of long-term partnerships rather than isolated or "spot collaborations", paving the way for joint decision-making and co-creation essential for building integrated supply chains, networks, or industrial districts (Company A). Vendor management web-based applications exploit CC technology to strengthen focal company's relations with its own suppliers by providing advanced systems for suppliers monitoring and rating, which in turn ensure transparency in purchasing practices, compliance with the company's policies and alignment with sustainability objectives (Company A). Based on the findings above, we formulate the following two propositions.

P4. AI, BDA, BC, CC, and IoT technologies, by enabling the ability to recognize the best-performing supply chain configuration, positively affect the development of navigating capability.

P5. AI, BDA, CC, and IoT technologies, by enabling the ability to adopt the best-performing supply chain configuration widely, positively affect the development of navigating capability.

5.2.4. Digital technologies enabling stabilizing capability

The adoption of DTs significantly affects the level of consumers' trust, which is fundamental for strengthening customer engagement.

The combination of BC and IoT technologies permit to track the entire product life cycle. This is particularly needed on luxury items for whom proofs of authenticity and transparent information on product's history i.e., responsible sourcing and ownership changes, have to be vehiculated in a secure way i.e., through BC-based platforms (Company A), from manufacturers to final customers. As another example, digital product passports, often referred to as a "*digital identity cards*," offer to customers comprehensive information about a product, including its composition, the provenance of its materials, certifications, and even the machinery used in its production (Companies D, E). Companies are increasingly focusing on generating detailed digital contents for each product, highlighting not only its physical characteristics but also its sustainability attributes. This implies providing transparent information transparency about the supply chain, production locations, materials used, and raw material certifications, thus enabling more informed and responsible consumer experiences (Company E).

Digital market channels and social shopping tools further strengthen the relationships with consumers (Company F). Social media platforms, websites, and other technologies for digital storytelling are crucial for promoting the company's vision and activities to external stakeholders including international audiences, investors, industry critics, and even young customers. These are strategic means not only to consolidate brand's circularity but also to increase consumers' awareness on the importance of responsible consumption behaviours, driving their engagement in product redesign (Companies E, G). Improved customer experience is a further crucial aspect that enhances customer satisfaction and loyalty. CC technologies advance digital marketplaces and omnichannel communication tools, thus providing end customers with a better personalized shopping experience (Company A). This personalization can be further enhanced through the integration of VR technologies. For example, VR headsets allow end customers to select the preferred furniture products, by choosing them directly from a virtual showroom, and checking how they would look like within their own home (Company B). They also can easily test product's functionalities and customize their own products, based on the desired features including colour, dimension, material, and others. Beyond enhancing customer experience, VR technologies also serve as effective tools for employee education on critical topics, such as ocean literacy, environmental conservation, and the adoption of sustainable practices, fostering greater awareness and responsibility (Company A). DTS technologies allow firms to create 3D models of fashion products (e.g., shoes), which faithfully reflected every detail (size, shape, material, and colours). The embedded configurator allows customers to interact with the 3D model and customize it based on their preferences (Company A). AM technology enhances the effectiveness of visual merchandising strategies that, by affecting consumer purchase behaviours, strengthen relationships with them. AM in fact allows the creation of 3D printed retail stores characterized by the same architecture of high-fashion clothes stores (Company A). Based on the findings above, we formulate the following two propositions.

P6. AM, BC, CC, DTS, IoT, and VR technologies, by strengthening the relationships with key stakeholders, positively affect the development of stabilizing capability.

Fig. 6 shows the enabling role of DTs on each SCTC. Table B2 (see Appendix B) reports the relevant quotes on the DTs enabling each SCTC.

6. Conclusions

Modern SCs are constantly transforming towards circular and resilient systems in response to internal and external pressures. Understanding how to effectively enable SC transformations thus represents one of the major concerns for both scholars and practitioners.

We addressed this emerging issue by developing a novel conceptual framework that investigates, under the theoretical lenses of SESs (Gualandris et al., 2024; Wieland and Durach, 2021; Wieland, 2021; Wieland et al., 2023) and DCs (Teece et al., 1997), the enabling role of DTs in supply chain transformations. The framework was explored through the analysis of eight case studies referring to companies operating in Made-in-Italy sectors that have recently undertaken SC transformations toward circularity or resilience. Based on our empirical findings, transformative SCs are endowed with triggering, envisioning, navigating and stabilizing capabilities which are positively influenced by the adoption of specific DTs. More specifically, AI, BDA, BC, CC, CS, and IoT enable the development of triggering capability. These technologies facilitate the monitoring and control of internal processes, enabling the rapid identification of risks and vulnerabilities related to product quality and authenticity, as well as environmental scanning through the analysis of demand patterns and consumer behaviors. AM technology plays a pivotal role in supporting R&D activities for product innovation and experimenting with new SC configurations on small scales, thereby enabling the development of envisioning capability. Navigating capability is enabled by the application of AI, BDA, BC, CC, and IoT technologies. They enhance decision-making processes, particularly during the product design and development phases, by improving the accuracy of operational tasks and facilitating information sharing and collaborative strategies with upstream supply chain partners. Finally, AM, BC, CC, DTS, IoT, and VR technologies, by strengthening the relationships with key stakeholders, enable the development of stabilizing capability. They are fundamental in enhancing communication strategies, while improving customers' experience and their commitment to responsible material usage behaviors.

This study provides both theoretical contributions and managerial implications. First, it contributes to the SC management literature by providing a better understanding of transformative SCs. We conceptualize transformative SCs as "*social-ecological systems capable of transforming towards new configurations more consistent with internal pressures and external challenges*" through a specific set of DCs i.e., the SCTCs. In so doing, we complement the recent studies investigating social-ecological SCs by focusing on the interconnected components (Nacchiero et al., 2024), the relationships that SCs have with other SESs (Wieland and Durach, 2021), and the organizing principles of transformative SC management (Gualandris et al., 2024; Wieland, 2021). In this way, we also respond to recent calls for empirical investigations on how SC transformations unfold in practice (Zils et al., 2023). Second, this study extends the literature on the antecedent factors of SCDCs by investigating the factors enabling SC transformations. In particular, we underscore the critical importance of DTs and advance new propositions concerning the enabling role played on each SCTC.

From the managerial point of view, our results recommend managers developing triggering, envisioning, navigating, and stabilizing SCTCs to support the transformation of their SCs into resilient and circular systems. In this regard, our findings suggest novel practices for successful transformation. They include conducting market research to capture the

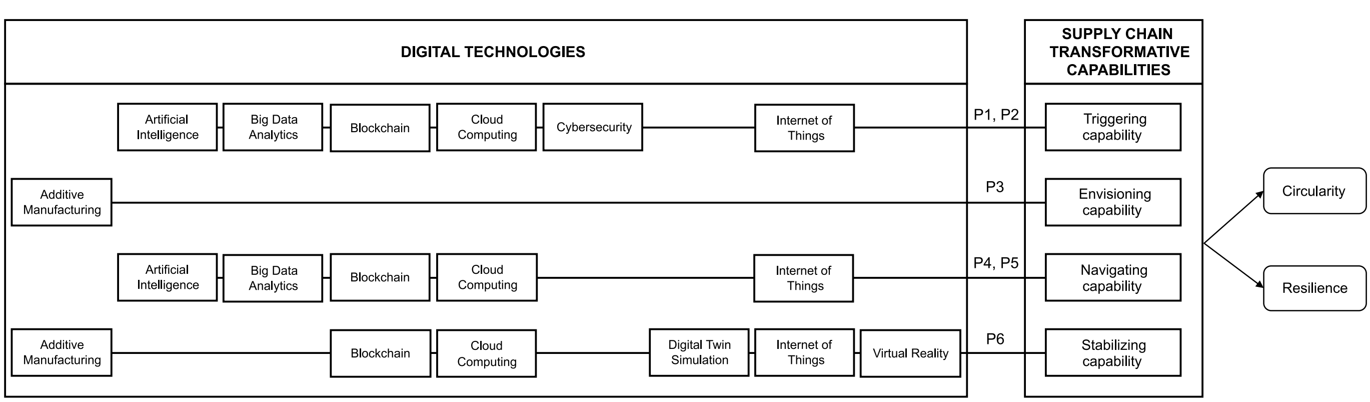


Fig. 6. The validated framework explaining how DTs enable SCTCs for circularity and resilience.

evolution of industry trends, identifying key performance indicators for measuring, accounting, and reporting on resource circularity, exploring "local" SCs and learning new opportunities from them, feeling dynamic customers' sensitivity towards circular products, and refining risk management culture and correspondent methodologies to trigger the transformation. To envision new SC configurations, carrying out research projects to design sustainable raw materials (e.g., recycled wool/polyester fibers), developing patents, conducting laboratory tests for life-cycle analyses on a limited set of products, and, finally, conducting pilot projects to test the feasibility of technological solutions (e.g., DNA tracers) result to be essential practices. Navigating the transformative change mainly involve selecting sustainable suppliers to purchase high-quality secondary raw materials, adopting new codes of conduct current suppliers have to comply with, and upgrading production plants to comply with stricter environmental regulations and circularity standards. Finally, best-practices for stabilizing the transformation concern the intensification of the collaborations with universities and R&D institutions, the establishment of partnerships with non-governmental organizations to increase material circularity out of the original sector's border, the adoption of standard rules and codes of conduct enduring circularity over time, the consolidation of the relationships with end-customers through gamification, the development of academies for talent scouting and empowerment programs for better employees' education and experience.

Our findings also inform managers who are engaged in SC transformations on most-effective DTs i.e., those simultaneously enabling different transformative capabilities, and provide to them specific suggestions to prioritize the adoption of certain DTs. In this regard, we recommend the adoption of key technologies for data collection and analysis, such as BDA, AI, IoT and BC, and those for SC security (cybersecurity technologies) to identify inefficiencies, losses, and bottlenecks characterizing current SC configurations and scan the external environment. Managers should thus consider and intensify the adoption of self-learning algorithms (Ivanov et al., 2018), SC analytics platforms, risk management, and business continuity tools (Ivanov and Dolgui, 2021). In addition, they may also leverage the adoption of collaborative robots since these are proven to reduce the frequency of human errors and inefficiencies along the SC (Khan et al., 2022; Liu et al., 2022; Romagnoli et al., 2023). The technologies for automated manufacturing are recommended for conceiving new SC configurations and experiment them on small scales. In this regard, beyond AM, managers may consider the adoption of CC-based manufacturing technologies providing access to scalable manufacturing capabilities (Fisher et al., 2018). Even if not emerged directly from our case studies, we recommend them adopting DTS tools endowed with advanced tools for data analytics, visualization, simulation, and prediction, to envision new products, processes and/or SC configurations and experiment their effectiveness through multiple scenario-based analyses (Alcácer and Cruz-Machado, 2019). Our results also highlight the need for a combined adoption of the technologies for data collection and analyses and those for data storage and information sharing (e.g., digital platforms and cloud-based servers), to quickly recognize the best-performing SC configurations and adopt them widely. In light of this, we recommend managers using data-driven decision--support systems providing advanced optimization tools automatically selecting best-performing SC configurations (Liu et al., 2022). Finally, to consolidate the relationships with customers and institutionalize new SC configurations, we recommend managers to fully exploit the technologies for data collection and sharing and those for automated manufacturing but also to empower their e-commerce platforms with advanced technologies for SC simulation, such as VR and DTS. This study could be a first step to develop a roadmap for successful adoption of DTs for fostering circular and resilient transformation of SCs.

This study is not exempt from limitations. First, the theoretical framework is validated on a limited number of samples operating within Made-in-Italy sectors. This aspect may limit the generalizability of our findings. Future studies could extend the analysis including other case studies related to different sectors. Second, we focus on the SCTCs as aggregated constructs while identifying the microfoundations underlying them would complement their understanding (Chari et al., 2022; Khan et al., 2020; Santa-Maria et al., 2022). We address this aspect in future studies.

CRediT authorship contribution statement

Giovanni Francesco Massari: Writing – original draft, Methodology, Conceptualization. **Raffaele Nacchiero:** Writing – original draft, Methodology, Data curation. **Ilaria Giannoccaro:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Appendix A

This appendix presents the questionnaire used to conduct the semi-structured interviews. It consists of four open-ended questions.

1) Which supply chain transformation has your company recently undertaken towards circularity and/or resilience?
2) Which are the distinct phases of the transformation process you mentioned?
3) Which are the digital technologies implemented in your company?
4) How have the digital technologies you mentioned enabled the supply chain transformation process towards circularity and/or resilience?

Appendix B

In this appendix, we report the relevant quotes used by practitioners when referring to SCTCs (see Table A1) and the DTs (see Table A2) enabling them.

Table B1
The quotes on SCTCs.

Supply Chain Transformative Capability	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Triggering	Studying the efficiency of "*internal processes*", examining the behavior and awareness of "*primary stakeholders*", [addressing ESG risks, and not only financial, legal, and regulatory risks].	[Monitoring and assessing] "*the performance and quality*" [of production processes], [analyzing the external context to identify potential supply shortages], "*formalizing*" [the commitment to circular economy to] "*make tangible a circular journey that had evolved over time*".	[Committing to sustainable development] "*in a more systematic manner*", [monitoring] "*all the sustainable and circular activities already done*" [and the new ones to advance].	[Searching for new sources of competitive advantage] "*to get economic savings and increase* [resource] *efficiency*", aligning with the "*general sensitivity emerging among the main stakeholders*".	Following "*the ownership's vision*", analyzing the emerging customer behavior and "*aligning with the market demand*".	[Monitoring through measurements and analyses] "*to understand where there are losses and where improvements can be made, identifying areas in production where action can be taken to prevent losses and enhance production efficiency*".	"*Aligning with the owner's vision*", [committing to sustainable development prescribed by] "*regulatory directives*", [identifying drivers to leverage, new regulatory directives to comply with, and emerging market trends to follow].	[Committing to sustainable development prescribed by regulatory directives, identifying drivers to leverage, new regulatory directives to comply with, and emerging market trends to follow], "*collecting signals*" [and interpret them to uncover new] "*market trends*", [capture evolving sensitivities among consumers, anticipate disruptions, and respond to] "*external pressures*".
Envisioning	[Establishing] "*a project management hub for the circular initiatives*", [implementing preliminarily on partial elements] "*through pilot tests on specific areas such as sales department*".	[Conceiving innovative proposals from] "*a combination of internal research efforts and ideas originating from the market itself, particularly from manufacturers*", [conducting laboratory] "*experiments and testing activities*" [required to produce and certify the final product], [implementing preliminarily on] "*partial elements*".	[Carrying out] "*pilot projects*" [to evaluate the efficacy of new technologies i. e., wool fiber tracer systems, on small fabric samples before scaling them up], [implementing across all fashion collections] "*to apply changes as much as possible*".	[Conceiving innovative proposals] "*together with consulting firms*", [implementing preliminarily on partial elements].	[Carrying out experimental activities without a public disclosure of the corresponding activities and results], [implementing preliminarily on partial elements].	[Implementing preliminarily on partial elements].	[Developing new patents out of the envisioned solutions].	[Studying new insights and ideas] "*not only direct and indirect competitors*" [but also from] "*innovative companies and virtuous multinational corporations*". "*Try to implement them [new ideas] internally, or perhaps enhance that type of strategy, implementation, and process*"
Navigating	"*Establishing a district-based collaborative structure rather than working in silos*" [to develop partnerships to create value for the entire network they belong to].	[Complying with specific] "*standards and requirements*", [replacing carbon-based energy sources with environment-friendly ones].	[Developing stronger collaborations with upstream suppliers], [replacing carbon-based energy sources with environment-friendly ones], [adopting advanced systems for resource recovery] "*to transform the entire organization, […] rather than just a part of it*".	[Developing stronger collaborations with all the "business-to-business sphere through] "*promotional campaigns*".	[Developing stronger collaborations with downstream logistic providers], "*incorporating the best-tested proposals*" [into the collections].	[Adopting advanced systems for resource recovery].	[Developing stronger collaborations with all the main partners].	[Developing close collaborations that go beyond] "*commercial purposes*" and pursue mutual "*contamination*" [of know-how and resources].

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Table B1 (*continued*)

Supply Chain Transformative Capability	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Stabilizing	"*Solidifying change processes"* [so that these become new organizational routines] "*aiming for a regularity that transforms […] the organization*".	"*Establishing enduring and trustworthy relationships with suppliers* […] *to maintain stability, ensuring that* […] *circularity can endure over time*".	[Promoting new initiatives] "*such as an* "*internal academy welcoming external individuals and hosting events on circular topics*" [to communicate and disseminate circular economy culture among end-customers and hence overcome resistances from them].	[Developing with] "*non-profit organizations*" [joint initiatives to disseminate circular economy culture].	Fostering new initiatives "*increasing involvement and openness towards the external context*"	[Stabilization is achieved] *when the customer has fully understood the solutions we can provide, from when we sell the fabric to post-sale; [when he/she] is fully aware about our zero-waste supply chain, or that our product is entirely recycled, and the fabric's cutting waste can be recycled*".	"*Continue talking to customers and reiterate everything we have"* [in terms of circularity and sustainability] "*and repeating the solutions*".	[Strengthening relationships with customers and interpret] "*the feedback coming from the market*".

Table B2
The quotes on digital technologies for SCTCs.

Supply Chain Transformative Capability	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Triggering	"*Blockchain is one of the projects the company is working.[…] for traceability and validation of raw material characteristics.* […] *Through blockchain, we can ensure that the raw material actually comes from a specific facility that recycles material, for instance, from the oceans, which is what we are currently doing.*" [Combining the use of cloud computing, big data analytics and artificial intelligence helps gather information about consumers' behaviors, their interactions with their own retailers or even with other brands]. [Combining the use of blockchain, Internet of Things, and cybersecurity		[Big Data and Artificial Intelligence have been implemented within human-based quality control tasks for enhancing and streamlining quality control processes. They are useful] "*where distinguishing between very difficult-to-see defects*", [small imperfections, and style features], "*a complex task that should be repeated three times* [on the same item before introducing it]. [Blockchain has been successfully integrated into digital platforms and software solutions, allowing for the tracking of] "*wool fibers and yarn origins to ensure the sustainability of the final textiles*"			[Blockchain has been implemented to provide full control over every phase of the production process, spanning from raw material sourcing to spinning, from coning to warping, from weaving to finishing]. [Together with cloud-based platforms, they provide information about real-time product status and location data, integrating with quality test results to quickly identify bottlenecks and assess organizational strengths and weaknesses].		

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Table B2 (*continued*)

Supply Chain Transformative Capability	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
	technologies helps quickly identify and address frauds and counterfeiting, check for the authenticity of products through RFID tags, protect supply chain data and systems from cyber threats through intrusion detection systems].							
Envisioning	[Additive manufacturing has been implemented to envision alternative configurations for retailers' facilities characterized by the same] "*complex architecture of* [high fashion] *stores*" [and to reproduce new garment and accessory prototypes using physically accurate textiles, including leathers, in an increasingly sustainable way].	"[…] *if you mention 3D printing, we apply in some cases where it's also useful, for example, if we need to create a prototype of a handle or other products*".						[Additive manufacturing has been implemented to produce 3D printed furniture out from recycled materials, and hence can become crucial in the construction of] "*3D printed houses*", [while] "*reducing supply risks by creating the opportunity to replace missing materials with the 3D printed ones*".
Navigating	"*We use a Transportation Management System software that encompasses not only transportation logistics but also warehouse management to make our activities visible to our suppliers and ride along with us in these activities. This fosters a perspective of partnership rather than just spot collaboration, but also to create this supply chain, network, or district we were talking about earlier*". [Product Lifecycle Management systems exploit the potential of Internet of	[Artificial Intelligence applications permit] "*to gather, collect, and study information more effectively and immediately* […] *to acquire new knowledge*".		[Internet of Things] factory management software systems allow manufacturers to reach an optimal level of production efficiency through] "*savings in personnel patrolling and also cost savings because, with the machine stopping at a fixed time, there is no risk that it might continue running and consuming energy beyond the established cycle period* […]".	[Ad-hoc software solutions leveraging cloud computing and big data analytics ensure real-time monitoring of sales and distribution processes].	[Cloud-based digital servers support the creation of digital fabric models and the storing of detailed information, including] "*article code and color*" [and technical features about every fabric and garment] "*that enters and leaves our company*". [The digital archive thus permits the buyer and/or the stylist to search for the desired fabric directly through the server, without the need of receiving the corresponding physical fabric	[Blockchain ensures] "*that we maintain the same quality and the same offering to customers, avoiding variations. It allows us to control all points of the tubes at 4000 m per minute, to understand and monitor all the graphs. This, in my opinion, ensures that the product always follows that criterion with low variation*".	

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Table B2 (*continued*)

Supply Chain Transformative Capability	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
	Things and artificial intelligence to identify and execute optimal product design, production, planning, and disposal strategies]. [Vendor management web-based applications exploit cloud computing to strengthen relations with suppliers by providing advanced systems for suppliers monitoring and rating, while ensuring transparency in purchasing practices, compliance with the company's policies and alignment with sustainability objectives].					sample]. [Supply chain data management software exploits artificial intelligence, big data analytics, and Internet of Things technologies are used to provide a systemic view of supply chain functions including procurement, production, inventory, logistics, and sales. This facilitates data collection, integration, and the corresponding information-sharing among key supply chain partners].		
Stabilizing	"*In recent years, especially, social networks have been crucial in externally promoting the company and its activities, thus gaining credibility and visibility from customers. They are indicative of the impact the company has on external stakeholders, including both customers and non-customers*". "*In addition to the production of individual products, our company has a core business tied to the store, thus to the design and architecture of its owned stores. The architecture of these stores is meticulously studied and replicated in our dedicated facilities, as if they were real stores, through 3D printing*". [Virtual			"*Currently, the staff prints forms that they place on the machines, and on these paper forms, the article in production is identified. There is also a form where staff can note mechanical anomalies, yarn breakages, and the cause of the breakage. We want to eliminate all this paperwork and have everything digital, so the machines will have a QR code. Staff can then read the QR code, which identifies the machine, what is currently in production, and the product specifications. They can record any notes on their smartphones or tablets instead of on the paper form.*"	"*We are approaching the use of a digital identity card for now because it's not yet big enough to become a 'passport,' something we will do sooner or later when regulations guide us on what to include. We are currently finalizing the generation of digital content related to each individual product, detailing its characteristics both physically and in terms of sustainability. This includes information about the supply chain, where it was produced, the materials used, and certificates covering the raw materials.* […] *This is done to inform customers*		[Social-media applications have been implemented to enhance the digital storytelling in order to attract external stakeholders including international audiences, investors, industry critics, and even young customers].	

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Table B2 (*continued*)

Supply Chain Transformative Capability	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
	reality has been implemented to enhance employee education on critical topics, such as ocean literacy, environmental conservation, and the adoption of sustainable practices, fostering greater awareness and responsibility]. [Digital Twin has been implemented to create 3D models of fashion products e.g., shoes, which faithfully reflected every detail, allow customers to interact with and customize them based on their preferences].				*about what they are buying, the quality, and the work behind it, as well as the possibilities a garment may have in terms of maintenance and references on how to handle the packaging.* […] *It's a growth path that will allow the customer to have a level of awareness about what they are purchasing, enabling them to make informed choices and create awareness.*" [Social-media applications have been implemented to enhance the digital storytelling in order to attract external stakeholders including international audiences, investors, industry critics, and even young customers].			

Data availability

Data will be made available on request.

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