Data-driven digital transformation for supply chain carbon neutrality: insights from cross-sector supply chain

Abstract

Following the growing pressure on firms and supply chains regarding their environmental impact, carbon neutrality of supply chains is gaining substantial attention among scholars and practitioners. Data-driven digital transformation supports supply chains in achieving higher carbon reduction while improving efficiency and economic performance. However, the conditions under which data-driven digital transformation can provide the desired effect remain unclear due to a lack of empirical evidence. This study aims to address this gap by examining how data-driven digital transformation, enabled by data analytics capabilities, contributes to establishing a win-win situation between carbon and economic performance in the face of several sources of carbon uncertainty through fostering supply chain carbon transparency. Drawing upon the organizational information-processing theory, we posit that the fit between information needs to reduce carbon uncertainties and the information capabilities provided by data-driven digital transformation is critical for enhancing supply chain carbon transparency and balancing supply chains' economic and carbon performance. We examine these relationships using regression tests based on survey data from 437 manufacturing companies from different regions (i.e., Europe, Africa, and Asia). Our results reveal that data analytics capabilities alone cannot enhance supply chain carbon transparency until integrated into a comprehensive business transformation. In that case, carbon transparency would positively mediate overcoming carbon uncertainties and improve the supply chains' carbon and economic performance.

Keywords: data-driven digital transformation; data-analytics capabilities; carbon transparency; carbon uncertainties; carbon neutrality; OIPT

1. Introduction

As climate change intensifies, evidenced by extreme weather events, the critical role of supply chains in global carbon emissions has come into sharp focus. This has led to an increased emphasis on achieving carbon neutrality in supply chains, recognizing their substantial impact on environmental sustainability. Today's businesses are not only expected to be transparent about their carbon footprints but are also urged to actively pursue carbon neutrality in their operations and supply chains (Jira & Toffel, 2013; Villena & Dhanorkar, 2020; Qian & Schaltegger, 2017). This imperative reflects a shift from mere awareness to action, as supply chains are critically positioned at the intersection of environmental impact and business operations. The transition to carbon-neutral supply chains is a strategic priority for sustainable business practices and compliance with evolving global environmental standards (Lintukangas, et al., 2022). The drive towards carbon neutrality is increasingly aligning with adopting data-driven digital technologies. These technologies, from big data analytics to Artificial Intelligence, are redefining the approach to sustainable supply chain management, moving away from traditional practices towards more efficient, technology-driven solutions (Sheng, et al., 2023). Recent trends showcase the synergy between data-driven digital transformation and carbon neutrality, as evidenced by Walmart's Gigaton program. Utilizing data analytics, this initiative significantly reduces greenhouse gas emissions by enhancing energy and transportation efficiency within its supply chain, akin to the impact of removing numerous vehicles from the road (Walmart Sustainability Hub, 2020). This illustrates a broader shift where businesses integrate data-driven digital transformation to achieve economic goals alongside carbon neutrality. The importance of examining digital transformation's role in supply chain dynamics and carbon neutrality is thus highlighted.

The pursuit of carbon neutrality through data-driven digital transformation not only amplifies operational efficiency, customer value, and overall performance but also integrates data analytics capabilities into strategic, structural, and procedural aspects of supply chain management (Belhadi, et al., 2021; Enrique, et al., 2022). However, the transformation's pace varies across firms, influenced by factors such as capital requirements and the risk of financial strain, particularly in industries like manufacturing, known for significant carbon emissions (Papanagnou, et al., 2022; Sheng, et al., 2023; Villena & Dhanorkar, 2020). This variation in the pace of digital transformation across firms necessitates empirical research to explore its impact on supply chain performance. We define 'supply chain carbon performance' as the effectiveness of a supply chain in managing and reducing its carbon emissions, a crucial aspect of environmental sustainability (Villena & Dhanorkar, 2020). Similarly, 'supply chain uncertainties' refer to the varied challenges and unpredictabilities in supply chain operations, especially regarding carbon management. These uncertainties can arise from fluctuating market demands, supply chain disruptions, and evolving environmental regulations (Sheng, et al., 2023).

The imperative for harmonizing economic performance with carbon reduction emphasizes the critical role of supply chain carbon transparency (Jira & Toffel, 2013; Hahn, et al., 2015). This transparency, which involves providing stakeholders with detailed carbon emission information, is increasingly recognized as crucial for meeting sustainable development goals and making informed decisions to mitigate environmental impact while enhancing operational efficiency (Villena & Dhanorkar, 2020; Hassan & Romilly, 2018; Liesen, et al., 2017). In this context, supply chain carbon transparency emerges as a critical mechanism through which data-driven digital transformation can harmonize economic performance and carbon neutrality. This alignment is supported by the Organizational Information Processing Theory (OIPT), which highlights the importance of effective information management in gaining a competitive edge. OIPT provides a theoretical lens to understand how integrating data-driven digital transformation with supply chain strategies can align with broader organizational goals, influencing sustainable supply chain strategies and overall performance in a rapidly evolving business environment (Galbraith, 1974; Simon, 1957). Consequently, data-driven digital transformation equips firms with the necessary human, technical, and organizational capabilities to manage information effectively, particularly in supply chain carbon transparency initiatives.

A critical gap exists in current research on carbon transparency within supply chains, particularly its empirical validation in the era of data-driven digital transformation. While theoretical models posit that carbon transparency could be a critical mediator between digital transformation and the dual goals of economic performance and carbon neutrality (Lintukangas, et al., 2022; Shui, et al., 2022; Sheng, et al., 2023), empirical evidence to support these assertions is notably lacking. This gap is more pronounced considering the challenges in balancing economic efficiency with carbon footprint reduction in supply chain operations. The complexity and uncertainty of supply chain carbon data further accentuate the need for a robust, empirically grounded framework. Such a framework is essential to explore and validate the intertwined relationship between economic performance and carbon management in supply chains, moving beyond theoretical conjectures to practical, data-driven insights. Addressing this gap, our study contributes novel empirical insights, setting itself apart from existing theoretical discourse. We provide concrete, data-driven evidence of how digital transformation facilitates carbon neutrality in supply chains, offering a practical framework for effectively understanding and implementing these technologies.

This paper proposes an integrated conceptual framework to answer two fundamental research questions (RQs).

> RQ1. How can data-driven digital transformation influence supply chain carbon transparency?
>
> RQ2. How does supply chain carbon transparency, facilitated by data-driven digital transformation, influence the dual objectives of economic and carbon performance in the presence of carbon uncertainties?

To address the research above questions, we posit that firms operating in uncertain environments need to process more information, which can be facilitated by the development of information processing capacity (Srinivasan & Swink, 2018; Aben, et al., 2021; Zhu, et al., 2018). In this study, we argue that data-driven digital transformation represents a form of information-processing capacity that can help firms overcome carbon uncertainties and enhance supply chain carbon transparency, thus influencing economic and carbon performance. To test our argument, we conducted a quantitative survey of 437 firms from various regions (i.e., Europe, Africa, and Asia) belonging to different supply chains. The collected data were analyzed using regression and bootstrapping techniques.

Our research distinctly contributes to the literature on supply chain management by providing empirical insights into the application of data-driven digital transformation for achieving carbon neutrality. Diverging from prior theoretical explorations, this study specifically examines the role of digital transformation in enhancing carbon transparency within supply chains, particularly in contexts marked by uncertainty. The findings illuminate the intricate balance between achieving carbon neutrality and maintaining economic performance, offering a nuanced understanding of how supply chains can navigate the dual challenges of environmental responsibility and business efficacy.

2. Background literature

2.1. Organizational Information Processing Theory

OIPT, as conceptualized by Galbraith (1974), provides a robust framework for understanding organizational information processing, particularly in contexts of high uncertainty. This theory is instrumental in explaining how firms can effectively manage information by reducing their need via “mechanistic” strategies or enhancing their processing capabilities. The relevance of OIPT in supply chain management, a field characterized by inherent uncertainties, is well-established (Srinivasan & Swink, 2018). The advent of data-driven digital transformation has extended OIPT's applicability in supply chain contexts. Aben et al. (2021) explore how digital transformation necessitates and facilitates enhanced information processing capabilities in organizations. This is particularly relevant in managing supply chain carbon transparency, where the processing of extensive carbon data is crucial for operational and environmental decision-making. In aligning economic performance with carbon neutrality, the role of OIPT becomes increasingly significant. Galbraith's (1974) proposition regarding information processing aligns with firms' challenges in balancing these twin objectives within their supply chains. Zhu et al. (2018) reinforce this perspective, highlighting the effectiveness of information processing strategies in navigating the complexities of sustainable supply chain management.

Empirical studies further validate OIPT's utility in the era of data-driven digital transformation. For example, research demonstrates that leveraging digital tools for information processing can significantly enhance decision-making in environmental sustainability (Srinivasan & Swink, 2018). Such evidence underscores the theory's effectiveness in understanding the dynamics of information management in digitally transformed supply chains. Therefore, our study's application of OIPT offers a theoretical basis to investigate how data-driven digital transformation impacts supply chain carbon transparency. This approach is consistent with OIPT’s principles and provides new insights into its application in supply chain carbon management, particularly in the digital age.

2.2. Data-driven digital transformation

Digital transformation involves the integration of digital technologies into business operations, processes, and value creation, resulting in a transformation of the organization (Sheng, et al., 2023; Papanagnou, et al., 2022). Hanelt et al. (2021) defined digital transformation as the organizational transformation induced and shaped by the pervasive dissemination of digital technologies across the organization. Data-driven technologies such as big data (Matthias, et al., 2017), data analytics (Akter, et al., 2016), artificial intelligence (Fosso Wamba, et al., 2022), and machine learning (Filom, et al., 2022) are at the center of these technologies, using either data analytics capabilities (Papanagnou, et al., 2022). According to Akter et al. (2016), data analytics capabilities enable firms to extract business insights by combining three elements, i.e., technology, management, and human skills. This has been demonstrated to be a prerequisite capability to transform businesses into a competitive force (Awan, et al., 2021; Mikalef, et al., 2019). Based on the literature on digital transformation (for a detailed review, see Hanelt et al., 2021; Gong and Ribiere, 2021), we define "data-driven digital transformation" as a fundamental process triggered by the innovative use of data analytics capabilities to radically improve organizational performance. This transformation is powered by the vast data generated within the firm's environment, often called "the new oil" (Aben, et al., 2021), driving transformative changes facilitated by the firm's ability to process information effectively. From an OIPT perspective, data-driven digital transformation empowers firms to enhance their capacity for processing information. They can proactively gather data from various facets of their operational landscape and strategically process it to instigate and steer profound organizational change (Srinivasan & Swink, 2018). This definition underscores the synergy between data analytics capabilities and information processing capacity, collectively driving the metamorphosis brought about by digital transformation. We follow several information systems studies to reflect on data analytics capabilities (Srinivasan & Swink, 2018; Akter, et al., 2016) and digital transformation (Belhadi, et al., 2021) as the intersection of three elements, i.e., infrastructure, processes, and skills. *Infrastructure* refers to the IT tools and digital technologies that drive data-driven digital transformation. This includes data collection tools (e.g., sensors, big data…) and data-processing technologies (e.g., machine learning, artificial intelligence…). *Processes* are defined as organizational structures and instances that direct infrastructure use toward the firm's maximum value. *Skills* refer to the human competencies and abilities needed to leverage the insights drawn from data analytics processes to drive organizational transformation.

Therefore, data-driven digital transformation is a function of these three dimensions, each contributing uniquely to the change achieved through data.

2.3.Supply chain carbon transparency and carbon performance

In our study, 'supply chain carbon performance' is expressly defined to capture the effectiveness of a supply chain in reducing its carbon emissions. This definition aligns with the understanding of contemporary supply chain management literature, where reducing carbon emissions is increasingly seen as a critical aspect of operational efficiency and sustainability (Villena & Dhanorkar, 2020; Hassan & Romilly, 2018). 'Carbon performance' in this context refers to the quantification of emissions and the strategies and actions taken to minimize these emissions across the supply chain.

In today's focus on carbon neutrality, increasing carbon transparency in the supply chain has become a growing interest for companies due to several regulatory and operational purposes (Villena & Dhanorkar, 2020). On an international level, there has been a rise in voluntary initiatives, such as the nonprofit Carbon Disclosure Project (CDP), compelling companies to disclose their greenhouse gas (GHG) emission efforts and performance. Additionally, mandatory initiatives have emerged nationally, geared toward increasing transparency and improving emissions management (Hahn, et al., 2015; Luo, et al., 2018).

Drawing upon the literature on transparency (as reviewed by Shui et al. (2022) and Schnackenberg et al. (2021)), supply chain carbon transparency can be defined as the provision of high-quality and specific carbon emission data by and to all supply chain partners and stakeholders (Villena & Dhanorkar, 2020). In this context, our conceptualization of supply chain carbon transparency encompasses three pivotal dimensions: supply chain disclosure, information accuracy, and information clarity. *Supply chain disclosure* pertains to a supplier's commitment to openly sharing relevant carbon information with all stakeholders, ensuring transparency extends beyond selective disclosure to influential parties. Transparent suppliers, in contrast, embrace openness by sharing information even with stakeholders who might critically assess such data, including non-governmental organizations (NGOs) and the wider public. *Information accuracy* underscores the essential reliability of carbon-related data provided by the supplier. Transparent information should be free from bias and grounded in robust data sources to ensure its credibility. *Information clarity* emphasizes the extent to which suppliers communicate environmental information. Greater clarity and comprehensiveness of carbon information contribute to higher transparency. Thus, these three dimensions collectively shape the overall degree of supplier transparency, highlighting that each dimension uniquely establishes a comprehensive transparency framework. While these definitions may not be standardized in the strictest sense, we have synthesized insights from established literature sources to ensure their relevance and coherence within our study's scope.

According to Shui et al. (2022), although the outcomes resulting from supply chain carbon transparency in carbon neutrality are expected to attract the most scholarly attention, this is not the case in the current literature. Even worse, the few available investigations of the association between carbon transparency and carbon neutrality reveal conflicting results. Based on the relational view, the study by Lintukangas et al. (2022) highlighted the role of carbon information transparency in achieving the supply chain carbon management goals. Qian and Schaltegger (2017) propose that supply chain carbon disclosure can be a valuable management tool for companies seeking to enhance their carbon performance by reducing their emission intensity. Their research indicates that businesses can subsequently achieve a positive correlation with supply chain carbon neutrality by improving the quality of information disclosed. However, other studies, such as Hassan and Romilly (2018) and Kim and Lyon (2011), found no causal link between carbon transparency and carbon performance. They even discovered that some companies used participation in disclosure programs to greenwash their emissions. Their research indicated that disclosure programs had no significant impact on changes in carbon performance. Despite the conflicting findings in the past literature, the question, according to Schnackenberg et al. (2021), needs to go beyond positive/negative association to the underlying mechanisms and conditions under which carbon neutrality can be an outcome of carbon transparency in the context of the supply chain.

3. Theoretical framework and hypotheses

Grounded on the premises of the OIPT, we propose the theoretical research framework depicted in Figure 1. The framework focuses on the organizational fit between data-driven digital transformation as the information-processing capacity and supply chain carbon transparency as the information-processing need. Afterward, we investigate the spillover effect on both carbon neutrality and economic performance. Accordingly, we compare the organizational fit among the elements of data-driven digital transformation, i.e., data analytics capabilities (H1), business transformation (H2), and their combination (H3). Additionally, our model contends that supply chain carbon transparency affects both carbon neutrality and the economic performance of the supply chain and acts as a mediator between data-driven digital transformation and supply chain carbon neutrality (H4) and economic performance (H5). Lastly, we consider supply chain uncertainties as information-boundary conditions that create tensions for the information-processing fit (H6).

After that, we detail the suggested hypotheses illustrated in Figure 3, associating data-driven digital transformation, uncertainties, and carbon transparency with two-level performance, i.e., carbon neutrality and economic performance.

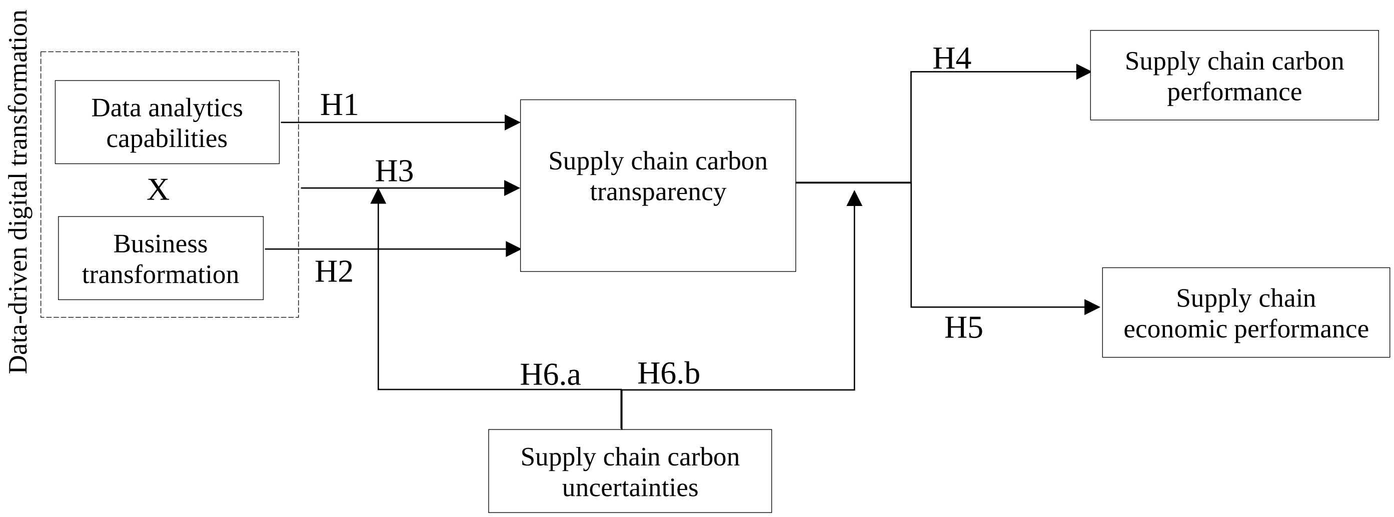

Figure 1. Theoretical framework

3.1.Data-driven digital transformation and supply chain carbon transparency

As discussed earlier, data-driven digital transformation can be defined through two dimensions, i.e., data analytics capabilities and business transformation. Regarding data analytics capabilities, past literature has primarily established a positive link between data-driven technologies and transparency in the supply chain context. For instance, Shafiq et al. (2020) and Fernando et al. (2018) established that supply chain analytics have significant spillover effects on supply chain transparency based on a resource-based perspective. The same finding has been reported in the study of Zhu et al. (2018) from an OIPT point of view. Indeed, the OIPT asserts that a result of developing data analytics capabilities is that firms can strike the organizational fit between information processing requirements and information processing capabilities (Zhu, et al., 2018). In the supply chain context, firms can acquire data-driven capabilities to collect, retain, and connect data from supply chain partners located both upstream and downstream (Kache & Seuring, 2017). These capabilities are widely proven to bring higher visibility throughout the supply chain, enabling firms to be more transparent in numerous supply chain sustainability issues such as GHG emissions and climate change (Roßmann, et al., 2018; Fernando, et al., 2018). Accordingly, as suggested by OIPT, alongside a large part of the existing body of knowledge, there are reasons to believe that data analytics capabilities could enhance carbon transparency by enabling firms to proactively determine and alleviate carbon-related issues throughout their partners. Thus, we assume that:

H1. Data analytics capabilities lead to higher supply chain carbon transparency

On the other hand, several studies assert that business transformation will likely lead to higher transparency at firm or supply chain levels. For instance, the studies of Santharm and Ramanathan (2022) and Barrane et al. (2021) found a strong link between digitally enabled transformation and visibility and transparency throughout the supply chain. Additionally, Akter et al. (2022) found that digital-driven innovation in organizational transformation leads to supply chain transparency. Indeed, business transformation is an antecedent of several supply chain attributes positively related to greater supply chain visibility and transparency, such as agility and collaboration. Thus, we can project these premises to supply chain carbon transparency to hypothesize that:

H2. Business transformation leads to higher supply chain carbon transparency.

Given the evidence above, combining data analytics capabilities and business transformation, i.e., data-driven digital transformation, is deemed to have mutually reinforcing effects on supply chain carbon transparency. The reason behind this assumption is the large body of knowledge asserting that data-driven technologies constitute an enabler for business transformation toward more transparency in several contexts (Keller, et al., 2021; Pappas, 2018). Hence, we assume that:

H3. Data-driven digital transformation (the combination of the two dimensions, i.e., data analytics and business transformation) has a greater effect on increasing supply chain carbon transparency than only one of the two dimensions.

3.2. The mediating effect of supply chain carbon transparency

OIPT asserts that the fit between information and its proper utilization is a potential source of enhanced performance at different levels. In the supply chain context, many firms’ carbon emissions may stem from their suppliers (Villena & Dhanorkar, 2020). Hence, information on suppliers' carbon emissions is beneficial to assess the carbon impact of the supply chain and direct initiatives for carbon emissions reduction (Luo, et al., 2018; Hahn, et al., 2015). We follow several studies to establish a link between supply chain carbon transparency and two levels of performance: "straightforward" economic performance and "less self-evident" carbon performance of supply chains (Lintukangas, et al., 2022; Shui, et al., 2022; Sheng, et al., 2023). Supply chain carbon performance refers to the efficiency of efforts to reduce carbon emissions associated with the organization and supply chain processes. This encompasses the reduction of carbon emissions generated throughout procurement, production, transportation, distribution, and other supply chain and organization-related processes. On the other hand, supply chain economic performance pertains to the efficiency of financial outcomes associated with the organization and supply chain activities. This includes procurement, production, distribution, and other supply chain and organization-related activities.

Data-driven digital transformation provides an advanced perspective to effectively generate and use transparent carbon information throughout the supply chain. This is naturally a source of both economic and carbon performance. Indeed, despite the varying opinions among researchers about the extent to which carbon transparency is relevant in terms of economic and carbon performance, several studies provide reasons to postulate that carbon transparency, stemming from data-driven digital transformation, is a source of both economic and carbon performance. For instance, Liesen et al. (2017) posit that investors can attain risk-adjusted returns from firms that disclose their GHG emissions through analytical approaches, as opposed to those that do not. The authors contend that investment returns can be maximized by investing in firms that disclose a comprehensive level of GHG emissions, encompassing Scope 1, 2, and 3 emissions through a transformational approach, in contrast to those that only disclose incomplete information. Similar conclusions can be drawn from studies concerning carbon neutrality, such as Qian and Schaltegger (2017), Hassan and Romilly (2018), and Kim and Lyon (2011). Hence, there are enough reasons to put forward:

H4. Supply chain carbon transparency mediates the relationship between data-driven digital transformation and supply chain carbon neutrality.

H5. Supply chain carbon transparency mediates the relationship between data-driven digital transformation and supply chain economic performance.

3.3.The moderating effect of supply chain carbon uncertainties

In dynamic business environments, firms face uncertainties that require them to respond through investment and implementation of information-acquiring and processing capabilities (Enrique, et al., 2022; Frank, et al., 2022). Supply chain carbon uncertainties refer to the uncertainties associated with estimating the carbon emissions and carbon footprints of products and services across their entire supply chain (Mohammed, et al., 2017; Haddadsisakht & Ryan, 2018). Based on the OIPT framework, our analysis suggests that companies facing supply chain carbon uncertainties require increased information-processing capabilities to make informed decisions. Data-driven digital transformation is especially relevant in such turbulent environments, as it reinforces the importance of data analytics capabilities in a business transformation perspective for achieving organizational goals (Chen & Tian, 2022). The primary sources of supply chain uncertainty are upstream uncertainties caused by the variety of suppliers' geographic locations and regulations (Mohammed, et al., 2017; Haddadsisakht & Ryan, 2018), and the opportunistic behavior of partners to hide or greenwash some pollutant activities (Kim & Lyon, 2011). Carbon uncertainties may constitute a boundary for the relationship between data-driven digital transformation and supply chain carbon transparency. Indeed, in such uncertainties, the supply chain may be required to reinforce the data-driven digital transformation throughout the supply chain to achieve carbon transparency. Based on this, we propose the following hypothesis:

> H6.a: Supply chain carbon uncertainties negatively moderate the relationship between data-driven digital transformation and supply chain carbon transparency.

Following similar logic, in the presence of carbon uncertainties, Carbon information should be spread over a significant disparity of supply chain nodes with higher accuracy and clarity (Lintukangas, et al., 2022). Thus, firms are expected to attain higher levels of carbon transparency to leverage carbon information to achieve both carbon neutrality and economic performance. Hence, we assume that:

> H6.b: Supply chain carbon uncertainties negatively moderate the relationship between data-driven digital transformation and both carbon neutrality and the economic performance of the supply chain.

4. Research Methodology

4.1.Data collection

Our research used a mixed-method approach that integrated quantitative and qualitative data to better comprehend the research context.

In our qualitative research phase, we selected 13 focal firms representing diverse sectors within the supply chain industry. These sectors included but were not limited to, automotive, textiles, energy, and food production, encompassing a broad spectrum of supply chain dynamics. The firms were located across three distinct geographic contexts: Europe, Africa, and Asia. This selection was intentional to ensure a comprehensive understanding of data-driven digital transformation across varied supply chain environments. Firm size was categorized based on the annual revenue. Small firms had annual revenues of up to $50 million, medium firms from $50 million to $500 million, and large firms over $500 million. Supply chain tiers were defined based on the firm's overall supply chain network position. Tier-1 firms are direct suppliers to the final manufacturer, Tier-2 firms supply to Tier-1 firms, and so on. The firms are selected as they have accomplished the data-driven digital transformation according to our conceptualization. To gain practical experience and better understand the phenomenon studied, we conducted semi-structured interviews with individuals in various roles (CEOs, supply chain managers, and sustainability executives). We observed the data-driven digital transformation in use at different levels of the supply chain. Upon completing the interviews, we conducted a rigorous data analysis process. The transcribed interview data underwent thematic analysis, a systematic approach that involved coding segments of text to identify recurring patterns, concepts, and themes. This coding process involved carefully examining textual data, where segments of interviews were systematically tagged and labeled to capture specific ideas, concepts, or sentiments. The coded segments were then organized into broader categories based on shared themes and commonalities. Through this iterative process, we identified recurring patterns that elucidated the nuances of data-driven digital transformation, supply chain carbon neutrality, and economic performance within each firm and across different sectors and regions. The interviews provided qualitative insights to support our quantitative findings and aided in survey creation while minimizing bias. We were able to confirm the presence and relevance of certain concepts in the different countries and supply chain sectors, identify primary data-driven digital transformation aspects, and determine appropriate variables to measure. Participants indicated that carbon neutrality at the supply chain level was their performance's primary objective and indicator.

The quantitative phase involves surveying various supply chain sectors and seeking input from experts in the supply chain, operations, sustainability, and environmental management. The survey targeted high-level executives, directors, and managers in large manufacturing firms located in Europe, Africa, and Asia. In selecting the countries for our study, we focused on Europe, Africa, and Asia due to their diverse and representative nature in global supply chain dynamics. Europe was chosen for its advanced digital transformation initiatives and stringent carbon footprint reduction policies. Africa was included to represent emerging economies with growing digital transformation trends and increasing awareness of carbon footprint management. Asia was selected for its significant role in global supply chains and its varied approach to digital transformation and carbon reduction efforts. This diversity provided a comprehensive perspective on the implementation and impact of data-driven digital transformation across different economic and environmental contexts. We targeted companies based on two criteria: i.e., a high level of data-driven digital transformation adoption and a high level of activity in carbon footprint reduction across the supply chain. To ensure the validity of the survey, we first shared a preliminary version with executives in the relevant fields and received feedback from 27 individuals. We then emailed the survey questionnaire to our target population through the SurveyMonkey platform thrice between January and May 2022. We targeted 1098 enterprises in the three countries. These companies were identified through a business association representing industrial supply chain activities. Finally, we received 437 valid responses. The response rate is 39.8%. The main characteristics and profiles of the sample enterprises are depicted in Table 1.

Table 1. Characteristics and profiles of the sample firms

Firms characteristics	**#**	**%**	**Respondent profile**	**#**	**%**
Supply chain sector			**Department**		
Automotive	87	19,91%	General direction	39	8,92%
Airline	65	14,87%	Supply chain	109	24,94%
Textile	52	11,90%	Operations	57	13,04%
Agrifood	49	11,21%	Environment	105	24,03%
Energy	47	10,76%	Sustainability	127	29,06%
Electric equipment	44	10,07%	**Experience**		
Chemical	43	9,84%	Less than five years	37	8,47%

Transportation	39	8,92%	Between five and 15 years	103	23,57%
Other	11	2,52%	More than 15 years	297	67,96%
Firm's size					
Small	22	5,03%			
Medium	88	20,14%			
Large	327	74,83%			
Supply chain Tier					
Focal firm	179	40,96%			
Tier-1	135	30,89%			
Tier-2	84	19,22%			
Tier-3	39	8,92%			
Country					
Europe	167	38,22%			
Asia	139	31,81%			
Africa	131	29,98%			

4.2.Measures

Validated measurements from previous studies were utilized in this research. To establish the scale items, we used two versions, i.e., one in English in the Asian context and one in French in both French and Moroccan contexts. Accordingly, the English version was translated into French, and back-translation was employed to ensure cultural equivalence, as suggested by Sheng et al. (2023). Then, the measurement scale has undergone a thorough review by both researchers and practitioners. A pre-test was conducted with 15 participants, and questionnaire modifications were made based on their feedback. A seven-point Likert scale was used to measure the items.

4.2.1. Dependent variables

In assessing the dependent variables of supply chain carbon performance and supply chain economic performance, our approach was guided by established literature. Specifically, we developed a construct for supply chain carbon performance based on synthesizing existing measures and definitions found in relevant studies. We adopted a multifaceted approach, integrating aspects such as energy usage, carbon emissions, and utilization of carbon-intensive materials, as indicated by Böttcher & Müller (2015) and Sheng et al. (2023). These measures were chosen for their relevance and consistency with the broader conceptualization of supply chain carbon performance in current research, which views it as the effectiveness of supply chain operations in minimizing carbon emissions. This includes (1) energy usage, (2) carbon emissions, and (3) carbon-intensive materials usage. Second, supply chain economic performance was assessed using four measures following the study by Kim (2014), which are (1) supply chain costs as a percentage of revenue, (2) Return on investment (ROI), (3) Inventory turnover, and (4) Perfect order rate. All the selected measures were assessed in the percentage of variation (increase or decrease). To prevent answers influenced by social desirability and bias towards a positive response, the dependent variable was operationalized by asking the respondents a multiple-choice question about the range of product unit costs in the preceding three years. The five possible answers were: (a) less than a 10% reduction, (b) between a 10% and 3% reduction, (c) a reduction or increase within 3%, (d) between a 3% and 10% increase, and (e) more than a 10% increase. We computed an unbiased cost reduction dummy variable based on the responses, which was equal to 1 if the manager reported answers (a) or (b) and 0 if they indicated answers (c), (d), or (e).

4.2.2. Independent variables

Data-driven digital transformation. To operationalize data-driven digital transformation constructs, we first followed Srinivasan & Swink (2018) and Akter et al. (2021) in operationalizing *data analytics capabilities* as a firm's data-driven analytics tools and techniques, alongside the ability to leverage their output to inform the decision-making in the business transformation process. The measurement is based on several factors, including their adeptness in utilizing statistical and data visualization techniques and their ability to effectively deploy decision-making dashboards. In addition, we evaluated the firm's proficiency in gathering information from a wide range of sources and utilizing root cause analysis to dissect the data and identify underlying trends and issues. Second, we operationalized *business transformation* based on the studies by Sheng et al. (2023) and Belhadi et al. (2021). We used factors illustrating the depth of change made to organizations and the firm's business models.

Supply chain carbon transparency. To assess supply chain carbon transparency, we follow studies such as Shui et al. (2022), Schnackenberg et al. (2021), and Villena & Dhanorkar (2020) in using three attributes: supply chain disclosure, information accuracy, and information clarity. First, we focus on information clarity as it is the key to the transparency of carbon information. The process used to develop this variable is inspired by past studies by Villena & Dhanorkar (2020) and Jira and Toffel (2013), which involved using the CDP's questionnaire and 19 key questions answered by the firms. These questions are related to identifying risks and opportunities linked to climate change, GHG emissions levels, and governance of climate change issues. Information clarity was calculated by summing the number of questions answered by the firm out of the 19, with a score of 10, for example, indicating that the firm responded to 10 out of the 19 questions. Second, information accuracy was assessed based on the percentage of uncertainties received in carbon information at the supply chain level. An ordinal measure of accuracy ranging from 0 to 10 was created using these percentages, where lower uncertainty levels indicate higher accuracy. Third, supply chain disclosure is critical to measuring carbon transparency because firms can choose to disclose carbon information with all supply chain partners or just to the requesting partners (Villena & Dhanorkar, 2020). This constitutes the primary measure of supply chain disclosure.

Supply chain carbon uncertainties: We followed studies such as Haddad-Sisakht and Ryan (2018) and Villena and Dhanorkar (2020) in measuring three dimensions of carbon-related uncertainties within the supply chain. First, we included items to measure the level of uncertainties in regulations and carbon thresholds. This is mainly related to the country and region of the firm and the supply chain operations (Haddad-Sisakht & Ryan, 2018). Second, we measure the uncertainties caused by the fluctuations in demand and supply. This is mainly associated with unexpected changes in demand for products or raw materials, which can result in shifts in supply chain activities. Third, we include items to measure the inaccurate carbon accounting throughout the supply chain.

4.2.3. Control variables

We categorized control variables into four groups to mitigate biases from omitted variables. For firm characteristics, we focused on size and supply chain tier. Firm size was dichotomized (large firms as '1', small/medium as '0') to highlight differences in digital transformation approaches between larger and smaller firms. This dichotomy facilitated an analysis that sharply contrasts the impacts on and strategies of firms of different sizes. Similarly, supply chain tiers were simplified into two categories (focal firm and sub-tiers) to underline the varying roles and impacts at different supply chain levels. This allowed a more effective comparison of digital transformation experiences across the supply chain. Second, we controlled for supply chain characteristics using one variable: complexity, which is associated with the degree of uncertainty, variability, and interdependence of the different components in the supply chain. We used three dummies for three levels of supply chain complexities (simple, moderate, and complex). Third, we included two variables to control for country characteristics, i.e., institutional background and technology development. To do that, we used two dummies (where "1" indicates institutional solid background or technology development and "0" denotes medium to weak institutional background or technology development). The control procedure ensures the reliability and validity of our research findings, thereby upholding the highest standards of professionalism in our study.

4.3.Bias countermeasures

Using a firm-level survey where data on independent and dependent variables were collected from a single respondent within each firm may generate a common method bias where data on independent and dependent variables were collected from a single respondent within each firm (Doty & Glick, 1998). We employed procedural and methodological approaches to minimize the effect of this bias. First, our respondents were experienced and held mid/senior management positions, which ensured that they possessed the required knowledge, thus mitigating some of the issues related to single-source bias (Chin, et al., 2012). Additionally, we used separate sections for dependent and independent variables in the survey design and ensured anonymity to minimize social desirability bias. We also used indirect questions to mitigate social desirability bias (Malhotra, et al., 2006). Second, to further assess and minimize common method bias, we employed the widely-used Harman's single-factor test and conducted confirmatory factor analysis by running a separate model incorporating a single latent common method factor (CMF) (McFarlin & Sweeney, 1992; Sanchez & Brock, 1996). The single latent CMF model yielded a $\chi2 = 1668.7$ with 191 degrees of freedom (compared with the $\chi2 = 285.6$ and d.f. = 84 for the initial model). The results indicate that the fit of the single latent CMF model was notably worse than the initial model, implying that common method bias is not a significant concern in this study. We also used the Widaman (1985) approach to compare models with and without CMF, which showed that the method factor accounted for only 1.62% of the total variance. Finally, we separated early and late responses based on timestamps to address non-response bias concerns. In addition, we conducted group comparison tests, which showed little significant difference between the two groups in means and variations ($p<0.05$).

4.4.Data analysis

We conducted hierarchical Ordinary Least Squares (OLS) regression analyses on our data to test our hypotheses. Hierarchical OLS regression enabled us to assess the hierarchical relationships between variables, which was suitable for addressing specific hypotheses related to the influence of different factors step-wise. First, we standardized all independent variables using mean-centering Z-scores before conducting the analyses. Afterward, we ran three models, each of which began with a control variables model in the first stage, followed by varying combinations of data-driven digital transformation constructs, supply chain carbon transparency constructs, and supply chain carbon uncertainty constructs. The hierarchy of sets varies depending on each model. For example, we included data analytics capabilities in the second stage and business transformation in the third stage for supply chain carbon transparency. In contrast, their combination was included in the fourth stage. The fifth stage consists of the moderating effect of supply chain carbon uncertainties. We included supply chain carbon transparency in the second stage for supply chain carbon performance and supply chain economic performance. In contrast, the moderating effect of supply chain carbon uncertainties was included in the third stage. Afterward, we followed Hayes and Rockwood (2017) in using the PROCESS macro for the mediation effect and calculated indirect effects to assess mediation effects. As recommended by Hayes and Rockwood (2017), we used a bootstrapping procedure with 5000 samples to test conditional indirect effects.

Before conducting the analyses, we checked for assumptions such as linearity, homoscedasticity, normality, multicollinearity, and power design (Cohen, 1992). We analyzed collinearity using partial regressions, checked homoscedasticity visually, and assessed normality by examining skewness and kurtosis parameters. We also checked the variance inflation factor (VIF) for multicollinearity. We found the values of VIF to be less than 5 for all variables, which is acceptable following the threshold of Hair et al. (2009). Finally, we used G-power analysis following the procedure of Cohen (1992) to verify the feasibility of using an OLS approach with our sample size (n = 437). Our sample size was larger than the minimum necessary to achieve a statistically significant power level.

5. Results

5.1.Descriptive statistics

Figure 2 compares the adoption rates of data-driven digital transformation between the three countries (Europe, Africa, and Asia). The findings indicate that more than 50% of interviewed companies in the three countries have implemented at least one data-driven digital transformation dimension: data analytics capabilities and business transformation. However, the adoption rates of data analytics capabilities and business transformation are higher in Europe and lower in Africa.

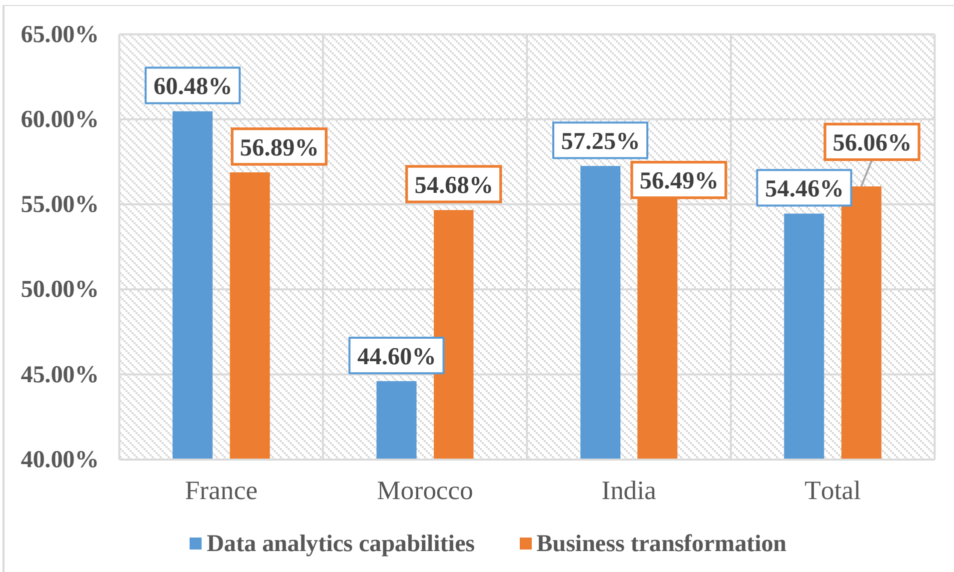

Figure 2. The adoption rates of data-driven digital transformation between the three countries

5.2.Hierarchical OLS regression analysis

Our findings reveal a hierarchical structure comprising four independent models, each distinct model. We also adopt a unique structure for our mediation analysis, which follows Hayes's (2017) method of computing indirect effects as a post-hoc analysis. Table 2 illustrates our preliminary results from the regression analysis using the OLS procedure. Accordingly, we found that all the models at the final stages (i.e., 2, 3, and 4) were significant at 0.01.

The findings of Model 2 indicated that data analytics capabilities do not significantly impact supply chain carbon transparency (β=0.165, $p>0.1$), which does not support hypothesis H1. On the other hand, business transformation positively influenced supply chain carbon transparency (β=0.256, $p<0.01$), supporting hypothesis H2. Interestingly, this impact is amplified when combining business transformation and data analytics capabilities in data-driven digital transformation (β=0.418, $p<0.01$). This provides support for hypothesis H3.

Table 2. Regression of hierarchical OLS regression analysis. ** <0.01, * <0.10.

Predictors	**Hypo.**	**Supply chain Carbon transparency**				**Supply chain carbon performance**			**Supply chain economic performance**		
		Model1	Model2	Model3	Model4	Model5	Model6	Model7	Model8	Model9	Model10
F-value		1.523*	8.647**	13.736**	10.341**	8.369**	17.855**	6.946**	6.589**	1.769*	18.43**
R^2		0.138	0.092	0.213	0.243	0.156	0.078	0.223	0.131	0.198	0.228
Adjusted R^2		0.114	0.073	0.183	0.207	0.128	0.051	0.196	0.113	0.169	0.201
Direct relationships											
Data analytics capabilities	H1		0.165	0.148	0.151						
Business transformation	H2		0.256**	0.295**	0.307**						
Data-driven digital transformation	H3			0.418**	0.408**						
Supply chain carbon transparency	H4, H5						0.528**	0.497**		0.391**	0.447**
Moderators											
Supply chain carbon uncertainties x Data-driven digital transformation	H6.a				-0.117**						
Supply chain carbon uncertainties x Supply chain carbon transparency	H6.b							-0.215**			-0.316**
Controls											
Firm size		0.011	0.065	0.168	-0.034*	0.167*	0.643	-0.148*	-0.006	0.001	-0.119
Firm tier		0.227	0.115*	0.005	-0.016*	0.211*	0.518	-0.098*	-0.002	-0.102	-0.113
Supply chain complexity		0.215	0.176*	-0.116*	-0.051*	0.216*	0.409	-0.102*	-0.006	-0.009	0.528
Institutional background		0.175	0.182*	0.007	0.000	0.184*	0.669	0.118*	-0.012	-0.115	-0.228
Technology development		0.184	0.119*	0.106	-0.145*	0.173*	0.571	-0.109*	-0.042	0.428*	0.288

Furthermore, the results of Models 6 and 9 demonstrate a positive impact of supply chain carbon transparency on both supply chain carbon performance (β=0.528, $p<0.01$) and supply chain economic performance (β=0.391, $p<0.01$).

To evaluate the mediating effect of supply chain carbon transparency proposed in hypotheses H4 and H5, we employed the bootstrapping approach proposed by Hayes (2017). Table 3 depicts the mediation analysis results. Our findings indicate that the constructs of supply chain carbon transparency (i.e., information disclosure, information accuracy, and information clarity) have a significant and direct association with both supply chain carbon performance and supply chain economic performance. This provides support to hypotheses H4 and H5.

Regarding hypotheses H6, the findings of Models 7 and 10 provide statistical evidence of the negative moderating effect of supply chain carbon uncertainties on both supply chain carbon performance (β=-0.215, $p<0.01$) and supply chain economic performance (β=-0.316, $p<0.01$). Therefore, H6.a, and H6.b are supported.

Table 3. The bootstrapping results of the mediating effect of supply chain carbon transparency

Path	Direct effect	Indirect effect	95% confidence interval		Total effect
			Lower	Upper	
Data-driven digital transformation ➔ Information disclosure ➔ Supply chain carbon performance	0.312**	0.129	0.002	0.512	0.442**
Data-driven digital transformation ➔ Information accuracy ➔ Supply chain carbon performance	0.259**	0.097	0.12	0.548	0.355
Data-driven digital transformation ➔ Information clarity ➔ Supply chain carbon performance	0.618**	0.175	0.544	0.811	0.793**
Data-driven digital transformation ➔ Information disclosure ➔ Supply chain economic performance	0.217**	0.108	-0.006	0.619	0.325**
Data-driven digital transformation ➔ Information accuracy ➔ Supply chain economic performance	0.196	0.073	-0.138	0.481	0.269**
Data-driven digital transformation ➔ Information clarity ➔ Supply chain economic performance	0.284	0.115	0.008	0.519	0.399**

5.3.Robustness checks

To ensure the stability and consistency of our results, we conducted a series of robustness checks. We employed three distinct approaches to explore how the results of our regression analyses might vary. First, we introduced a new construct called "data analytics resources," which we hypothesized to be an antecedent to enable data-driven digital transformation. Using the confirmatory factor analysis approach, we measured “data analytics resources” with a five-item scale construct that included the necessary information, human resources, technological resources, financial resources, and organizational culture necessary to develop data-driven digital transformation in the supply chain. Our assumption was confirmed when we added this construct to the models where supply chain carbon transparency, economic performance, and supply chain carbon performance were the dependent variables, as "data analytics resources" were not statistically significant in all models. Second, we analyzed the individual effect of each construct in our models and found consistency with our main findings presented in Table 2. Finally, we utilized a financial performance construct as a competing model to confirm that our primary model is not overfitted and that we have consistency in our analysis. As expected, the competing model was not supported, while our direct model showed robust results. These procedures suggest that our models are consistent and not overfitted and provide additional support for the validity and reliability of our findings. Overall, the robustness checks demonstrate the stability and consistency of our results, providing additional confidence in the validity and reliability of our findings.

6. Discussion

In this empirical study, we examine the impact of data-driven digital transformation on economic and carbon performance through the OIPT lens while considering the mediating effect of supply chain carbon transparency alongside the moderating effect of supply chain carbon uncertainties. The primary thrust of our first research question (RQ1) revolves around delineating the intricate pathways through which data-driven digital transformation influences supply chain transparency. To address the query concerning the precise mechanisms underpinning this influence, let us delve into the pragmatic facets of implementation. Our analysis reveals a nuanced understanding of the role of data analytics capabilities in enhancing supply chain carbon transparency. When employed independently or in isolation —without being integrated into broader organizational strategies — these capabilities do not significantly influence supply chain carbon transparency (Awan, et al., 2021; Enrique, et al., 2022). However, their impact becomes markedly significant when these data analytics capabilities are incorporated into a more comprehensive business transformation strategy, embracing organizational, cultural, and operational changes (Belhadi, et al., 2021). This synergy between data analytics and holistic business transformation profoundly influences supply chain carbon transparency. It allows for effectively utilizing data to inform and drive sustainable practices throughout the supply chain (Sheng, et al., 2023). This empirical revelation underscores the symbiotic relationship between data analytics capabilities and the comprehensive restructuring encapsulated within business transformation—a hallmark of data-driven digital transformation.

In addressing our second research question (RQ2), we explored how supply chain carbon transparency facilitates a balance between economic performance and carbon neutrality, particularly under the complexity of carbon uncertainties. Our analysis reveals a significant impact of supply chain carbon transparency on both carbon management effectiveness and economic outcomes in the supply chain. This impact is evident through several key aspects of carbon transparency, such as the thoroughness of information disclosure, accuracy, and clarity (Villena & Dhanorkar, 2020). These aspects link strongly with the supply chain's ability to manage carbon emissions and achieve financial success. The role of supply chain carbon transparency emerges as a crucial factor, effectively bridging the goals of economic growth and carbon emission reduction. Additionally, our study highlights the substantial influence of carbon-related uncertainties in the supply chain. These uncertainties significantly shape how supply chains manage carbon emissions and perform economically, affecting the pursuit of carbon neutrality and economic balance. Our findings illuminate the nuanced role of carbon uncertainties in the supply chain, demonstrating their effect on the interplay between carbon management and economic performance. This insight is critical in understanding the dynamics of achieving carbon neutrality while maintaining economic viability in supply chains. The findings of our study and the connection to the OIPT are illustrated in Figure 3. The figure shows that the data-driven digital transformation strategy is positioned at the top of the structure; indeed, combining data analytics capabilities and business transformation strategy can provide a comprehensive organizational view to facilitating the implementation of data-driven digital transformation and support increased carbon transparency and performance (Belhadi, et al., 2021; Sheng, et al., 2023). From the OIPT standpoint, this implies establishing strategic alignment for an organizational information-processing fit, as depicted in Figure 3. In other words, companies must develop a data-driven digital transformation strategy that supports all the supply chain carbon transparency dimensions (i.e., information disclosure, accuracy, and clarity) to create an information-processing capability that meets their information processing requirements (Villena & Dhanorkar, 2020). Our findings demonstrate that this is a fundamental requirement for achieving higher carbon transparency and carbon performance in the supply chain amid carbon uncertain environments.

Interestingly, data analytics capabilities are unrelated to higher supply chain carbon transparency. However, carbon neutrality is a particular topic that needs cultural and organizational transformation to leverage data analytics capabilities (Belhadi, et al., 2021). Indeed, these capabilities positively moderate the effect of a comprehensive business transformation on transparency. Therefore, we expect combining data analytics capabilities and business transformation in the data-driven digital transformation to provide more carbon transparency in the supply chain. From an OIPT perspective, the connection between data-driven digital transformation and supply chain carbon transparency entails the organizational fit between information processing capabilities and information processing requirements (Sheng, et al., 2023). This fit can overcome the supply chain carbon uncertainties which constitute information processing boundaries to enhance supply chain performance at carbon and economic levels (Keller, et al., 2021).

The conclusions of our study transcend the mere recognition of the correlation between data-driven digital transformation and supply chain carbon transparency as we explore the intricate relationship between data-driven digital transformation, economic performance, and carbon neutrality. In today's supply chain landscape, firms face the daunting challenge of balancing the pursuit of economic performance with the imperative of reducing carbon emissions (Villena & Dhanorkar, 2020). Our research reveals that the adoption of data-driven digital transformation can serve as a means of resolving this dual pressure, with supply chain carbon transparency acting as an intermediary that effectively facilitates the improvement of economic and carbon performance in the supply chain (Sheng, et al., 2023; Belhadi, et al., 2021). By leveraging the potential of data analytics capabilities and business transformation, firms and supply chains can significantly enhance carbon transparency, balancing environmental and economic performance goals.

6.1. Theoretical implications

This study makes substantial theoretical contributions, particularly enriching the Organizational Information Processing Theory (OIPT) in data-driven digital transformation and supply chain carbon management.

First, by empirically demonstrating the interplay between data-driven digital transformation and supply chain carbon transparency, this research advances our understanding of the OIPT framework (Galbraith, 1974). Contrary to the primary theoretical focus of prior studies (e.g., Awan et al., 2021; Belhadi et al., 2021), our findings provide concrete evidence that integrating data analytics capabilities with broader business transformation is critical for enhancing carbon transparency. This novel insight extends OIPT by showcasing how information processing capabilities, a core element of the theory, can be strategically aligned with environmental sustainability goals. Second, the study offers fresh perspectives on the synergistic impact of data-driven digital transformation on both economic and carbon performance, bridging a gap noted in previous research (Chen & Tian, 2022; Enrique, et al., 2022; Papanagnou, et al., 2022). Our findings contribute to the OIPT by illustrating how enhanced information processing capabilities can improve economic efficiency and carbon reduction, offering a more holistic view of organizational performance. Third, our research enriches the OIPT (Galbraith, 1974; Zhu, et al., 2018) by exploring how data-driven digital transformation aids in navigating supply chain carbon uncertainties. We demonstrate that effective information processing, central to OIPT, is critical in achieving supply chain carbon transparency amidst these uncertainties. This extends the application of OIPT to address the contemporary challenges of environmental sustainability in supply chains, providing a nuanced understanding of how information processing capabilities underpin successful carbon management strategies.

In sum, our study not only responds to calls for empirical examination within these domains (Belhadi, et al., 2021; Pappas, 2018) but also significantly contributes to the OIPT by demonstrating its applicability and relevance in the context of digital transformation and carbon management in supply chains.

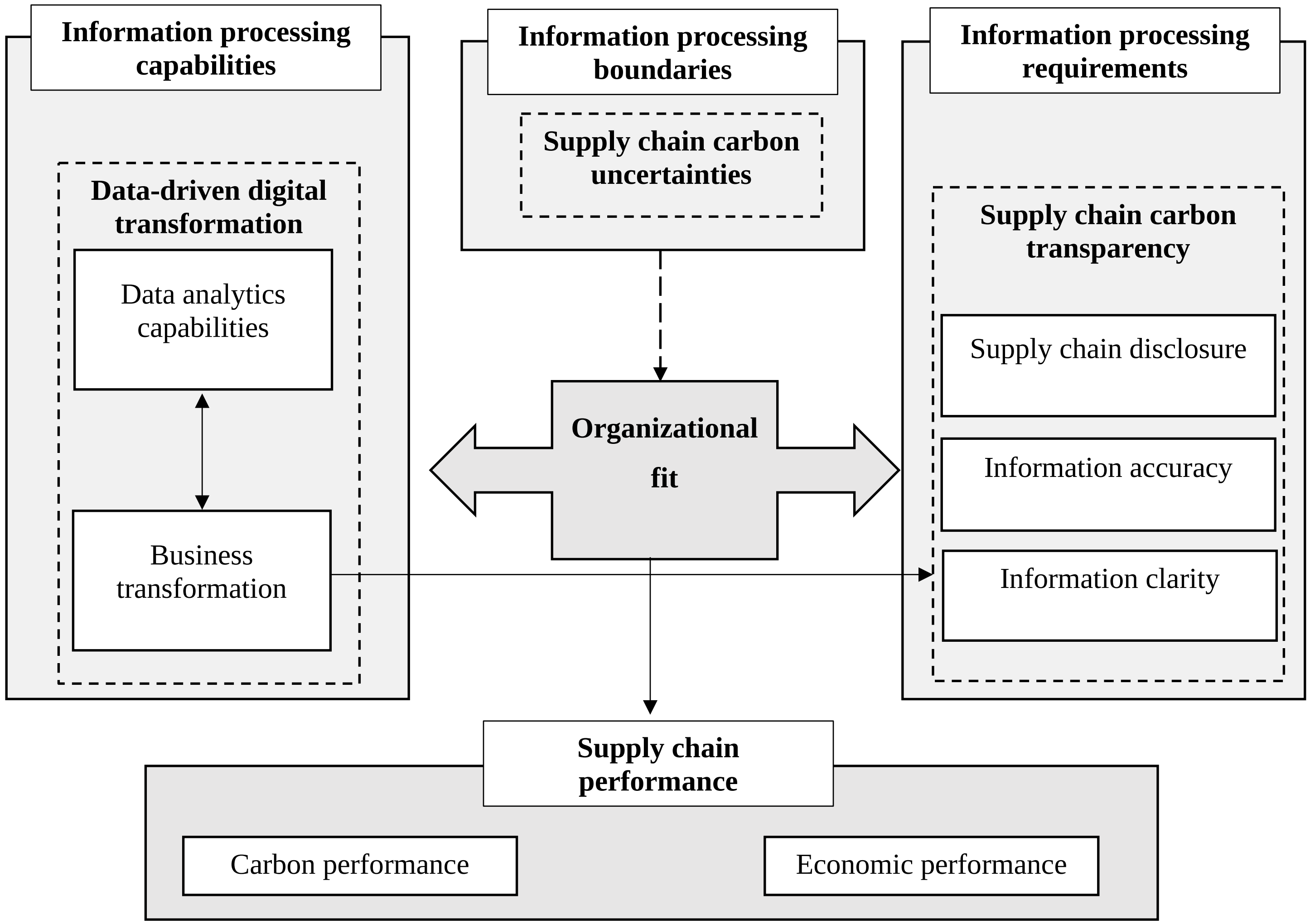

Figure 3. Revised framework based on OIPT

6.2. Managerial implications

Based on our research findings, we provide the following recommendations for supply chain practitioners. The study highlights the imperative for supply chain managers to strategically adopt data-driven digital transformation strategically, focusing on integrating data analytics capabilities within broader business strategies. This approach is essential for improving supply chain carbon transparency, a critical factor in achieving carbon neutrality. The findings suggest that merely possessing advanced data analytics tools is insufficient; their effective integration into organizational operations is critical. Managers should prioritize initiatives enhancing carbon transparency, including establishing robust data collection and reporting systems. This prioritization is vital in light of uncertainties surrounding carbon neutrality in supply chains. By adopting such practices, managers can significantly improve their ability to manage carbon emissions and meet carbon reduction targets. Additionally, recognizing the role of carbon transparency in balancing economic performance with carbon reduction goals is crucial. Managers should operationalize this by embedding sustainability metrics into performance assessments, prioritizing investments in carbon-efficient technologies, and fostering a culture of sustainability within their organizations. These actions are crucial for supply chain managers to navigate the challenges of achieving carbon neutrality while maintaining economic efficiency, as revealed by the study's empirical findings. Implementing these recommendations will enable organizations to leverage better data-driven digital transformation for enhanced carbon transparency and performance in supply chains.

7. Conclusion

In this study, we have investigated the impact of data-driven digital transformation on balancing economic and carbon performance in the highly uncertain supply chain context. Accordingly, we have explored the role of supply chain carbon transparency as a mediating factor between data-driven digital transformation and the simultaneous improvement of economic and carbon performance. As a result, we found that data analytics capabilities are only sufficient to enhance the supply chain carbon uncertainties once included in the broader business transformation, enabling the deployment of the necessary skills, infrastructure, and processes. Moreover, supply chain carbon transparency is found to overcome the negative effect of carbon uncertainties and support data-driven digital transformation in simultaneously improving supply chains' economic and carbon performance.

Although our study contributes to the literature on data-driven digital transformation and supply chain carbon neutrality, it also has some limitations that suggest promising avenues for future research. First, we used cross-sectional data to examine the mediating role of supply chain carbon transparency, which precludes establishing causal relationships and limits our ability to assess the long-term effects of carbon transparency. Hence, future studies employing longitudinal research designs could provide a more comprehensive understanding of the relationships between digital data-driven transformation, carbon transparency, and performance. Second, our study found that supply chain carbon uncertainties weaken the impact of data-driven digital transformation on supply chain carbon transparency due to the vital need for information processing capabilities. Future research could explore additional key digital features that can mitigate the impact of carbon uncertainties using different theoretical perspectives, such as the dynamic capabilities perspective and resource-based view. Third, we used survey data collected from firms from three countries, i.e., Africa, Europe, and Asia, which can limit the generalizability of our findings to other contexts. Therefore, future studies could replicate our study in diverse settings and extend the scope of inquiry to include other types of firms, such as service providers and retailers. These avenues for future research could shed further light on the complex relationships between data-driven digital transformation, supply chain carbon transparency, and performance.

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