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Harnessing digital technologies in circular supply chains: The role of technological opportunism capability and technological turbulence

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ABSTRACT

This study investigates the role of digital technologies (DTs) in enhancing circular supply chain capability (CSCC), as well as the role of technological opportunism capability (TOC) as an enabler and technological turbulence (TT) as a moderator. Using data gathered through a cross-sectional survey from companies in the Indian automotive industry, the relationships in the proposed model were analyzed using PLS-SEM via SmartPLS software. The findings reveal that digital technologies positively and significantly affect CSCC. Importantly, TOC enhances the positive effect of digital technologies on CSCC but not directly affect CSCC. Finally, TT moderates the relationship between TOC and firms' adoption of digital technologies. The uniqueness of this study is in testing a novel model that demonstrates the importance of TOC adoption in driving firms to adopt DTs that in turn enhance CSCC under a high level of TT.

1. Introduction

Recent research indicates that the circular economy (CE), as a strategy, can enable companies to transition from the conventional linear economic model to a circular model [1]. CE aims to assist industrial firms in making environmental contributions toward developing a sustainable economy in partnership with a socially equitable society. Previous research examining CE applications has highlighted the significant benefits of this economic model compared to the linear model. The CE concept has been implemented across various domains, including construction [2], manufacturing [3], and services [4], with its principles also being integrated into supply chain management practices [5].

Within supply chains (SCs) field, extensive discussions have taken place around concepts such as sustainable/green/ closed-loop/ and circular SC [6]. Nonetheless, circular SC (CSC) specifically emphasizes restoration and regeneration cycles, aiming to maximize the value extracted from natural resources used as inputs in a production system [7]. After distinguishing CSC from other concepts such as sustainable/green/ and closed-loop SC, Farooque *et al.* [6] define CSC as "the integration of circular thinking into the management of the SC and its surrounding industrial and natural ecosystems". It methodically recovers technical and biological materials, aiming to achieve zero waste. This is accomplished through SC functions, covering everything from "product design" to "end-of-life (EoL)", as well as waste management. It involves all stakeholders throughout the product lifecycle, including "component and product manufacturers, consumers, and end-users" [7]. Within this context, CSC enables the circularity of a broad range of resources, including products, by-products, as well as waste. It integrates the forward movement of primary raw materials from upstream to downstream with the reverse movement of secondary raw materials from downstream to upstream [8]. Additionally, CSC fosters sustainable design methods and reuse practices, extending the life of materials and reducing waste [9]. As such, the successful implementation of sustainability practices in the SC can be attributed to the firm's sustainability capabilities [10]. Building CSC capability (CSCC) can enhance the effectiveness of implementing CE practices in the SC. Based on the research work of Agyabeng-Mensah *et al.* [11], CSCC is defined as "the abilities, attributes, organizational processes, skills, and knowledge that empower a firm to integrate, develop, and adapt competencies for

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implementing CE initiatives". This capability emphasizes resource efficiency, waste minimization, and material recovery and reuse within the SC (Ibid).

In the CE literature, research has investigated the factors influencing CSCC in both large and small firms. Some studies focus on sustainable manufacturing practices [12], sustainable SC flexibility [13], capabilities related to sensing, seizing, and reconfiguring, as well as organizational routines [14], CE readiness [15] and environmental sustainability commitment, engagement and alliance capabilities [11] as drivers of CE capabilities. However, there is a gap in understanding how environmentally committed firms can develop CSCC, enhancing their sustainability.

Although adopting CSC offers additional circular opportunities [16], the heightened challenges associated with the CE system necessitate the support of digital technologies (DTs; [17]). Given the various uncertainties surrounding CE systems, DTs like blockchain (BC), internet of things (IoT), and big data analytics (BDA) have proven to be effective in properly closing the loop and ensuring reliable returns [18–20]. In principle, the adoption of DTs can undoubtedly enhance CSCC by linking the ecosystem to organizations and aiding the decision-making process [21], while also reducing the overall SC system's volatility [22]. In particular, DTs enable organizations to acquire valuable information that can be utilized to refine strategies for circular systems [23].

Studies (e.g., [5,23]) reveal that DTs aid firms in effectively implementing and managing CSC. However, adopting these DTs necessitates that companies vigilantly monitor the opportunities and risks associated with new technologies and adapt to them promptly [24]. Accordingly, scholars have suggested the concept of technological opportunism capability (TOC)—the capability of firms to sense and respond to new technologies—to explain the variations in radical technology adoption among different companies. This capability enables technologically opportunistic firms to identify technologies that might pose potential threats or opportunities. Since TOC can ease the adoption of radical technologies [25], it is widely agreed that TOC should lead to improved business performance [26]. Prominent technology firms with TOC, like Google, Apple, and Amazon have indeed achieved significant economic gains amid digital disruption [27]. Indeed, TOC enables companies to gain, absorb, and integrate both internal and external knowledge as well as market insights related to new technologies. This allows them to effectively allocate their resources to deal with potential technological opportunities and threats [25].

Recent studies analyze the adoption and diffusion of technologies within a firm simultaneously ([28],b; [25]) for the transition to a circular business model, but none have studied the relationship with technological opportunism. This study seeks to fill this gap by investigating whether TO drives the adoption of DTs to enhance CSCC.

This research offers several contributions. Firstly, unlike existing literature, which primarily concentrates on effective strategies for fostering dynamic capabilities within traditional SC structures, such as resilience [29] and agility [30], this study investigates the effect of DTs on enhancing CSCC within the context of the Indian automotive industry. In doing so, the study builds on and complements the existing literature by applying these constructs to a specific industry and geographic context that presents unique challenges and opportunities. When CSC practices are supported by DTs, their circular capacity is heightened, leading to improved business performance and contributing to the overall economic sustainability of the business model [23]. Drawing inspiration from this framework, we investigate the influence of DTs on enhancing CSCC. Second, this study delves into the enabling role of technological opportunism. While prior research has often examined the influence of innovative technologies on firms' sustainability achievements, this study demonstrates the role of technological opportunism for the adoption of DTs within the context of the Indian automotive industry. Third, this study investigates the connection between TOC and DTs, highlighting the conditions under which TOC varies in its impact on the adoption of DTs. Specifically, the study probes how technological turbulence moderate the effect of TOC on firms' adoption of DTs. Forth, this study adopted the TOE and DCT theories, as theoretical lenses, to examine the constructs involved in our framework and explore its influencing paths on CSCC, which furthers applies TOE and DCT theories toward CSCC. Finally, this study evaluated the proposed model within the automotive industry in India, an emerging economy; where the adoption of a circular approach encounters distinct challenges stemming from diverse manufacturing practices and standards, inadequate infrastructure, absence of government policies, and consumer perceptions of recycled products, which differ from the socio-technical landscape of developed nations [31]. In India, the recycling of EoL vehicles remains without regulation and operates informally, with these recycling practices have yet to be integrated into the automotive SC. However, following the recent implementation of EoL vehicle regulations, automotive companies are now embracing a circular perspective to enhance resource efficiency. This includes recycling components such as "reinforced glass, laminated glass, tires, car batteries, and engine oils" [32]. Indeed, the principles of the circular approach embraced by the European automotive industry have impacted Indian automotive industry, prompting a transition from a service-oriented business model [33] to CE model [1]. This transition necessitates automotive companies to focus on EoL strategies "reuse, refurbish, remanufacture, and recycle", which aid in establishing circular loops, which include slowing, narrowing, and closing resource loops [34]. Consequently, automotive companies can leverage CSCs in this context [35].

2. Theoretical background and hypotheses development

2.1. Theoretical lens

The current study relies on Technology-Organization-Environment (TOE) theory and Dynamic Capabilities Theory (DCT) as a theoretical foundation for explaining the relationships between TOC, DTs, TT, and CSCC in the proposed model (See Fig. 1).

2.1.1. Technology-organization-environment theory

Transitions to CE in the SC requires understanding how technology integrates into CSC and evaluating the behaviors needed for digitalization in CSC. Many real-world cases fall short of achieving the expected outcomes from adopting DTs, mainly due to insufficient knowledge about the application context, specifically CSC. Therefore, the current study employs TOE theory, which clarifies the sequential procedure of embracing technological innovations by considering both the inner and outer technological aspects within the company. TOE theory was initially suggested to comprehend technology adoption in companies. Tornatzky and Fleischer introduced this framework in their 1990 work, "The processes of technological innovation" [36]. Following this proposition, numerous studies (e.g., [37,38]) began utilizing TOE theory for their problem analysis. TOE framework is believed to assist practitioners in identifying the most influential factors in technology adoption [37]. Besides enhancing the understanding of technologies, the TOE theory allows for the adoption of new research contexts by considering different influential factors. Indeed, many research endeavors have embraced the TOE theory as an analytical framework owing to its compatibility with technological systems and theories (e.g., [39]).

The TOE theory encompasses three distinct dimensions: the 'Technology' dimension, which pertains to the specific technologies examined in the research (such as BC, BDA, IoT, etc.); the 'Organization' dimension, which involves the resources and competencies of a firm (including all relevant SC members) engaged in technology adoption; and the 'Environment' dimension, which includes factors influencing both inner and outer elements necessary for the company to thrive in the business environment [40]. While various other theories, such as Diffusion of Innovation and Institutional Theory, address business innovation and digitalization models, the TOE framework stands out for its

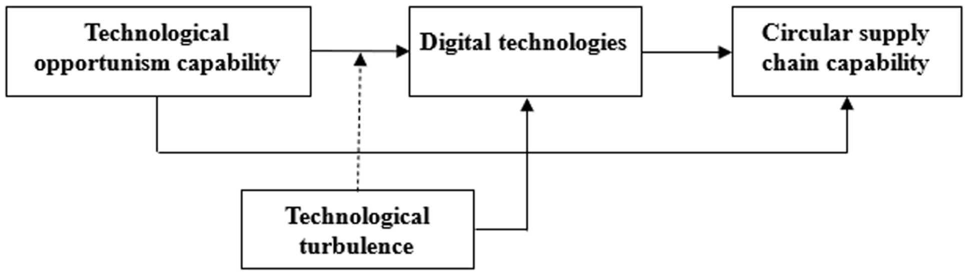

Fig. 1. Research model.

comprehensive approach to technology adoption. In contrast to alternative theories, TOE stands out for its notable success due to the substantial evidence supporting its effectiveness in existing studies on technology adoption. This has prompted numerous researchers to choose TOE to investigate the impact of adoption of various technologies such as BC, IoT, and BDA on promoting CE practices (e.g., [40]), which can be facilitated by CSCC (in our case).

2.1.2. Dynamic capabilities theory

According to DCT [41], an organization's long-term performance hinges on its capability to adapt to changing circumstances and develop new functions. Essentially, staying ahead of the competition requires an organization to build a structure that allows it to respond effectively to external changes. DCT identifies three primary capabilities organizations need to cultivate and oversee: sensing, seizing, and transforming capabilities [42]. Successful development of adaptable capabilities, as per DCT, occurs in an environment that prioritizes learning and innovation at every level of the organization [43]. Moreover, organizations need to demonstrate readiness to undertake risks and make strategic investments in cutting-edge technologies and capabilities [42,44].

Essentially, DCT aids in understanding how firms can detect and capitalize on opportunities, as well as adapt and reorganize resources to ensure CSCC is built [45]. It demonstrates the impact of dynamic capabilities of an organization in enhancing CSCC in general, and specifically, their role in CSC-focused digitalization [46]. In the context of the current study, we posit, based on DCT, that TOC correlates positively with CSCC through the adoption of DTs. In addition, the utilization of a company's capability for TOC is contingent upon technological turbulence [26]. From the perspective of DCT, dynamic capabilities like TOC empower companies to leverage different technological domains and cater to diverse market demands [47]. Firms characterized by TOC possess the capacity to both comprehend and assimilate knowledge regarding emerging technologies (technology-sensing capability) and demonstrate the readiness and capacity to react to newly identified technologies (technology response capability). These activities of sensing and responding enable firms to integrate advancements in technology into their new products and take proactive measures in the market ahead of their rivals, resulting in sustainable competitive advantages and enhanced firm performance [26].

While the previous focus of dynamic capabilities was on the "speed of change" in the business environment [41], it has shifted to the "prevailing degree of uncertainty" as the more significant outer factor [48]. As companies dealing with sustainability issues often encounter profound uncertainties, this reframing enhances the theoretical significance of DCT in elucidating companies' endeavors to adopt CSC capabilities [46].

2.2. Circular supply chain capability

Overall, CSC manifests as a self-sustaining ecosystem that integrates a multitude of stakeholders into a cohesive network to derive fresh value from EoL resources, prolong product lifespans, and ultimately improve resource efficiency to operate with minimal waste [49]. In other words, CSC involves establishing a range of processes including slowing, narrowing, closing, intensifying, and dematerializing, with multiple stakeholders engaged in re-introducing and re-delivering value [34]. Within CSC, resources traverse both forward SCs, where they were initially segregated, and reverse SCs [50]. Through the reverse SCs, resources return to companies within the original SC sector through closed loops or are directed to various sectors or directly to the natural ecosystem through open loops [51]. Thus, the waste produced by one SC are repurposed as input resources for another SC. For instance, recycled bottles can be transformed into construction materials [6]. Owing to this extra regenerative feature, CSCs are significantly distinct from reverse and green SCs. The latter involves a restorative element through the adoption of green practices throughout the value chain—such as eco-design, green procurement, and green distribution—aimed at reducing pollution and emissions, as well as implementing strategies for material recovery. CSCs broaden the scope of CLSCs by involving resources that circulate back to all stakeholders within both industrial and natural ecosystems, instead of exclusively returning to the initial manufacturer [51]. This approach curtails the recovered value's reach and still leads to significant waste generation, as it is often impractical to reuse or recycle undesirable materials in the same SC (Ibid).

Indeed, the efficacy of integrating sustainability practices into the SC hinges on the sustainability capabilities inherent to the company [10]. Enhancing CSC capabilities can enhance the efficiency of CE adoption within the SC. CSCC encompasses "the skills, attributes, organizational procedures, expertise, and knowledge enabling a company to integrate, develop, and realign competencies towards circular economy endeavors within the SC" [11]. In this context, de Sousa Jabbour *et al.* [52] proposed that building and cultivating suitable capabilities are essential requirements for achieving CSC objectives. CSC capability allows company to transition from a linear SC to a CSC [53]. Building appropriate CSC capabilities demonstrates firms' choices regarding the orchestration and deployment of resources to establish CSC. Thus, these capabilities pertain to an organization's capability to use its resources to meet its goals (Ibid). Using DCT to assess CSCC allows firms to identify the specific capabilities that influence the overall performance of the SC. Consequently, DCT was incorporated into this study to evaluate CSCC.

2.3. Digital technologies

DTs are rapidly transforming business operations. Beyond enhancing internal operational efficiency, these technologies also aid organizations in boosting their performance [54,55]. DTs are viewed as "*advanced technologies which give rise to a new market or a new avenue of business or research*" ([56], p. 1). The digitalization of businesses across various industries, driven by new technologies like BC, IoT, and BDA, is a growing trend. However, companies should effectively embrace DTs to attain substantial business improvements, like streamlining operations and developing new business models because failure so may lead to falling behind rivals who excel in these areas [57]. The adoption of new DTs is increasingly recognized as essential, not only for traditional operations and SC management but also for sustainable product management [46]. DTs can be applied to track products and components across multiple life cycles at the industrial level [58]. Additionally, DTs can improve sustainability decision-making at the product and process levels by providing the necessary data in terms of quantity and quality [59], as well as developing new sustainable business models, such as product service systems, at the organizational level [46]. For example, BC can enhance trust in information movements throughout value chains and boost transparency [60]. Likewise, IoT can improve the accuracy and efficiency of current data collection practices for products and processes, both internally and externally, and facilitate the creation of new information movements [61]. Finally, BDA offers significant potential by enabling the handling and automation of data analytics, thereby benefiting product design, manufacturing, SC management, and product assessment [46].

2.4. Technological opportunism capability

TO is seen as the processes that enable active sensing of suitable technologies and rapid response to technological advancements [62]. Technologically opportunistic companies actively seek out innovations [25]. Indeed, these companies consistently gather information on emerging technologies perceived as potential growth opportunities [63], respond proactively to disruptive technologies [62], and can adapt their business strategies to either capitalize on these opportunities or mitigate the risks associated with new technologies [26].

As dynamic capability, TOC incorporates the ability to recognize a need or opportunity for change, devise a response to it, and execute a plan of action [64]. It reflects a company's ability to sense and quickly respond to emerging technologies [65]. The TOC concept is assessed based on two dimensions: the capability to sense technological changes and the capability to respond to them [25,26,62]. Technology-sensing capability is defined as "the extent to which an organization has the capability to acquire knowledge and understand new technological developments". Technology-responding capability is related to "the extent to which an organization is willing and able to respond to new technologies". These abilities necessitate that companies consistently assess the marketplace, adjust and refresh their procedures, and utilize their resources to seize marketplace opportunities arising from IT innovations. TOC generates diversity among companies in sensing and responding to emerging technologies, potentially enhancing competitive edge and improving firm performance [25].

2.5. Technological turbulence

TT is defined as the rate at which technology changes [66], indicating the unpredictability, unfamiliarity with, or difficulty in comprehending technological advancements or changes in the external environment [67]. Indeed, a technologically turbulent environment is marked by short cycles of innovation and obsolescence [26], leading to inherent risks due to technological complexity and uncertainty in these industries.

A company planning to adopt new technology must run TT by leveraging its knowledge resources related to technology [68]. Therefore, it becomes apparent that enhancing employees' knowledge and skills is essential prior to technology adoption for achieving favorable outcomes. Consequently, a technologically turbulent setting could strengthen the correlation between an organization's intent to adopt technology and its overall performance (Ibid).

2.6. Hypotheses development

2.6.1. DTs and CSCC

Incorporating DTs can enhance the adaptability, openness, efficiency, and resource optimization within SCs, leading to enhanced sustainability [69]. It is crucial for companies to leverage DTs to align with economic, environmental, and social objectives, which are crucial for sustainable development and the adoption of CE principles [23]. Similarly, implementing DTs is essential for achieving the objectives of CSC, particularly when dealing with reverse logistics within global frameworks (Ibid). Digitalization emerges as a potent transformative element, supported by empirical evidence from [70], demonstrating its capacity to deliver environmental, social, and economic advantages. Indeed, the circular model is closely intertwined with technology, particularly in the meticulous design of goods and components for reuse to minimize waste [23]. The role of DTs is essential in enabling and enhancing CSCs, which are designed to minimize waste and maximize the efficiency of resource use. DTs provide the necessary infrastructure and tools to enable the transition to CSCs by improving visibility, efficiency, and collaboration across the entire value chain. They empower companies to redesign their processes and business models for sustainability and resilience in the face of resource scarcity and environmental challenges [71]. For instance, manufacturing firms utilize BDA to reassess and redesign current products and processes to achieve optimal resource allocation [72], enhance resource efficiency with minimized reliance on virgin materials and primary energy [73], and decrease carbon footprints and harmful substances [74]. Based on the above, we assume that:

H1. *DTs are positively associated with enhancing CSCC.*

2.6.2. TOC, DTs, and CSCC

The correlation between dynamic capabilities and the implementation of DTs has been examined in several ways [75,76], with some deductive studies also examining how dynamic capabilities impact the implementation of DTs [46]. For instance, Savastano *et al.* [77], drawing from a survey involving 110 managers in the manufacturing sector, found that advanced dynamic capabilities (TOC, in our case) have a direct impact on a company's digital manufacturing capabilities. Indeed, technologically opportunistic companies are proactive in seeking innovations. Some researchers explore TOC as the precedent for the adoption and utilization of new technologies across various contexts. Lucia-Palacios *et al.* [25], in their seminal work, confirmed that technologically opportunistic firms are not just more cognizant of technological advancements but are also more inclined to capitalize on these advancements as they are more likely to allocate the resources needed for adopting new technologies. Furthermore, opportunistic companies are more inclined to sense and respond to technological developments [27,62,78]. Such these firms are more likely to integrate technological developments with the market requirements, thus increasing their performance [25]. In addition, Li *et al.* [27] suggest that TOC can facilitate the adoption of radical technologies. TOC helps companies to assess the potential benefits and risks associated with DTs, enabling timely adoption and adaptation [24]. Consequently, embracing TOC enhances firm performance [26]. This is evident in leading technology companies like Amazon, Apple, and Google, which have achieved significant economic gains amid digital disruption due to their high levels of TOC. Therefore, drawing from the dynamic capabilities' perspective and the existing empirical understanding, we propose a positive correlation between TOC and the adoption of DTs. Hence it can be assumed:

H2. *TOC is positively associated with adopting DTs.*

Furthermore, dynamic capabilities that foster an environmentally oriented competitive edge can be observed through the amalgamation of diverse resources to address shifts in the environment. According to Leonidou *et al.* [79], dynamic capabilities, particularly TOC, have a pivotal role in fostering eco-friendly approach, which is fundamental to enhancing CSCC. By effectively sensing technological advancements pertinent to ecological concerns and promptly responding to them, companies can align their SC practices with environmental objectives.

Indeed, many authors attempted to clarify relationship between TOC and CSC practices. For example, Quayson *et al.* [80] suggest that sensing dynamic capability is crucial for developing CSC. Amui *et al.* [81] noted that firms require sensing capability to cope with outer obstacles to GSC. These obstacles include SC structure-related challenges arising from insufficient transparency within the SC and limited influence over sub-suppliers. Additionally, they include barriers related to environmental standards implementation, stemming from gaps in understanding environmental standards conceptually, as well as insufficient regulation and enforcement of such standards. Asim *et al.* [82] in their study found that technological opportunism contributes to enhancing the sustainable performance of Pakistan's SME sector. In essence, TOC, as well as adopting and exploiting technology is essential for sustainability performance. Khan *et al.* [14] concluded that the implementation of CE is greatly aided by dynamic capabilities, such as sensing, seizing, and reconfiguring capabilities. Hence, it is essential for companies must develop and adopt dynamic capabilities (TOC, in our case) to enhance CSCC. Accordingly, the following can be assumed:

H3. *TOC is positively associated with enhancing CSCC.*

On the other hand, TOC may influence CSCC through firms' adoption of DTs. According to Rosa *et al.* [83], companies ought to enhance their technological sensing and response capabilities. This involves remaining vigilant about emerging technological advancements related to environmental concerns, understanding the rate at which these technologies are adopted, acquiring the necessary skills to utilize them effectively, and identifying how to capitalize on them as opportunities. This is particularly crucial as digital transformation has become indispensable for firms aiming to cultivate sustainable business models, including CSC (Ibid). Indeed, companies with technological sensing and responding capabilities are more inclined to be at the forefront of recognizing the advantages of technology adoption; such these companies can pinpoint the most appropriate and least risky clean technologies to integrate and develop their practices and procedures around technologies that promise superior economic outcomes [79]. Within the CSC field, these technologies contribute in particular to waste reduction [83], energy savings [84], water consumption reduction [83], and air pollution control [85], in addition to more specific green practices, such as product recycling and reuse [1]. In essence, within the CSC approach, both products and manufacturing processes are designed to minimize waste entirely, while also ensuring that resources are continually utilized through effective recycling or recovery of unavoidable waste [80]. This necessitates advanced technology to track SC impacts and assess sustainability performance metrics within the reverse chain, particularly due to the heightened complexity involved [86]. Based on the above, in can be assumed that:

H4. *The effect of TOC on CSCC is mediated by DTs.*

2.6.3. Moderating role of TT

TT is a significant factor affecting the business landscape across industries [87]. According to several scholars, TT can reduce entry barriers, thereby benefiting new companies [88,89]. However, according to the dynamic capability perspective, TT can help existing companies gain competitive advantages when they effectively navigate ambiguity [47, 90]. Conversely, if these firms fail to restructure their resources in response to disruptions, their competitive edge can quickly diminish [91,90]. They may also be negatively affected by technological disruptions, which reduces the speed of technological growth and technology adoption [92]. Hence, there is no clear indication whether turbulence presents an advantage or disadvantage for companies. Moreover, there is no agreement on the strategic measures to transform uncertainty into opportunity during turbulent circumstances.

Indeed, greater technological turbulence means risks for companies but also greater opportunities [68]. As per Teece *et al.* [41], dynamic capabilities hold greater value in dynamic environments compared to static ones. Increased TT has the potential to enhance the correlation between a company's capabilities and its performance, as highlighted by Song *et al.* [67]. Likewise, amidst swiftly evolving landscapes, TOC empowers companies to manage technological shifts and pursue competitive advantages [93], alongside gaining deeper insights into the implications of evolving technologies on strategic and operational choices [26]. In technologically turbulent environments, a firm with TOC can attain competitive edge due to the growing ambiguity in causality and the hurdles to imitation (Ibid).

Dynamic capabilities, such as TOC, are anticipated to become more crucial in environments marked by high TT. This is because TOC enhances a company's capability to quickly adjust and react to emerging technologies in the market, thus mitigating the uncertainties stemming from TT [94]. Therefore, in scenarios characterized by high TT, the association between TOC and a firm's propensity to adopt DTs expected to be enhanced. Conversely, in scenarios characterized by low TT, where technological changes occur gradually and steadily, even firms with technological opportunities have the capability and resources to sense changes and respond accordingly. As a result, the correlation between TOC and the adoption of DTs becomes weaker. Therefore, the following hypothesis can be assumed:

H5. *TT is positively associated with adopting and implementing DTs.*

H4. TT moderates the relationship between TOC and adopting DTs; the positive effect of TOC on adopting and implementing DTs increases as TT increases.

3. Methodology

3.1. Participants and procedure

For this study, we adopted a quantitative methodology, with data gathered from a sample of Indian firms in the automotive industry. In doing so, we respond to a call by Lahane *et al.* [49], who advocated for more survey-based quantitative research in CSC studies, given the predominance of qualitative and case study methods in this field. A cross-sectional design is chosen due to its cost-effectiveness and flexibility [95]. India is chosen as a research context for several reasons: (i) Global Representation: The Indian automotive industry is a critical part of the global SC, with many firms either exporting components or collaborating with multinational companies. This integration enables insights derived from the industry to reflect broader global trends and challenges; (ii) Diverse Operational Practices: India represents a unique combination of developed and emerging market characteristics, offering a comprehensive view of SC dynamics, particularly in adopting circular economy principles and digital technologies. These characteristics help extrapolate findings to both developed and developing economies; and (iii) Relevance to Sustainability: The industry's efforts to transition to CSC practices—driven by regulatory changes and global pressures—are consistent with international trends, making it an ideal context for studying such practices' applicability worldwide.

Overall, the companies were selected from the "Society of Indian Automotive Manufacturers" and the "Automotive Components Manufacturers Association of India" databases. The survey/questionnaire was crafted and dispatched to 600 managers across 120 companies via email. The authors hired a private agency for market research to manage the survey and gather data in collaboration with HR departments in firms under study. Respondents' involvement in the survey was entirely voluntary and limited to individuals with a minimum of two years' experience in the automotive sector to ensure a basic familiarity with the industry. Additionally, only respondents with previous knowledge of DTs and circular approaches were invited to participate. The target participants comprised managers in roles related to SC/logistics, marketing, manufacturing/production, digitalization, and IT. To encourage participation and enhance response rates, the questionnaire assured respondents' anonymity and regular email reminders were dispatched.

Among the 600 questionnaires distributed, 352 respondents representing 120 automotive firms, resulting in a response rate of 59 %. These

352 participants varied on the demographic and organizational traits. In terms of gender (Male-81.8 % and Female-18.2 %); age (20 to 30years-3.98 %, 31 to 40years-19.03 %, 41 to 50years-56.53 %, and above 50years-20.46 %); education (Secondary and below-17.33 %, Undergraduate-39.20 %, and Postgraduate-43.47 %); work experience (<15years-24.43 % and 15years and above-75.57 %); and functional specialization (logistics-28.69 %, Marketing-27.85 %, production manager-33.52 %, and digital technology/IT manager-9.94 %).

To address the potential concern of duplicate data and ensure the robustness of our analysis, all statistical analyses were conducted using a single value derived by averaging multiple responses from the same company across all items. This approach ensured that each company was equally represented in the dataset, minimizing the risk of over-representation by firms with higher participation rates. Aggregating responses at the organizational level also allowed us to capture a holistic perspective on organizational constructs by integrating diverse insights from managers in various functional roles. This method enhanced the validity of our analysis by reducing the potential bias introduced by individual-level variability while maintaining the richness of multi-respondent data. We chose this multi-respondent approach to enhance the reliability of our organizational-level constructs, as our study focuses on organizational and SC issues rather than individual-level factors ([96], p.81). Thus, the final sample consisted of 120 organizations (N = 120). This sample size was deemed appropriate for conducting confirmatory factor analysis (CFA) and structural equation modeling (SEM), given the exploratory nature of the study on DTs and its relationship with CSC [97].

Regarding the studied firms, they varied in terms of period of firm's existence (<20years-19.88 % and 20years and above-80.12 %) and firm's size/or number of employees (<500employees-59.37 % and 500employees and above-40.63 %). Data collection occurred over a four-month period, from October to January 2024.

3.2. Measures

Based on the previous studies, the questionnaire was designed with two sections: (i) respondents' demographic profiles; and (ii) respondents' perception of TOC, DTs, TT, and CSCC. Appendix 1 provides a comprehensive breakdown of the measurement items utilized in the constructs. Based on previous work [25,26,62], we measured TOC using 7 items assessing two dimensions, namely "Technological sensing capability" and "Technological response capability". Regarding the DTs variable, it was measured as a multi-dimensional construct using 9 items assessing three components, namely IoT technology (adapted from [98]), BC technology (adapted from [19]), and BDA technology (adapted from [44]). TT was measured by four items drawn from Chen and Lien [26]. Finally, we measured CSCC using four items drawn from Agyabeng-Mensah *et al.* [11] and Del Giudice *et al.* [74]. These items were measured using a five-point Likert scale, where 1 denotes "Strongly Disagree" and 5 signifies "Strongly Agree". In addition, to ensure consistency and accuracy in the analysis, all negatively worded items, such as TRC2, TRC3, and TRC4, were reverse-coded before the analysis procedures, thus maintaining the reliability and validity of the measures.

3.3. Statistical methods

The data underwent analysis through "the partial least squares-structural equation modeling (PLS-SEM)" method, facilitated by Smart-PLS 4.0 software. PLS-SEM enhances analytical precision and ensures more reliable estimates, as indicated by Sarstedt *et al.* [99]. PLS-SEM was preferred due to its model specification, simplicity, and avoidance of stringent distributional assumptions (Ibid).

3.4. Common method bias (CMB) and multicollinearity test

To examine CMB, we performed Harman's single factor test, as recommended by Harman [100]. In this investigation, the initial component accounted for 45 % of the total variance, notably lower than the 50 % threshold advised by Podsakoff *et al.* [101]. A lower total variance in this test indicates reduced risk of CMB, ensuring that a single factor does not dominate the variance and compromise the validity of the study. This is because when a single factor explains a large proportion of the total variance, it suggests that the responses may be influenced by a common source (e.g., respondent mood, measurement context), rather than reflecting the true relationships between the constructs [102]. By keeping the total variance below the threshold, the risk of such systematic bias is minimized, which enhances the credibility of the findings.

Additionally, CMB assessment was conducted using variance inflation factors (VIF), with values ranging from 1.417 to 1.795, which are below the threshold of 3.3 [103]. According to Kock [103], lower VIF values are desirable because they indicate low multicollinearity among the predictors, while high VIF values can inflate standard errors and compromise the reliability of regression coefficients. Therefore, maintaining VIF values below 3.3 ensures model stability and more reliable estimates in the analysis. Consequently, there are no concerns regarding multicollinearity or the presence of CMB in this study.

4. Results

4.1. Measurement model assessment

The measurement model was assessed through both construct reliability and validity, encompassing convergent and discriminant validity. To assess construct reliability, Cronbach's alpha coefficients were evaluated to measure the reliability of core constructs in the measurement model. As per the results, all Cronbach's alpha coefficients, ranging from 0.884 to 0.941, exceeded the recommended threshold of 0.7 [104]. Furthermore, all composite reliability values, ranging from 0.901 to 0.944, surpassed 0.7 [105], indicating adequate fulfillment of construct reliability, as depicted in Table 1.

Factor loading was employed to assess item reliability, where the high loadings on a construct suggest that the respective items share considerable commonality, contributing to the construct [106]. Factor

Table 1
Reliability and convergent validity.

1-order constructs	2-order construct	Code	Loading	a (>0.7)	CR (>0.7)	AVE (>0.5)
Technological sensing capability	TOC	TSC1	0.890	0.870	0.872	0.794
		TSC2	0.902			
		TSC3	0.881			
Technological response capability		TRC1	0.777	0.946	0.953	0.867
		TRC2	0.981			
		TRC3	0.974			
		TRC4	0.977	**0.941**	**0.944**	**0.744**
IoT	DTs	IoT1	0.893	0.871	0.872	0.796
		IoT2	0.897			
		IoT3	0.886			
BC		BC1	0.896	0.690	0.701	0.760
		BC2	0.847			
BDA		BDA1	0.862	0.847	0.848	0.766
		BDA2	0.894			
		BDA3	0.869	**0.910**	**0.912**	**0.616**
Technological turbulence		TT1	0.853			
		TT2	0.940			
		TT3	0.908	**0.884**	**0.901**	**0.812**
Circular supply chain capability		CSCC1	0.870			
		CSCC2	0.861			
		CSCC3	0.860			
		CSCC4	0.900	**0.896**	**0.901**	**0.762**

Source: Authors' analysis.

loadings exceeding 0.70 were deemed particularly noteworthy (Ibid). As depicted in Table 1, all item loadings surpassed the recommended threshold of 0.7, except for item BC3 and TT4, which were removed from the scale due to insufficient loadings.

To assess convergent validity, which measures the degree of association between a scale and alternative scales of the same construct, we employed the average variance extracted (AVE). As per the results, all AVE values exceeded the recommended threshold of 0.50 (Ibid), ranging from 0.616 to 0.812, demonstrating adequate convergent validity, as illustrated in Table 1.

Furthermore, the measurement model's discriminant validity, which assesses the extent to which items distinguish between constructs or measure distinct concepts, was evaluated using the heterotrait-monotrait ratio (HTMT) criteria. As per Henseler *et al.* [107], the HTMT value should be <0.85. All values as shown in Table 2 were less than the recommended threshold of 0.85, reflecting the discriminant validity of the model.

4.2. Structural model assessment

At this stage, the structural model was evaluated to examine the hypothesized relationships, as outlined in Table 3. Before that, the effectiveness of the structural model was validated using R^2 and Q^2 metrics [106]. R^2 reflects the proportion of variance in the dependent variable due to exogenous variables. According to the findings, the model explained 45.8 % of the variation in DTs and 44.1 % of the variance in CSCC. Additionally, the Q^2 measure was used to assess the model's predictive quality, focusing on predictive relevance through the blindfolding technique [108]. This technique involves a resampling procedure to compare original and estimated data values. Hair *et al.* [109] suggested that the cumulative redundancy Q^2 value for predictive constructs should be above zero to confirm predictive relevance. In this regard, the study's findings showed that the Q^2 values for DTs and CSCC were greater than zero, thereby confirming the model's predictive relevance.

The bootstrapping technique (with 5000 resamples) was employed to assess the path estimates of the hypothesized relationships.

The results of PLS-SEM in Table 4 demonstrate that DTs positively affect CSCC ($b = 0.59$, t-values = 10.76, $p < 0.05$). Hence, H1 is supported. In addition, DTs are significantly and positively influenced by TOC ($b = 0.46$, t-values = 9.19, $p < 0.05$), thus supporting H2. By contrast, TOC significantly not influences CSCC ($b = 0.11$, t-values = 1.87, $p > 0.05$). Therefore, contrary to expectations, H3 is not supported. An examination of the effect of TT on DTs is presented in H5. According to the findings ($b = 0.28$, t-values = 5.06, $p < 0.05$), which reveal that the link is positive and significant, thus H5 is supported.

4.3. Mediation analysis

Following Preacher and Hayes' [110] indirect effect procedures, the mediating effect of DTs between TOC and CSCC, as proposed in H4, was investigated. For mediation analysis, Hair *et al.* [109] propose the PLS-SEM bootstrapping technique. They advise bootstrapping the sampling distribution in accordance with Preacher and Hayes' [110] methodology, which provides a more reliable approach than the conventional "causal procedure" that Baron and Kenny [111] support. SEM is a better method since it enables the simultaneous examination of relationships between variables [109]. Table 5 shows that TOC has a considerable indirect impact on CSCC through DTs ($b = 0.27$, t-values = 7.712, $p < 0.05$). According to the investigation, DTs fully mediated the relationship between TOC and CSCC.

Table 2
Discriminant validity using HTMT.

Construct	(1)	(2)	(3)	(4)
(1) TOC				
(2) DTs	0.656			
(3) TT	0.500	0.570		
(4) CSCC	0.507	0.723	0.625	

Source: Authors' analysis.

Table 3
Model evaluation indicators.

Constructs	R^2	Q^2
TOC		
TT		
DTs	0.458	0.267
CSCC	0.441	0.324

Source: Authors' analysis.

4.4. Moderation analysis

This study proposed that TT could act as a moderator in the TOC-DTs relationship. Accordingly, an orthogonalization method was used to evaluate the moderation analysis. A statistically significant p-value ($P < 0.05$) and the lack of zero in the lower and upper confidence intervals supported the moderation hypothesis. The findings confirm H6 by demonstrating that TT moderates the TOC-DTs relationship ($b = 0.18$, t-value = 2.916, $p < 0.05$), as indicated in Table 6.

To better understand the moderating effect, the interaction impact on DTs at different levels of TT and TOC was examined using visualization techniques based on the guidelines of Aiken and West [112]. A graphical representation was generated to depict the relationship between TOC and DTs, with TT acting as a moderator, as depicted in Fig. 2.

5. Discussion

Drawing on TOE and DCT theories, we investigated the relationship between TOC, DTs, TT, and CSCC. According to the results, DTs positively and significantly affect CSCC. This result indicates that the adoption of DTs can reinforce CSCC by improving transparency, efficiency, and resource management. Essentially, these technologies enable better tracking of materials, optimize processes, and facilitate the reuse and recycling of resources, ultimately contributing to more sustainable and effective SC operations. This aligns with Romagnoli *et al.* [23], who found that DTs like internet of things is an efficient technology for managing transportation and product flow in the CSC. On the contrary, this finding contradicts previous studies that showed that the usage of new DTs does not have a strong positive impact on the implementation of sustainability and CE practices (e.g., [46]).

In line with our anticipations, we found that TOC positively and significantly affects DT adoption. This is in line with a study by Li *et al.* [27], which suggest that TOC can facilitate the adoption of new technologies. Indeed, TOC helps companies to assess the potential benefits and risks associated with DTs, enabling timely adoption and adaptation [24]. Accordingly, a company that possesses TOC, which includes the capability to sense and respond to new technologies, is more likely to succeed in adopting and integrating advanced DTs. This is because this company becomes better equipped to identify, evaluate and effectively implement these advanced technologies. As such, this ability helps the company stay ahead of technological trends and leverage these technologies to accomplish competitive edge.

It was further found that TOC enhances the positive effect of DTs on developing CSCC but that it does not directly affect CSCC. While the indirect effect of TOC on CSCC was significant, the direct effect was also non-significant, implying that DTs fully mediates the TOC—CSCC relationship. This is supported by Leonidou *et al.* [79], who found that dynamic capabilities, especially TOC, play a critical role in promoting eco-friendly practices, which are essential for improving CSCC. The positive indirect relationship between TOC and CSCC aligns with the

Table 4
Structural path analysis results.

H	Path	β	Std Error	t-value	*p*	LL	UL	Result
H1	DTs→ CSCC	.591	.055	10.760	.000	.479	.693	*Supported*
H2	TOC→ DTs	.458	.050	9.192	.000	.361	.556	*Supported*
H3	TOC→ CSCC	.108	.057	1.874	.061	−0.002	.222	*Not supported*
H5	TT→ DTs	.278	.055	5.057	.000	.168	.385	*Supported*

Source: Authors' analysis.

Table 5
Mediation analysis results.

H	Path	β	Std Error	t-value	*p*	LL	UL	Result
H4	TOC→ DTs→ CSCC	.271	.035	7.712	.000	.204	.343	*Supported (Full mediation)*

Source: Authors' analysis.

Table 6
Structural path analysis results.

H	Path	β	Std Error	t-value	*p*	LL	UL	Result
H6	TOC*TT→ DTs	.180	.042	2.916	.044	.005	.160	*Supported*

Source: Authors' analysis.

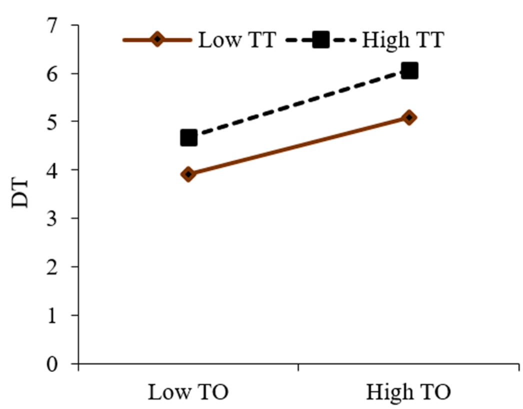

Fig. 2. Moderating effect of TT.

premise that TOC represents a form of dynamic capability that leverages unique competencies to navigate dynamic environments [41]. In the context of technological progress, companies with TOC efficiently and effectively create new resource pools to sense and respond to new technologies through distinct operational and strategic practices [47]. These companies gain a competitive edge over less technologically opportunistic companies by leveraging new technologies to exploit business opportunities and develop applications based on these innovations. By adopting TOC, companies can sense and respond to technological advancements, identify the most suitable and least risky clean technologies, and develop strategies and processes around these technologies. This contributes to CSC approach by minimizing waste and continuously utilizing resources, ensuring that any unavoidable waste is recycled or recovered [80]. Through DTs adoption, firms with TOC capability can enhance CSCC. The result suggests that the capability of a company to sense and respond to technological opportunities does not directly enhance CSCC. Instead, this capability indirectly impacts these practices through the adoption of advanced DTs. In other words, companies that are good at detecting and reacting to new technologies are more likely to adopt digital tools, which in turn facilitate the implementation of CSC practices. In contrast, this finding is inconsistent with the results of Rauer and Kauffman's [113] study, which conducted on ten green tech companies, that sensing capability is one of the barriers related to the SC structure and environmental standards when adopting green SC management.

As anticipated, TT, which signifies the uncertainty stemming from rapid and substantial changes in technological environments, enhances the link between TOC and firms' adoption of DTs. The success of an organization's capability to seize technological opportunities seems to hinge on the characteristics of its technological surroundings. Therefore, the approaches for translating sensing and response capabilities into newly adopted technologies vary based on specific technological circumstances. A company with TOC in highly volatile technological markets achieves superior performance due to its ability to manage challenges such as technological obsolescence and the emergence of new technical information [26]. This evidence is in line with prior research (e.g., [94]), which assumed that TT moderates the association of dynamic capabilities with firm performance. Overall, our results indicate that the level of TT influences how strongly TOC affects a firm's adoption of DTs. Specifically, in environments with high TT, companies that are more opportunistic in leveraging new technologies are likely to adopt DTs more readily. Conversely, in stable environments, the impact of TOC on DTs adoption might be less pronounced. Furthermore, TT not only moderates the TOC–DTs relationship but also has unique positive effect on DTs adoption.

6. Conclusions

Several theoretical and managerial implications can be drawn from this study.

6.1. Theoretical implications

This research has several theoretical implications. First, the positive effect of DTs on CSCC provides a new direction for the CSC management research. Contradicts some studies (e.g., [46]) that found limited impact of DTs on sustainability, highlighting the context-specific nature of these relationships. Furthermore, the inconsistency with Rauer and Kauffman's [113] findings on sensing capability as barriers to green SC management indicates the need for further research to understand the conditions under which sensing capabilities either facilitate or hinder sustainable practices.

Second, our results confirm the key role of TOC in driving firms toward DTs adoption. This generally aligns with the TOE framework, which posits that organizational readiness, technological context, and environmental context drive technology adoption. The finding also extends the DCT by illustrating how dynamic capabilities, particularly TOC, facilitate the adoption of advanced DTs, leading to enhanced CSCC. Accordingly, this study did not identify a direct impact of dynamic capabilities (such as TOC) on CSCC. Instead, the influence was facilitated by DTs. Specifically, DT fully mediates the TOC—CSCC relationship, indicating TO's impact on CSCC is indirect through DTs. This implies that while TOC is crucial for identifying and adopting new technologies, the direct impact on CSCC is realized through the implementation of these technologies.

Third, the results suggest that TT moderates the TOC-DTs adoption relationship, emphasizing the contextual dependence of TOC's effectiveness in technology adoption. Prior empirical research shows that companies in highly disruptive environments derive greater benefits from the positive effects of dynamic capabilities on ordinary capabilities [114]. Specifically, frequently sensing and promptly responding to new information are vital strategies in highly volatile markets due to the heightened opportunities and potential for enhanced capabilities [115]. Some researchers argue that turbulence can help an established company attain competitive edge if it is well-prepared to respond effectively to ambiguity [47]. However, others contend that turbulence can swiftly erode competitive advantage if a company fails to reorganize its resources to adapt to a turbulent environment [91]. Indeed, many firms function in unstable and volatile environments characterized by TT, which often leads to market exit due to financial challenges stemming from insufficient revenue and production capacity [90]. However, empirical evidence remains limited and inconclusive regarding both assertions. Therefore, our findings contribute fresh insights to this ongoing debate.

6.2. Managerial implications

This study provides several guidelines for managers and policy makers. First, managers should prioritize adopting advanced DTs as they significantly enhance CSCC. The study indicates that while TOC helps firms identify and adopt new technologies, its impact on CSCC is realized through the implementation of these DTs. Overall, the study highlights the importance of dynamic capabilities, particularly TOC, in driving the adoption of DTs. Therefore, managers should invest in developing these capabilities to stay competitive and enhance their CSC performance.

Second, managers should be aware of the level of TT in their environment. In highly turbulent markets, being opportunistic and quick to leverage new technologies can lead to better firm performance. Conversely, in more stable environments, the emphasis on opportunism may be less critical. Therefore, TT should not be neglected when assessing the benefits of TOC. Indeed, there is no clear evidence that TT is either an advantage or a disadvantage for companies. Moreover, there is no agreement on the strategic actions needed to transform TT into an opportunity in the context of TOC. For instance, while some researchers argue that turbulence enables firms to gain competitive advantages if they can effectively respond to uncertainty, others contend that the prevailing view is that turbulence can swiftly erode competitive advantage if a firm does not reorganize its skills and resources to adapt to the turbulent environment. Depending on the circumstances and the intensity of the turbulence, it can either pose a threat or offer an opportunity. Our study counters this perspective by showing that a higher level of TT amplifies the effect of TOC on DTs adoption. Despite that, managers and policymakers need to recognize the dual nature of TT. While it can create opportunities, it can also pose challenges. Therefore, policies should aim to reduce the negative impacts of turbulence by providing stability through regulatory frameworks and support mechanisms for firms to navigate rapid technological changes.

Third, policymakers should create favorable conditions for the adoption of DTs. This can include providing incentives for technology adoption and supporting infrastructure development to facilitate digital transformation in industries.

6.3. Limitations and future research

Despite the abovementioned contributions, this study also has a number of limitations. Some of these limitations are connected to common problems that are associated with the prevalent logic in research, including "cross-sectional surveys, self-reports, Likert scales, methodologies, and structural equation models" [1]. Therefore, in order to better understand the linkages within the structural model, future studies should concentrate on employing longitudinal data. Future research could test this model in other industries or countries, whether they are developed or developing, or compare findings across different countries since the study was carried out in the context of the automobile industry in India, a developing nation. Moreover, future research directions could include assessing the distinct effects of TOC aspects or examining how the adoption of different technologies (BC, IoT, and BDA) affects CSCC. The variables that may moderate the influence of DTs on CSCC, such as organizational agility, could also be taken into account.

CRediT authorship contribution statement

Abdullah Kaid Al-Swidi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Mohammed A. Al-Hakimi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Hamid Mahmood Gelaidan:** Writing – review & editing, Writing – original draft, Resources, Project administration, Data curation, Conceptualization. **Mohamed Mohamed Al Haifi:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation. **Ahmed Abdullah Ahmed:** Resources, Software, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100492.

Data availability

Data will be made available on request.

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