



Twin transition in manufacturing firms: The role of supply chain orchestration and supply chain business model innovation

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ABSTRACT

Twin transition, the concurrent development of digitalization practices and circular practices, are believed to be the key to firm performance. However, empirical evidence is currently scarce regarding the effect of twin transition on firm performance and the complementary practices that enable and realize it. This study draws on a survey of 188 Swedish manufacturing firms and employs PLS structural equation modelling to test the hypothesis. The results indicate that firm performance can be improved through digitalization practices but with circular practices as a mediator. Moreover, our results show a significant and positive moderation effect of supply chain orchestration and supply chain business model innovation as complementary mechanisms for enabling and realizing the process. This implies time sequencing between the two twin transition dimensions. These results carry theoretical implications for twin transition research and circular economy literatures. The results also provide novel managerial insights by showing that digital investments must be coupled with early orchestration of supply chain partners and aligned business model innovation to effectively scale circular practices and realize performance benefits.

1. Introduction

Digitalization practices and circular practices are increasingly adopted by manufacturing firms to enhance firm performance and long-term competitiveness (Nayal et al., 2022; Yu et al., 2022). Digitalization practices empower firms to streamline operations, leverage emerging digital technologies, such as data analytics, to improve decision making, and foster innovation by introducing new market solutions (Frishammar et al., 2025; Hallikas et al., 2021). For example, Siemens, a global leader in digitalization and process automation, leveraged digital platforms to achieve an 11.5% increase in revenue and a 56% rise in net income within a year by launching new solutions (Siemens AG, 2021; Siemens, n.d.). Simultaneously, circular practices are increasingly adopted with the aim of reducing environmental impacts, improve resource efficiency, and align with regulatory requirements (Myshko et al., 2024). Circular practices encompass a broad set of strategies that focus on decoupling value creation from material consumption, extending product lifecycles, and optimizing resource use (Ranta et al., 2021). A notable example is Ericsson, which is committed to achieving net zero emissions by 2040 and reducing emissions by 50% by 2030 (Ericsson, n.

d.).

While the benefits of digitalization practices and circular practices are well established, relying solely on one of these is no longer sufficient to achieve sustainable competitive advantage (Almansour, 2022; Fouquet and Hippe, 2022). Manufacturing firms are increasingly integrating both approaches under the umbrella concept of “twin transition”, which refers to the simultaneous adoption of digitalization and circularity to enhance operational efficiency and sustainability outcomes (Tabares et al., 2025). Twin transition is theorized to create a super-additive resource configuration, where their combined effect yields a performance outcome greater than the sum of their individual contributions, essentially, a $1 + 1 = 3$ effect (Herterich et al., 2023; Muench et al., 2022). Despite the potential advantages of twin transition, the existing literature largely focuses on their conceptual foundations, with empirical insights into how practices for twin transition unfold or need to be sequenced to improve firm performance remaining limited (Fouquet and Hippe, 2022). We argue that the progressive interplay between the two core dimensions, digitalization practices and circular practices, requires deeper exploration (Wade et al., 2022). Furthermore, the underlying mechanisms that facilitate the effective

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implementation of twin transition to enhance industrial firm performance remain insufficiently explored (Ranta et al., 2021). Together, these observations establish the first research gap motivating this study.

A primary reason for this narrow focus is the prevailing conceptualization of twin transition as a firm-centric phenomenon (Amir et al., 2023; Farooque et al., 2019). However, the supply chain literature suggests that firms cannot achieve this transformation in isolation (Suali et al., 2024). Many manufacturing firms lack the internal capabilities required to advance digitalization and circularity simultaneously, necessitating the involvement of supply chain partners to bridge these capability deficiencies (Frishammar and Parida, 2019). To foster collaboration, manufacturing firms must typically assume the role of keystone players, strategically aligning with supply chain partners to orchestrate resources and capabilities, collectively known as supply chain orchestration (Adner, 2017). Supply chain orchestration assists in the enabling process of twin transition by integrating digital tools for data sharing, establishing governance structures for role clarity, and coordinating sustainability initiatives (Gebhardt et al., 2022; Parida et al., 2019). In this paper, we refer to “enabling” as the process of establishing the foundational conditions, resources, and capabilities necessary to support and facilitate the desired outcomes (Jansen et al., 2005). It involves acquiring, assimilating, and configuring key assets, knowledge, and relationships to create an environment conducive to twin transition implementation through capacity building, stakeholder alignment, and laying the groundwork for sustainable operations (Simatupang and Sridharan, 2005). Although previous studies recognize the potential of supply chain orchestration for twin transition, what specific role enabling mechanism plays in facilitating twin transition remains an essential area for empirical investigation (Simatupang and Sridharan, 2005; Zekhnini et al., 2022). This informs the second gap for this study.

Beyond orchestrating supply chain partners, firms must focus on realizing twin transition. Here, “realizing” refers to the process of transforming established capabilities into tangible outcomes through effective execution, integration, and optimization of strategies (Jansen et al., 2005). It emphasizes operationalization, value creation, deliver and capture by leveraging the foundational elements established during the enabling process for performance enhancement (De Angelis et al., 2018). Here, supply chain business model innovation plays a critical role by helping firms to redesign their business models in alignment with circular economy goals and digitalization objectives (Duong and Chong, 2020). For example, the adoption of “energy-as-a-service” models allows firms to integrate digital technologies, such as IoT-enabled monitoring and AI-driven analytics, with circular strategies, such as refurbishment and life cycle management. This approach enhances the utilization of resources, extends product lifespan, and minimizes environmental impact while improving operational effectiveness and customer value (De Angelis et al., 2018). Despite its potential, the third gap revolves around limited research into the contextual factors that influence the effective implementation of supply chain business model innovation in realizing twin transition (Lai et al., 2023; Myshko et al., 2024). Moreover, investigating how these two mechanisms complement each other, in other words, how the enabling and realizing processes of twin transition interact and collectively contribute to firm performance, is crucial in coming to understand twin transition outcomes (Fehrer and Wieland, 2021; Ranjbari et al., 2024).

Against this background, our research question is: **What practices do manufacturing firms draw on to successfully pursue twin transition and to improve firm performance?** Based on the prior literature (Ivanov and Dolgui, 2021; Pan et al., 2023; Zekhnini et al., 2022), we focus on the role of two mechanisms, that is, supply chain orchestration and supply chain business model innovation. We opted for a survey, thereby aligning with the call for more quantitative studies (Baratsas et al., 2022). Our sample comprises 188 Swedish manufacturing firms. This study makes several contributions to the literature on twin transition by addressing the call for empirical validation and process-oriented

explanations (Almansour, 2022; Fouquet and Hippe, 2022). It provides new insights into how enabling and realizing twin transition are linked to firm performance through the integration of digital and circular capabilities (Rehman et al., 2023; World Economic Forum, 2022). Furthermore, the study highlights the amplifying role of supply chain orchestration in enhancing the relationship between digitalization practices and circular practices, and it demonstrates how supply chain business model innovation supports the commercialization of circular offerings to enhance firm performance (Geissdoerfer et al., 2023; Govindan and Hasanagic, 2018). The remainder of this paper is structured as follows: The next two sections present the theoretical background and develop the hypotheses. Section 4 outlines the research methodology, followed by the results in section 5. The discussion of findings, theoretical contributions, and managerial implications are provided in section 6. Finally, section 7 concludes with the limitations of the study and makes suggestions for future research directions.

2. Theoretical background

Twin transition is envisioned as an economic policy to drive simultaneous decarbonization and digital transformation of the global economy. There are two key priorities, i. digital transformation aligned to Digital Europe Programme, the EU eGovernment Action Plan (European Commission, 2020) ii. Green transformation aligned to European Green Deal (Montresor and Vezzani, 2023). Conceptually, the twin transition refers to the “coupling” of digital technologies with sustainable development to generate positive impacts on firm performance (Myshko et al., 2024). While it is broadly defined through the synergy between digitalization and sustainability (Fouquet and Hippe, 2022), recent studies emphasize the integration of circular practices as a crucial sustainability dimension (Zheng et al., 2024). Accordingly, this study adopts circularity as a central element of sustainability and defines twin transition as the simultaneous adoption of digitalization and circular practices to enhance firm performance (Tabares et al., 2025). Manufacturing firms increasingly pursue twin transition to leverage digital tools for aligned with circular principles like recycling, upgrading, and extending product lifespan (Husain et al., 2022).

The twin transition concept has two constituent parts. First, digitalization practices are described as a sociotechnical process that involves the use of digital technologies and data to improve business, replace traditional business processes, create new value-producing opportunities and create revenues (Gong and Ribiere, 2021). This includes not only the use but also the outcomes of implementing digital technologies, such as increased efficiency, competitiveness, and improved relationships among ecosystem partners (Parolin et al., 2024). Thus, it is important to note that digitalization practices are more than just digitizing business processes; they involve a fundamental change in how businesses operate and deliver value to customers (Ritter and Pedersen, 2020). Second, circular practices are a sustainable development approach that minimizes waste and reduces the use of linear material and energy flows by recycling materials and using renewable energy sources (Suárez-Eiroa et al., 2019). The emphasis is placed on prolonging the lifespan of resources, components, and products for as long as possible, extracting maximum value, recovering and regenerating products or materials at the end of service life (Sharma et al., 2023). Crucially, these are not siloed; twin transition denotes their interdependent progression, where mutual reinforcement accelerates necessary transformations (Muench et al., 2022).

However, pursuing twin transition solely through a firm's internal capabilities is not sufficient (Husain et al., 2022; Rehman et al., 2023). Assuming that manufacturing firms take a central and coordinating role in their respective ecosystems, namely, as a hub firm or “keystone player” (Adner, 2017), prior literature highlights the pivotal role of supply chain actors in complementing the internal capabilities of traditional firms to amplify twin transition (Pan et al., 2023). Table 1 presents a summary of the key literature on twin transition along with

Table 1
Overview of studies discussing twin transition and factors affecting twin transition implementation.

Author(s), year, and journal	Type of study and sample	Key findings on twin transition for firm performance	Motivation for the present study
<p>Tabares et al. (2025) <i>Technological forecasting and social change*</i> Reason for inclusion: Conceptualization of twin transition at firm-level. Can address research gaps: Research gap 1 and 2</p>	Literature review with thematic content analysis of 82 peer-reviewed firm-level studies.	<ul style="list-style-type: none"> - Organizational antecedents for twin transition. - Organizational practices to implement twin transition. - Outcomes and success factors of twin tradition. 	<ul style="list-style-type: none"> - Highlights the importance of understanding strategies for twin transition implementation for firms from initial to maturity stages. - Emphasizes the importance of developing external capabilities beyond firm level in driving successful twin transition. - Need for understanding how to integrate supply-chain actors to drive implementation and performance outcomes for twin transition.
<p>Husain et al. (2022) <i>Technology in Society*</i> Reason for inclusion: Conceptualization of twin transition at firm-level. Can address research gaps: Research gap 1 and 2</p>	Empirical study using real time data that focused on green bond and green equity indices in the US economy. The study applies the cross-quantilogram approach.	<ul style="list-style-type: none"> - Climate policy uncertainty drives the adoption of green practices and digital technologies. - Green and digital transitions complement each other to mitigate risks and enhance market performance. - Long-term investment in green bonds yields positive returns under policy uncertainty. 	<ul style="list-style-type: none"> - Encourages deeper insights into the relationship between twin transition processes and firm performance. - Assumes green and digital transitions progress simultaneously, highlighting the need to explore their sequential interplay. - Calls for future research to examine the role of external factors in strengthening digital and circular transitions.
<p>Fouquet and Hippe (2022) <i>Energy Research & Social Science*</i> Reason for inclusion: Conceptualization of twin transition at firm-level. Can address research gaps: Research gap 1</p>	Historical analysis using long-run data from 1850 to present, examining energy and communication intensity trends across European economies.	<ul style="list-style-type: none"> - Digitalization and decarbonization exhibit co-evolution during industrialization, followed by divergence in later stages. - The speed of digital transitions is faster compared to energy transitions. - Structural transformation toward green growth requires alignment of low-carbon energy and ICT industries. - Policy coordination is crucial to avoid unbalanced growth and achieve synergies. 	<ul style="list-style-type: none"> - Highlighting the need for firm-level strategies to understand how twin transition evolves over time. - Encourages further exploration of the relationship between digital transitions and circularity, considering the pace of adoption and interaction dynamics. - Under explore various mechanisms influencing the synergy between digitalization and circularity for firm performance.
<p>Rehman et al. (2023) <i>Technology in Society*</i> Reason for inclusion: -How twin transition can improve competitive advantage, -Highlight the importance of supply chain for twin transition implementation Can address research gaps: Research gap 1 and 2</p>	Empirical study using PLS-SEM and regression analysis on data collected from 459 manufacturing firms in China, Italy, and Malaysia, focusing on Industry 4.0 and green practices.	<ul style="list-style-type: none"> - Digitalization, green human resource management, and investment in environmental management positively impact green competitive advantage. - Technological innovation mediates these above-mentioned relationships. - Green work climate perception moderates the effect of technological innovation on green competitive advantage. 	<ul style="list-style-type: none"> - Considers digitalization as an independent variable and technological innovation as mediator, leading to conceptual overlap and role clarity. - Highlights the importance of considering external factors alongside internal firm capabilities to gain a comprehensive understanding of twin transition. - Calls for further research on the combined impact of digitalization and green practices on firm performance, rather than assessing their effects in isolation.
<p>Zoppelletto et al. (2025) <i>IEEE Transactions on Engineering Management*</i> Reason for inclusion: How supply chain collaboration facilitates twin transition implementation. Can address research gaps: Research gap 1 and 2</p>	Quantitative study on 189 firms in the Italian fashion industry to explore the role of supply chain collaboration for improving the impact of digitalization on environmental purposes.	<ul style="list-style-type: none"> - Governmental regulations and market-related demands significantly increase firms' use of digital data for environmental purposes, showing how digitalization and green transitions connect. - Collaboration across the supply chain mediates this effect, enabling firms to translate external pressures and digital adoption into sustainability outcomes. - Firm size moderates the link between external pressures and collaboration, with stronger effects for SMEs, though under high pressure firms of all sizes show high collaboration. 	<ul style="list-style-type: none"> - Important to understand how firms utilize post-collaboration capabilities with supply chain (e.g., shared data, routines, platforms) to achieve performance improvements. - Underexplored studies across firm sizes, industries for investigating how twin transition can be implemented. - Highlight the necessity to understand the combined effect of digitalization and green transition on firm level performance.
<p>Gebhardt et al. (2022) <i>International Journal of Production Research*</i> Reason for inclusion: How Industry 4.0-enabled supply chain can drive vertical (supplier-buyer), lateral (cross-firm), and systemic (cross-industry) collaboration that collectively drive circularity. Can address research gaps: Research gap 2</p>	Systematic literature review of 76 peer-reviewed articles on Industry 4.0 technologies enabling collaboration in circular supply chains.	<ul style="list-style-type: none"> - Industry 4.0 technologies (IoT, blockchain) enhance supply chain collaboration via information sharing and resource efficiency. - Such collaboration helps overcome circular economy barriers and facilitates reverse logistics. - Three collaboration archetypes are recognized: information sharing, joint planning, and resource sharing. - Sustainability practices enhance supply chain resilience, with digital technologies strengthening the relationship as facilitators. 	<ul style="list-style-type: none"> - Highlights the empirical testing of the impact of digitalization on circular supply chains. - Calls for insights into the evolution of supply chain collaboration over time. - Emphasizes the importance of examining the mechanisms underlying different archetypes.
<p>Pan et al. (2023) <i>Frontiers in Environmental Science*</i> Reason for inclusion: Six approaches through which supply chain can improve digital capability for improved green</p>	Conceptual study based on a road-mapping taxonomy derived from a bibliometric analysis of 342 articles related to supply chain resilience and	<ul style="list-style-type: none"> - Sustainability practices enhance supply chain resilience, with digital technologies strengthening the relationship as facilitators. 	<ul style="list-style-type: none"> - Focuses on enabling the supply chain coordination for integrating digitalization and sustainability, creating scope for exploring the mechanisms driving its execution.

(continued on next page)

Table 1 (continued)

Author(s), year, and journal	Type of study and sample	Key findings on twin transition for firm performance	Motivation for the present study
<i>transition.</i> <i>Can address research gaps: Research gap 2</i>	digital technologies, using data from the Web of Science.	- The proposed taxonomy highlights the components: approach, dynamics, trust, visibility, collaboration, and sharing for shaping sustainable supply chain.	
Myshko et al. (2024) <i>Journal of Cleaner Production*</i> <i>Reason for inclusion: How supply chain collaboration can drive twin transition.</i> <i>Can address research gaps: Research gap 2</i>	Systematic literature review and qualitative analysis of policy documents covering 254 academic papers and 35 policy documents from 2012 to 2023.	- Digitalization in supply chains fosters sustainability by enhancing data-driven decision making, optimizing resource efficiency, and reducing environmental impact. - Smart technologies facilitate circular supply chain practices by enhancing transparency, traceability, and real-time collaboration among stakeholders.	- Primarily emphasizes conceptual frameworks, underscoring the need to investigate how digitalization-enabled supply chains facilitate scaling processes to achieve broader sustainability outcomes.
Cloutier et al. (2020) <i>International Journal of Production Research*</i> <i>Reason for inclusion: Conceptual grounding on collaborative mechanisms that connect digital transformation to sustainability outcomes.</i> <i>Can address research gaps: Research gap 2</i>	Systematic literature review of 404 papers published up to 2019, analyzing collaborative mechanisms in sustainability-oriented supply chains.	- Sustainability-oriented supply chain collaboration involves relationship management, governance, and technological sharing. - Digitalization enhances supply chain collaboration through data sharing and automation for sustainability goals. - Supply chain business model adaptation improves sustainability via collaborative value creation.	- Encourages the empirical testing of conceptual understanding. - Highlight the need for understanding how operationalization of supply chain collaborative mechanisms supports the scaling of digitalization efforts to improve sustainability outcomes.
Ivanov and Dolgui (2021) <i>Production Planning & Control**</i> <i>Reason for inclusion: How the design and implementation of digital supply chain twins translate data-driven and model-based approaches into improved decision-making, performance assessment, and business continuity.</i> <i>Can address research gaps: Research gap 3</i>	Literature analysis and practical examples based conceptual study focusing on digital supply chain twins for managing disruption risks and resilience in Industry 4.0.	- Digital supply chain twins drive strategies to enhance visibility, optimize resource use, and improve resilience. - It enables proactive risk management through real-time data analytics and adaptive learning, ensuring business continuity while supporting sustainability goals.	- Highlights the importance of specific mechanisms within digital supply chains for enhancing firm performance. - Emphasizes empirical validation of the strategic impact of digital supply chains in scaling beyond adoption.
Lai et al. (2023) <i>Transportation Research Part E: Logistics and Transportation Review**</i> <i>Reason for inclusion: How supply chain collaboration enhances firms' capabilities and value performance in advancing digital and green transitions.</i> <i>Can address research gaps: Research gap 2 and 3</i>	Qualitative study with both primary and secondary data collected through case studies and industry reports in the manufacturing sector.	- Green supply chain-enabled digital transformation improves internal coordination, strategic alignment, and leads to better firm performance. - The adoption is uneven, with stronger implementation in external practices and reliance on top management for coordination, especially among larger suppliers.	- Testing of the conceptual insights into how digitalization translates into firm-level performance through green supply chain practices. - Promotes understanding of different mechanisms related to green supply chain practices through which digital transformation enables firm performance.
Kumar et al. (2023), <i>Computers & Industrial Engineering***</i> <i>Reason for inclusion: Supply chain can improve adoption of digitalization which leads to improve competitiveness, sustainability and business model performance.</i> <i>Can address research gaps: Research gap 2 and 3</i>	Mixed-method study based on digital supply chain-based literatures and 10 cases.	- Technological adoption is the most important critical success factor for supply chains to enhance sustainability like operational efficiency, competitive pressure by improving visibility, data interoperability, and resource optimization.	- Highlights the need for a process model to understand how multiple variables, such as digitalization, supply chain, and sustainable practices, interact with each other for an improved outcome.
Ranjbari et al. (2024) <i>Technovation****</i> <i>Reason for inclusion: Digitally enabled supply chain collaboration can support business-model changes for circularity.</i> <i>Can address research gaps: Research gap 2 and 3</i>	Empirical study using a system dynamics simulation model applied to Italy's Too Good to Go platform from 2015 to 2060.	- Business model innovation leverages digitalization to reconfigure value creation, delivery, and capture, thereby boosting operational efficiency and measurable sustainability impact. - Digital platforms support circularity objectives by enabling information sharing and improving resource utilization through supply chain collaboration. - The effectiveness of circular business models depends on supply-chain engagement.	- Emphasizes the need to explore the role of supply chain actors in supporting the scaling of digital platforms through business model reconfiguration that enhances circularity.

Please note studies marked with '*' primarily focus on enabling, '**' on realizing, and '***' on both processes.

some studies that highlight the factors that can affect twin transition. The gaps highlighted (i.e. the fourth column of Table 1) in such studies highlight that existing research remains fragmented. It therefore calls for deeper insights into how manufacturing firms can implement twin transition effectively (Breiter et al., 2024).

Prior studies have acknowledged supply chain orientation as a strategic commitment by manufacturing firms to collaborate with supply chain partners in order to effectively integrate digitalization and

circular practices (Pan et al., 2023). However, in the context of twin transition, supply chain orchestration plays a more critical role by being activity oriented (Ranjbari et al., 2024). This mechanism supports the enabling process by collaborating and coordinating supply chain actors to develop capability, ensuring readiness for twin transition (Huikkola et al., 2022; Zoppelletto et al., 2025). This mechanism involves determining responsibilities within the supply chain on effective resource utilization to achieve the performance outcomes intended (Gong et al.,

2018). It plays a crucial role in driving digitalization practices to support circular practices (Kumar et al., 2023; Myshko et al., 2024). For instance, supply chain actors contribute to data-driven adaptations by learning from disruptions, enabling proactive maintenance, and improving operational efficiency. Ultimately, this leads to waste reduction and optimizing logistics as a form of circular practice (Lai et al., 2023).

While supply chain orchestration is crucial for enabling twin transition, it is not sufficient to achieve sustainable firm performance (De Angelis et al., 2018). Firms must go beyond orchestration and focus on realizing twin transition through strategic business model adaptations (Cloutier et al., 2020). Supply chain business model innovation acts as this realizing mechanism by facilitating value creation, delivery, and capture across ecosystem partners, ensuring successful commercialization of circular initiatives (Lahane et al., 2020; de Arroyabe et al., 2021). Supply chain business model innovation clarifies coordination and alignment across business model dimensions to enhance operational effectiveness and firm performance (Gebhardt et al., 2022; Liu et al., 2021). Continuous learning and adaptation within supply chains act as dynamic feedback mechanisms that enable firms to refine and reconfigure their business model components in response to circular and performance outcomes (Cloutier et al., 2020). For example, partner engagement can shift quality perceptions of remanufactured or recycled outputs, while shared resources (e.g., pay-per-use equipment) and intangible assets (e.g., cloud platforms for lifecycle tracking) foster joint knowledge creation and efficiency.

Despite the recognition of supply chain orchestration and supply chain business model innovation as critical to twin transition, existing research has largely remained conceptual, focusing on the benefits or discussing firm-level use cases (Tabares et al., 2025). Consequently, empirical insight into how twin transition unfold via supply chain engagement is underdeveloped (Husain et al., 2022; Rehman et al., 2023). This study addresses that gap by examining how manufacturing firms leverage orchestration to enable twin transition and business model innovation to realize it, thereby enhancing firm performance.

3. Hypothesis development

The conceptual model (Fig. 1) outlines the hypothesized relationships among the variables included in the study. The model is organized into two parts i.e., enabling and realizing twin transition. Enabling twin transition refers to the foundational issues, that is to say, the up-front impact of digitalization practices on circular practices and the role of supply chain orchestration in enabling this. In contrast, realizing is concerned with implementing the twin transition, centering on what

facilitates firm performance and, in particular, on the critical mediation role played by various circular practices in combination with the commercial engagement of supply chain partners in business model innovation.

3.1. Enabling twin transition

The relationship between digitalization practices and circular practices is not always straightforward. While digitalization is widely recognized for its potential to enhance circular practices through improved resource efficiency, waste reduction, and optimized operations (Schögl et al., 2024), its implementation often introduces significant complexities that manufacturing firms must navigate carefully (Husain et al., 2022). On the one hand, digitalization practices provide the infrastructure and intelligence necessary to enable transparency, traceability, and closed-loop systems (Husain et al., 2022). On the other hand, if not strategically aligned with circular practices, digitalization can inadvertently increase costs, complexity, and even environmental impact (Appiah-Kubi et al., 2025). For example, a manufacturing firm adopting digital twin technologies to monitor resource utilization found that the high integration and maintenance costs outweighed the immediate environmental benefits, creating financial strain and undermining the effectiveness of its circular initiatives (Ranta et al., 2021). Moreover, the rapid pace of digitalization often outpaces the realization of circular practices, creating misalignment between technological readiness and sustainability outcomes (Ranjbari et al., 2024). For instance, firms investing in digital product lifecycle tracking systems may encounter barriers when lack the infrastructure to support closed-loop processes, leading to delays, inefficiencies, and unmet circularity goals (Akbarieh et al., 2020).

These challenges highlight the need for manufacturing firms to adopt those digitalization practices that are explicitly aligned with their circular objectives (Liu et al., 2021). Firms must also comprehend that digitalization practices are not universally applicable across all circular initiatives – different approaches yield varying levels of success (Yu et al., 2022). For instance, for some manufacturing firms to enhance circular practices customer analytics platforms can work, while for others they need IoT-enabled tracking systems, and AI-driven demand forecasting, to gain deeper insights into customer preferences and product usage patterns.

As Trevisan et al. (2024) note, it is important to understand the stages for implementing transition to understand integral progression of digital and circular transformations. Many firms are already digitally mature but still experimenting with circular practices (Breiter et al., 2024). This asymmetry creates a maturity gap, where firms are more capable of leveraging digital capabilities for operational efficiency than

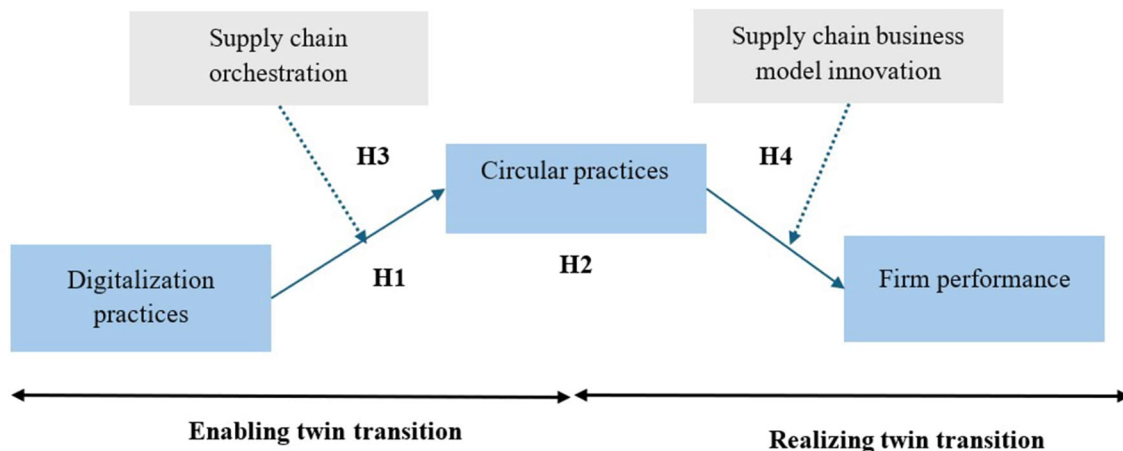


Fig. 1. How twin transition process evolves and impacts firm performance.

for systemic circularity (Christmann et al., 2024; Fang et al., 2024). As a result, firms, especially traditional manufacturing firms, must view digitalization practices as an enabler that prepares the foundation for circular practices rather than assuming both can evolve concurrently (Breiter et al., 2024; Trevisan et al., 2024). Sequencing these transitions can also buffer against the rebound effect, where digital efficiency gains inadvertently increase consumption or emissions due to expanded production or use (Appiah-Kubi et al., 2025).

When effectively aligned, digitalization practices can significantly facilitate the implementation of circular practices in manufacturing firms. By integrating these insights, firms can optimize resource utilization, improve recycling processes, and minimize waste generation, aligning with circular economy principles (Ranjbari et al., 2024). For example, Sandvik, a leading manufacturer of specialized mining products, utilized IoT sensors to collect real-time product usage data. It incorporated these insights into design improvements to enhance durability and recyclability, thereby minimizing resource consumption and environmental impact across the product lifecycle (Sandvik, 2022). Second, digital platforms, such as cloud-based manufacturing execution systems and blockchain-enabled supply chain monitoring, can optimize production processes, reducing waste generation and energy consumption while lowering the overall environmental footprint (Husain et al., 2022). SCA, a leading timber, pulp, and paper manufacturer, applied advanced analytics and IoT technology to enhance resource efficiency and minimize waste, thereby demonstrating how digitalization supports sustainable operations and circularity principles (SCA, 2022). Third, predictive maintenance systems, leveraging digitalization tools, such as AI-based condition monitoring and blockchain-enabled asset tracking, contribute to circularity by extending product lifecycles, enhancing maintenance capabilities, and ensuring transparency in resource utilization and material flow (Akbarieh et al., 2020). For instance, Volvo Group, a global manufacturer of trucks and construction equipment, employed predictive maintenance using digital platforms and IoT technologies, extending product lifespans, reducing downtime, and enhancing resource efficiency, thereby reinforcing its circularity goals (Volvo Group, 2021a).

Thus, achieving twin transition, integrating digitalization and circularity, requires an understanding of how specific digitalization practices can support various circular strategies across operational contexts. Manufacturing firms must assess the scalability and adaptability of digital tools to ensure they complement rather than hinder circular initiatives (Wade et al., 2022). Thus, empirical validation through hypothesis testing is essential to determine the effectiveness of digitalization in enhancing circular practices across different scenarios. Such validation will provide firms with actionable insights into the most effective digital tools and strategies for driving circularity, ultimately improving decision making and firm performance. Based on these arguments, we hypothesize:

H1. Digitalization practices have a significant positive impact on circular practices for manufacturing firms.

Prior research has demonstrated the positive impact of digitalization practices on firm performance (Ribeiro-Navarrete et al., 2021; Shen et al., 2024). For example, digitalization practices automate core processes, integrate operational and customer information, and support better operational decisions, leading to competitive advantages (Gartner et al., 2024). Real-time data analytics optimize supply chain management, reducing delays and costs. Digitalization practices also enhance customer engagement by linking customer-facing and operational processes, offering customized recommendations and promoting eco-friendly products through responsive customer service such as chatbots (Gong and Ribiere, 2021). Furthermore, they drive innovation by improving product performance and enabling new business models (Parida et al., 2019). For example, Volvo offers predictive maintenance services using IoT and data analytics, enhancing vehicle uptime and operational efficiency through subscription-based models (Volvo Group,

2021a).

Despite the potential benefits of digitalization, relying solely on digitalization practices is insufficient to achieve comprehensive improvements in firm performance. Complementary practices, such as circular practices, are necessary to bridge the gap between technological advancements and sustainable value creation (Upadhyay et al., 2024). Although digitalization facilitates data-driven decision making, process optimization, and operational efficiency, its direct impact on firm performance remains ambiguous without the integration of circular practices that enable resource efficiency and sustainable value delivery. This highlights the need to understand the interplay between digitalization practices and circular practices in achieving superior firm performance.

Manufacturing firms increasingly recognize circular practices as a critical mechanism for industrial transformation, particularly against the backdrop of stringent regulatory frameworks and ambitious sustainability goals set by major economies, such as the European Union and China (Bown and Clausing, 2023). Circular practices provide a structured approach to aligning operations with environmental objectives by decoupling value creation from resource consumption and improving waste management processes (Husain et al., 2022; Ranta et al., 2021). However, achieving these benefits requires firms to integrate circular practices effectively into their business models, thereby ensuring that digitalization efforts translate into tangible performance improvements.

First, circular practices allow manufacturing firms to decouple value creation from material use by transitioning toward service-oriented business models and dematerialization strategies (Awan et al., 2022; de Arroyabe et al., 2021). This strategic shift involves offering performance-based solutions and leveraging digital platforms to optimize product usage while minimizing material consumption. For example, Volvo Group implemented advanced vehicle designs supported by digital platforms to optimize vehicle performance, reduce material input, and meet evolving customer demands efficiently (Volvo Group, 2021a). Such approaches not only enhance operational efficiency but also generate financial benefits by reducing procurement costs and fostering recurring revenue streams through service-based models (Awan et al., 2022).

Second, circular practices encourage the adoption of secondary, recycled, and renewable materials, alongside lean and clean production processes, to achieve resource efficiency and waste minimization (Kalemkerian et al., 2022). This proactive approach contributes to environmental sustainability while enhancing firm performance through cost savings and reputational gains (Panda et al., 2025). Customers increasingly prioritize environmentally responsible products and are willing to pay a premium for sustainable offerings, leading to higher profitability and market competitiveness (Appolloni et al., 2022; Niu et al., 2023). For instance, Atlas Copco, a leading industrial tools manufacturer, integrated recycled materials into its production processes to reduce its carbon footprint and enhance sustainability credentials, thereby improving its brand reputation and attracting eco-conscious customers (Atlas Copco, 2022). Similarly, Stegra has secured long-term contracts with automotive giants, such as BMW and Audi, who are willing to pay a significant premium for sustainably sourced steel (Stegra, 2022, 2023).

Third, circular practices play a pivotal role in extending product lifecycles through strategies such as refurbishment, maintenance, and remanufacturing (Bocken and Geradts, 2020). By leveraging predictive maintenance enabled by digital technologies, manufacturing firms can extend the longevity of products, optimize resource utilization, and minimize waste, ultimately driving superior firm performance (Farooque et al., 2019). These strategies not only contribute to environmental sustainability but also improve operational efficiency by reducing downtime and maximizing asset value. For example, firms implementing remanufacturing initiatives have reported significant cost savings and improvements in customer satisfaction, further strengthening their competitive advantage.

While these benefits demonstrate the critical role of circular practices in driving firm performance, the extent to which digitalization practices contribute to this relationship remains an open question. Digitalization, when strategically integrated with circular practices, can act as an enabler to achieve higher firm performance. However, it does not automatically guarantee success. The effectiveness of digitalization in fostering circularity is contingent on various factors such as organizational capabilities, collaboration with supply chain partners, and supportive regulatory environments (Wade et al., 2022).

Thus, it is essential, first of all, to empirically examine the mediating role of circular practices in the relationship between digitalization practices and firm performance before evaluating the influence of supply chain-related intervening factors. Thus, we aim to test the following hypothesis:

H2. The relationship between digitalization practices and firm performance is positively partially mediated by circular practices.

There are several reasons why the positive relationship between digitalization practices and circular practices will be stronger if a manufacturing firm effectively orchestrates its supply chain partners (Amir et al., 2023; Simatupang and Sridharan, 2005). First, effective orchestration of supply chain actors leads to agreement on ecosystem goals by establishing rules, regulations, and the division of labor (Fang et al., 2024) – in other words, creating a tight alignment structure (Adner, 2017). This alignment structure ensures that all supply chain actors are working toward agreed sustainability and efficiency targets. For example, setting KPIs for waste reduction and resource efficiency, monitored through digital platforms, helps maintain a unified approach to achieving circularity (Voukkali et al., 2023).

Second, systematically assessing the probable roles of supply chain actors in relation to their capabilities, and negotiating their responsibilities, enhances the integration of digitalization practices and circular practices (Sarkis et al., 2021). By clearly defining roles and responsibilities, firms can leverage digitalization practices to optimize each actor's contribution to circularity (Barbieri et al., 2021). Similarly, supply chain actors promote the symbiotic relationship between digitalization and circular practices, for example, by creating innovative solutions that leverage digitalization practices to enhance circular practices (Hussain and Malik, 2020).

Finally, effective orchestration enables the joint establishment of potential flow costs, returns, and risks in cooperation with supply chain actors (Zoppelletto et al., 2025). This facilitates transparency and collaboration across various stages, from procurement to production and distribution (Konietzko et al., 2020). Such orchestration can allow supply chain actors to better leverage digital tools and optimize their specific contributions – such as sourcing materials, managing logistics, and handling recycling processes – ensuring the alignment of digitalization practices with circular practices (Suali et al., 2024). This coordinated effort enhances resource efficiency, minimizes waste, and reinforces sustainable practices, creating mutual benefits and a win-win relationship (Lerman et al., 2022). Therefore, we hypothesize:

H3. Supply chain orchestration moderates the relationship between digitalization practices and circular practices such that the relationship is stronger if the manufacturing firm is proficient at supply chain orchestration.

3.2. Realizing twin transition

The realization of twin transition in practice is contingent not only on orchestrating supply chain partners but also on engaging in supply chain business model innovation with the partners (Selviaridis and Spring, 2018). In other words, supply chain business model innovation moderates the relationship between circular practices and firm performance.

First, supply chain business model innovation helps firms to

implement servitization (Upadhayay et al., 2024), which is a strategy for assuring that circular practices have an impact on firm performance through new ways of creating, delivering, and capturing value (Han et al., 2020). For example, Volvo Group collaborated with supply chain partners to strategically prioritize servitization transformation, ensuring that circular practices were properly integrated into its business model. This collaboration has enhanced firm performance by improving circularity, operational efficiency, and long-term value creation (Volvo Group, 2021b).

Second, supply chain business model innovation helps to mobilize resources for value creation and delivery, which is necessary for the successful implementation of circular practices (Hofmann and Jaeger-Erben, 2020). By working together to understand and communicate the benefits of servitization, manufacturing firms can more effectively invest in the required skills and capabilities for improving firm performance (Awan et al., 2022; Huikkola et al., 2022). For instance, Atlas Copco's *AIR-as-a-Service* model integrates customers, digital service providers, and logistics partners in a pay-per-outcome system that delivers compressed air as a service. Through shared digital monitoring and predictive analytics, energy consumption is minimized, lifecycle costs are reduced, and all partners invest jointly in digital and circular capabilities to support performance-based contracts (Agoria, 2023).

Finally, supply chain business model innovation helps firms to design service contracts that balance risks and rewards (Aarikka-Stenroos et al., 2022). Through supply chain business model innovation, firms can ensure that keystone players (focal manufacturing companies) and their supply chain actors remain committed to circular practices, thereby improving firm performance (Visnjic et al., 2016). For example, SKF worked closely with its supply chain partners to design service contracts that included maintenance and refurbishment of industrial bearings (SKF, n.d.a). This collaboration not only extended the lifecycle of products and reduced waste but also strengthened customer relationships and generated consistent revenue streams. Such integrated efforts supported overall firm performance by enhancing resource efficiency and sustainability (SKF, n.d.b). Therefore, we hypothesize:

H4. Supply chain business model innovation moderates the relationship between circular practices and firm performance such that the relationship is stronger if the manufacturing firm is proficient at supply chain business model innovation.

4. Research approach

4.1. Sample and data collection

The study is based on Swedish manufacturing firms. We selected the manufacturing industry due to its substantial role in economic growth and general importance for the economy (World Economic Forum, 2021). The manufacturing industry is also a major emitter of greenhouse gases, annually releasing 880 million tonnes of carbon dioxide equivalents in Europe alone, (European Environment Agency, 2022; Our World in Data, 2024). It is therefore increasingly adopting circular practices and digitalization practices (Chauhan et al., 2022), making it ideal for the study of twin transition. In the manufacturing industries, we sampled firms with the following standard industrial classification (SIC) codes: Basic metals (SIC 33), fabricated metal products except machinery and equipment (SIC 34), machinery and equipment (SIC 35), motor vehicles, trailers, and semi-trailers and other transport equipment (SIC 37), and electrical equipment (SIC 38) (Eurostat, 2024; Statista, 2024).

Based on these SIC codes, the Retriever database revealed a total population of 14,334 Swedish manufacturing firms. We excluded micro-enterprises with fewer than ten employees because such firms often face scaling challenges that can hinder the transformation of digital initiatives into circular practices in collaboration with external partners

(Kolagar et al., 2024). This resulted in a population of 7378 firms. From this population, we drew a random sample of 1200 firms. Next, we prepared a registrar with the contact details of these manufacturing firms and mailed them a cover letter stating our purpose and providing the link to the online questionnaire. After the initial contact, two reminder emails were sent to selected firms, followed by phone calls to encourage participation. The questionnaire was pilot tested by three academic researchers and two manufacturing industry managers to ensure each item accurately reflected the dimension being measured. We received 192 responses from CEOs, directors, and other senior managers, with 188 responses being complete and useable in our analysis. This reflects an effective response rate of 16%.

4.2. Measures

We used five key variables grounded in the prior literature. All the variables were measured using a 7-point Likert scale. The original survey instrument was designed in Swedish to facilitate the data collection process. The English translated operationalization of the variables is shown in Appendix I. The scale for digitalization practices ($\alpha = 0.828$, composite reliability (CR) = 0.894) was adopted from Abou-foul et al. (2020), and all nine items remained unchanged. This scale measures the extent to which digitalization practices, such as analytics, mobile platforms, and embedded devices, help improve process, strengthen decision making, optimize operations, and add value to products and services by increasing performance and improve customer understanding.

The mediating variable, circular practices ($\alpha = 0.833$, CR = 0.842), was adapted from Kristoffersen et al. (2021), and all ten items remained unchanged. This scale measures circular practices under three sub dimensions: “reinvent and rethink,” “restore, reduce, and avoid,” and “recirculate”. The four items for “reinvent and rethink” measure the decoupling of value offerings from material use, supporting products with spare parts/repair services, providing results/performance as a service, and offering access to/usage of products as a service. Second, the three items under “restore, reduce, and avoid” focus on sourcing secondary/recycled/renewable materials, running lean and clean production, and optimizing product use to extend life, minimize energy use, and increase utilization. Finally, the three items under “recirculate” measure whether manufacturing firms practice activities, extend the use cycles of products and parts, introduce new use cycles, and prolong the lifespan of materials.

Supply chain orchestration ($\alpha = 0.762$, CR = 0.725) was measured using items adapted from Kolagar et al. (2022). We retained all eight original items but tailored them from an ecosystem orchestration focus to supply chain orchestration to align with our research aims. Specifically, we first clarified the types of supply chain actors and then reframed the items to assess the orchestration of supply chain actors. Action verbs were carefully adjusted to emphasize identifying, establishing, negotiating, and exploring goals, governance, role assessments, responsibilities, value propositions, revenue flows, and agreements on risk-reward distribution. This framing deliberately confines the construct's scope to capability establishment (enabling) rather than integration and execution (realizing).

Supply chain business model innovation ($\alpha = 0.786$, CR = 0.728) was based on the scale suggested by Abou-foul et al. (2020). Its nine items measure the aspects of servitization, how the supply chain business model is executed and integrated in manufacturing settings when digitalization and circularity are combined (Kolagar et al., 2022). The emphasis had been placed in three types of activities: (i) alignment around a shared vision and the strategic importance of servitization transformation; (ii) reviewing business cases, transformation progress,

and KPIs; and (iii) reconfiguring service contracts to share risk-reward and put servitized practices into operation. All nine items were adapted to our research objectives, with clarified introductory text that explicitly states scope and actors involved. For instance, the first item was adjusted to read: “Our firm works with [types of supply chain actors] to realize, i. e., convert foundational capabilities into outcomes to creation, delivery and capture of value from digitalization-enabled circular practices, ultimately improving firm performance. This is practiced by aligning around the strategic importance of servitization transformation”.

Although supply chain orchestration and supply chain business model innovation share a relational vocabulary (e.g., alignment, governance, and risk-reward considerations), they capture different capability layers in the twin transition process. The former is deliberately confined to capability establishment, i.e., setting collaborative conditions through goal-setting, governance rule formation, role/responsibility negotiation, and preliminary assessments of value and risk-reward logics. In contrast, the latter captures capability realization, i.e., translating established conditions into integrated execution and commercialization via servitization-oriented implementation, KPI and business-case steering, and contractual reconfiguration for value creation, delivery, and capture. Accordingly, the constructs are not interchangeable; they represent sequential but analytically distinct categories that operate on different stages of how digitalization-enabled circular practices are enabled and then realized through incentivization or monetization.

Finally, firm performance ($\alpha = 0.806$, CR = 0.844) was adapted from Ghasemaghahi and Calic (2020). We included all nine items without reframing. This scale has three dimensions for measuring firm performance: i) financial returns measure how a firm's ROI, ROE, and ROA compared to industry peers, ii) customer perspective evaluates customer perceptions of product quality, satisfaction, and firm image relative to competitors, and iii) operational excellence assesses productivity improvements, customer service timelines, and production cycle times compared to other firms in the industry. Firm size (number of employees), firm age (years since inception), and type of industry segment (SIC code) have been found to influence firm performance and have been used in previous studies related to twin transition (Andersen, 2021; Srouji et al., 2023). These variables were therefore used as controls.

4.3. Data analysis

4.3.1. Data normality, common method bias, and non-response bias

The final dataset, devoid of any missing values or outliers, was prepared for subsequent analysis. A Shapiro-Wilk test (p value greater than 0.05) for each variable suggests that normality concerns are not a major issue. Harman's single-factor test was employed to test common method variance problems (Podsakoff et al., 2003). This is important because our data were collected at a single point in time. The outcome of this test reveals that the highest single factor explained 36.44% of the variance, which is below the critical level of 50% (Habib and Qayyum, 2018). Following Podsakoff et al. (2012), we included a common latent factor (a method factor with no theoretical meaning) loading on all observed indicators to capture any shared method variance. We then compared the standardized outer loadings from the original model with those from the CLF-adjusted model. All loading changes were small ($|\Delta| \text{ loading} < 0.20$ across items), and the pattern and significance of structural paths remained unchanged, indicating that substantive relations were not driven by method effects. We also examined the variance accounted for by the CLF; the method factor explained a minor share of total variance (well below conventional concern thresholds; <50%). These findings confirmed that common method bias is not a significant concern in this study, ensuring the reliability and validity of

our results. That said, we tried to reduce the common method problem.

Non-response bias was assessed by comparing the initial one hundred respondents (early respondents) with the subsequent eighty-eight respondents (late respondents), following the recommendations of previous researchers (Lambert and Harrington, 1990). We reported the Welch t-test (as variances differed) with adjusted degrees of freedom (see Appendix II). We also examined effect sizes (Cohen's d) to gauge practical significance. Across all constructs, tests were non-significant and effect sizes were trivial to small ($|d| \leq 0.13$), indicating that responses from early and late participants did not differ meaningfully.

4.3.2. Assessment of measurement model

The validation of the measurement model was undertaken by examining the outer loading of each specific item, which should exceed 0.5 (Hair et al., 2019; Tabachnick and Fidell, 2007), as shown in Appendix I. Therefore, we have retained all the variables since our sample size permits this cutoff value (Hair et al., 2019). To evaluate the extent of multicollinearity, the variance inflation factor (VIF) values were calculated (Thompson et al., 2017). All VIF values were under the threshold of 4, indicating that multicollinearity was not a major concern (Becker et al., 2015). Additionally, the correlation matrix showed no pairwise correlations exceeding 0.75, the condition index remained below 25, and the variance decomposition proportions did not exceed 0.50 for any predictor. These results collectively confirm that multicollinearity is not a concern in our model (Kalnins and Praitis Hill, 2025). The descriptive statistics and the correlations of the variables have been presented in Table 2.

Composite reliability was evaluated using Cronbach's alpha (α), where values exceeded 0.7 for all variables and, therefore, fell within the acceptable range (Herrmann and Felfe, 2014). Finally, convergent validity was examined by assessing if items load significantly on their denominated latent variables. We therefore calculated the composite reliability and average variance extracted (AVE) estimate for each variable. All the composite reliability values are between 0.75 and 0.8, and AVE values exceed 0.50, surpassing the recommended thresholds set by previous research (Fornell and Larcker, 1981; Herrmann and Felfe, 2014).

Finally, discriminant validity was checked based on the measurement given by Fornell and Larcker (FL) (1981) and through the Hetero Trait Mono Trait (HTMT) ratio (Herrmann and Felfe, 2014). The HTMT test and FL criterion reveal that the values of all variables are less than the proposed threshold limit of 0.90, thereby confirming that a lack of discriminant validity is not a major problem (Hair et al., 2019).

4.3.3. Endogeneity, robustness and structural equation modelling

Because survey predictors may not be truly exogenous (e.g., omitted variables, reverse causality, measurement error), we tested endogeneity using the Gaussian Copula approach tailored for PLS-SEM (Hult et al., 2018). For each potentially endogenous predictor (digitalization practices, circular practices, interaction between digitalization practices and supply chain orchestration, interaction between circular practices and supply chain business model innovation), a copula term was generated. All copula terms were non-significant ($p > 0.10$) indicating substantive path estimates were stable (see Appendix III).

Table 2
Descriptive statistics and correlations.

	Mean	Std. deviation	DP	CP	SCO	SCBMI	FP
DP	5.028	1.193	1.000				
CP	4.384	1.237	0.587***	1.000			
SCO	5.280	1.205	0.738*	0.617***	1.000		
SCBMI	4.935	0.725	0.350	0.437**	0.510*	1.000	
FP	4.879	0.986	0.532**	0.593**	0.359	0.602*	1.000

Note(s): Significance at: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

DP: Digitalization practices, CP: Circular practices, FP: Firm performance, SCO: Supply chain orchestration, SCBMI: Supply chain business model innovation.

The hypotheses were tested by structural equation modelling (SEM) (Barrett, 2007). The bootstrapping method was used as part of the PLS-SEM to check the direct and indirect effects on firm performance (Ali et al., 2018). This method is preferred over covariance-based SEM in certain contexts due to its flexibility and robustness (Sarstedt et al., 2021). PLS-SEM is particularly advantageous for handling complex models with multiple variables and intricate relationships, making it suitable for studies involving latent variables and pathways (Ringle et al., 2023). One of its key strengths is its predictive power because it prioritizes the prediction of dependent variables rather than the estimation of latent variables (Ringle et al., 2023). Moreover, PLS-SEM has the ability to perform well with smaller sample sizes (Hair et al., 2019). To address the concern regarding the sample size, we conducted additional analyses to confirm the robustness of our results. A bootstrapping analysis with 10,000 subsamples was performed, yielding consistent and stable path coefficients and significance levels across iterations, which supports the reliability of our structural model (Levers-Landis et al., 2011). Additionally, a sensitivity analysis demonstrated that the sample size of 188 achieved a statistical power of 0.85, exceeding the standard threshold of 0.80 (Cohen, 1992). This indicates that the sample size was sufficient to detect medium to large effect sizes, further validating the robustness of our findings despite the relatively small sample.

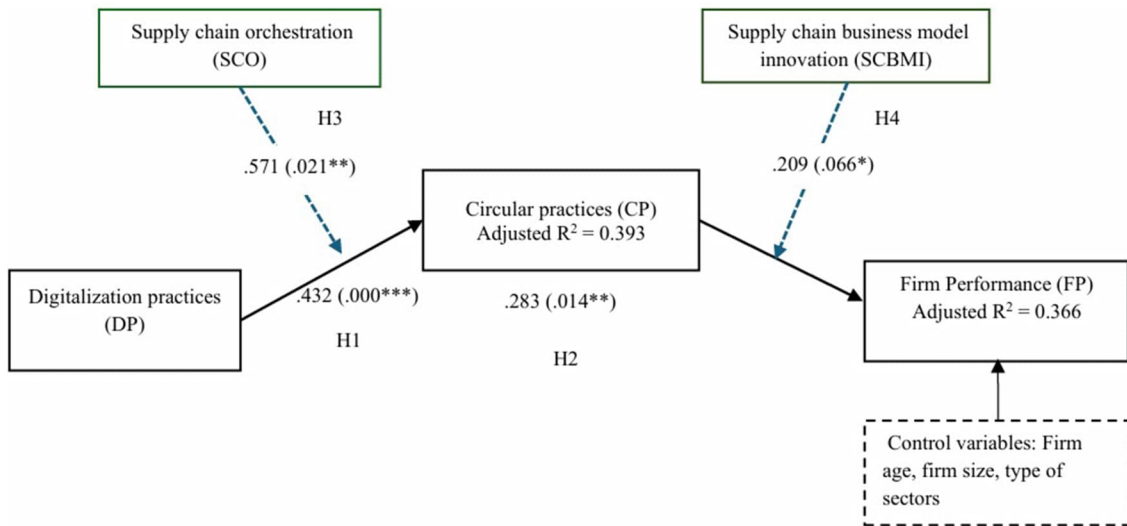
5. Results

The results are shown in Table 3. The coefficients along with the p-values and the adjusted R-square value are shown in Fig. 2. As displayed in Table 3, digitalization practices have a positive impact on circular practices in manufacturing firms ($\beta = 0.432$, $p < 0.001$), which provides support for H1. Furthermore, H2 was supported, with circular practices showing a significant direct and positive impact on firm performance ($\beta = 0.187$, $p < 0.05$) along with a significant partial mediation effect on the relationship between digitalization practices and firm performance ($\beta = 0.283$, $p < 0.05$). The partial mediation is further validated by examining the impact between digitalization practices and firm performance ($\beta = 0.174$, $p < 0.05$). The improvement in the coefficient indicates that combining circular practices with digitalization practices can improve firm performance more than solely practicing digitalization (Husain et al., 2022; Paiho et al., 2023).

Table 3
Summary of hypothesis testing.

Structural Path	Coefficient	t-value	p-value	Remark
H1: DP→CP	0.432	6.723	0.000***	Supported
Direct effect: DP→FP	0.174	1.749	0.041**	
Direct effect: CP→FP	0.187	2.011	0.023**	
H2: indirect effect: DP→CP→FP	0.283	2.223	0.014**	Partial mediation
H3: DP x SCO→CP	0.571	2.058	0.020**	Supported
H4: CP x SCBMI→FP	0.209	1.531	0.063*	Supported

Note(s): Significance at: *** $p < 0.001$, ** $p < 0.05$, * $p < 0.10$ (one-tailed). DP: Digitalization practices, CP: Circular practices, FP: Firm performance, SCO: Supply chain orchestration, SCBMI: Supply chain business model innovation.



*p ≤ 0.10; **p ≤ 0.05; ***p ≤ 0.01.

Fig. 2. Results of structural equation modelling with correlation coefficients, p-value, and adjusted R².

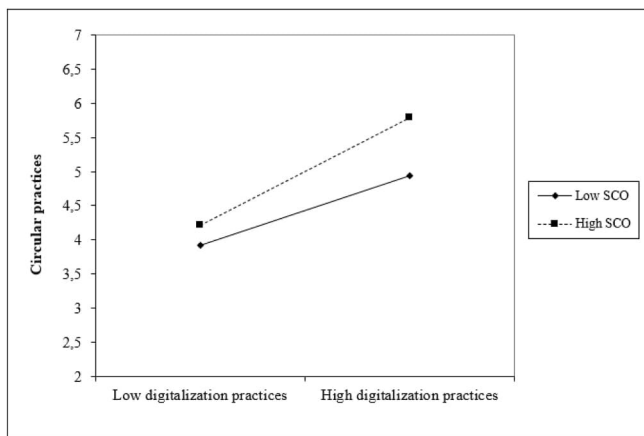


Fig. 3. The moderating effect of supply chain orchestration on the relationship between digitalization practices and circular practices.

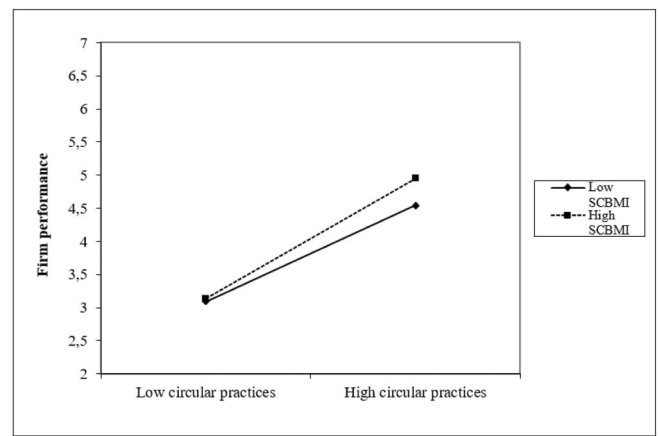


Fig. 4. The moderating effect of supply chain business model innovation on the relationship between circular practices and firm performance.

Regarding the moderation effects, supply chain orchestration positively moderates the strength of relationship between digitalization practices and circular practices ($\beta = 0.571$, $p < 0.05$), and supply chain business model innovation positively moderates the strength of relationship between circular practices and firm performance ($\beta = 0.209$, $p < 0.10$). This provides support for both H3 and H4. Fig. 2 outlines the adjusted R-square value to illuminate the explanatory power of the variable in accounting for the number of predictors in the equation (Plonsky and Ghanbar, 2018).

Digitalization practices explain 39.3% of the variance in circular practices, whereas circular practices explain 36.6% variance of firm performance. This indicates that both these variables play an important role as predictors. We validated the results by measuring the moderating effect through PROCESS MACRO 4.0. using model 7 and model 14, respectively (Sharma et al., 2023). The interaction effect of supply chain orchestration was found to be significant (R^2 change: 0.0109, F test: 13.67, df1: 1, df2: 184, p value: 0.0002). Similarly, the interaction effect for supply chain business model innovation was noted as significant at

the 10% level of significance (R^2 change: 0.0052, F test: 7.24, df1: 1, df2: 183, p value: 0.079). Figs. 3 and 4 visually represent this result.

Legate et al. (2023) proposed that the effect size of predictive ability (f^2) should range from 0.15 to 0.35 (medium) up to > 0.35 (strong). Our path model showed that all f^2 range from medium to strong. The model fit statistics are satisfactory [TLI = 0.981, NFI = 0.887, RMSEA = 0.031; SRMR = 0.027] (Andersen, 2021). This suggests that our model exhibits robust predictive power, and the proposed relationships fit the data well, supporting the validity and reliability of our path model.

For the control variables, we found that type of sectors ($p = 0.243$) and firm size in terms of the number of employees ($p = 0.337$) have no significant impact on firm performance. However, firm age since starting year is significant ($p = 0.080$). We then performed ANOVA, and the post-hoc test result shows that firms starting after year 2000 have the highest mean ($s = 3.87$) followed by firms starting between 1990 and 2000 ($s = 3.49$). Firms starting before 1990 have the lowest mean among the remainder ($s = 2.01$). This implies that younger manufacturing firms are more adaptable and agile in collaborating with supply chain actors

than older firms (Mishra et al., 2025).

6. Discussion and implications

The findings reveal that digitalization practices improve circular practices in manufacturing firms, supporting prior studies that show digital tools enhance resource efficiency, waste reduction, and sustainability performance (Husain et al., 2022). This relationship reinforces arguments that digitalization enables real-time monitoring and data-driven decision-making, which are essential for implementing circular strategies such as product life extension and closed-loop material flows (Fouquet and Hippe, 2022; Almansour, 2022). The analysis further demonstrates that digitalization practices positively influence firm performance, but this effect strengthens substantially when mediated by circular practices, confirming that digitalization combined with circular practices can better produce sustained competitive advantage and yields environmental and economic benefits (Nayal et al., 2022; Yu et al., 2022).

Guided by theoretical arguments emphasizing collaboration beyond firm boundaries, the moderation analysis confirms the significance of supply chain orchestration in enabling twin transition (Myshko et al., 2024). The results show that supply chain orchestration strengthens the positive relationship between digitalization practices and circular practices, underscoring establishing the importance of ecosystem-level coordination and governance (Pan et al., 2023). Effective orchestration aligns internal digitalization and circularity efforts with external supply chain processes, overcoming limitations in firms' internal capabilities (Cloutier et al., 2020). Firms demonstrating higher orchestration capability achieve stronger outcomes because they can coordinate complementary resources, distribute responsibilities, and align partner incentives (Wade et al., 2022). This finding supports prior research suggesting that orchestration fosters structured ecosystems where collaborative governance amplifies the impact of digitalization practices on circular practices (Myshko et al., 2024). For instance, establishing joint performance goals with partners enhances shared sustainability objectives, while well-defined governance frameworks improve regulatory compliance and operational efficiency.

While supply chain orchestration enables the alignment and activation of twin transition efforts, realizing its full potential requires extending beyond coordination toward strategic business model adaptation through supply chain (Lai et al., 2023). The findings indicate that supply chain business model innovation plays an emerging role in translating circular practices into firm performance (Kumar et al., 2023). The moderating effect of supply chain business model innovation on the circular practices – firm performance link is marginally significant, suggesting a directional but developing relationship. This partially supports prior work emphasizing the need to reconfigure existing business models to commercialize circular initiatives effectively (Ranjbari et al., 2024).

Manufacturing firms engaging in business model innovation are beginning to capture synergies between digital and circular strategies, yet outcomes remain uneven due to differing maturity levels across sectors (Gebhardt et al., 2022). Continuous learning and adaptive routines within supply chains are vital to strengthen this link, enabling refinement of business model components in response to operational feedback and new opportunities (Cloutier et al., 2020). Many manufacturing firms remain at the early stages of experimenting with business model innovation, struggling to embed circular logics within traditional manufacturing systems (Frishammar and Parida, 2019).

6.1. Theoretical contributions

This study contributes primarily to the emerging research on twin transitions (Almansour, 2022; Bianchini et al., 2023; Fouquet and Hippe, 2022). Existing research has largely conceptualized the twin transition phenomenon as the parallel or complementary adoption of digitalization and circular practices, and has called for stronger empirical explanations of *how* such transitions unfold and *what outcomes* they actually generate (World Economic Forum, 2022; Rehman et al., 2023; Tabares et al., 2025). While prior studies have discussed potential synergies and policy relevance, empirical evidence explaining implementation dynamics and performance implications remains limited (Husain et al., 2022; Paiho et al., 2023). We extend this literature by empirically demonstrating that twin transition is positively associated with firm performance and by explicating a dominant implementation sequence in which digitalization practices enable circular practices.

Building on this, we conceptualize twin transition as unfolding through two analytically distinct processes: an enabling process, focused on building foundational infrastructure and capabilities, and a realizing process, focused on integrating and leveraging these capabilities to generate performance outcomes. Our contribution lies in moving the twin transition literature beyond conceptual discussions toward a process-oriented, empirically grounded explanation of how twin transition is planned and implemented in manufacturing contexts and what the performance outcomes of such implementation will be.

Second, we contribute to the circular economy literature (Amir et al., 2023; Awan et al., 2022; Chauhan et al., 2022; Fang et al., 2024) by advancing the understanding of mechanisms that amplify twin transition processes, with particular attention to supply chain orchestration. Prior research has established that digitalization practices can support circular practices, especially when firms collaborate with supply chain partners (Bhattacharya and De, 2021; Kumar et al., 2023). However, existing studies provide limited insight into *how* such collaboration is structured and *when* it strengthens the translation of digitalization into circular outcomes. Our findings extend this work by showing that supply chain orchestration strengthens the impact of digitalization practices on circular practices by enabling role clarity, governance arrangements, and responsibility negotiation across supply chain actors, including startups, digital service providers, network providers, suppliers, customers, and service/logistics partners (Parida et al., 2019). Through orchestration, firms can better integrate complementary expertise, overcome fragmented infrastructures, and address misaligned priorities that often constrain circular initiatives (Gebhardt et al., 2022; Nayal et al., 2022). While prior studies have shown that regulatory and market pressures increase the use of digital data for environmental purposes, often mediated by supply chain collaboration (Zoppelletto et al., 2025), we extend this line of research by specifying how orchestration operationalizes collaboration through shared data, routines, and platform capabilities that amplify digitalization's impact on circular practices. In doing so, we respond to calls for deeper investigation into inter-firm collaboration and the specific role of supply chain partners in enabling twin transition (Roos Lindgreen et al., 2020; Tozanli and Saéenz, 2022; Welch and Soufani, 2024).

Third, we contribute by moving beyond orchestration and examining how twin transition is realized through supply chain business model innovation. Prior research has suggested that supply chain actors can enhance firm performance by communicating circular value propositions during value delivery (Sreedevi and Saranga, 2017) and by supporting the implementation of circular business models (Geissdoerfer et al., 2023). However, empirical evidence remains limited regarding how supply chain partners jointly engage in value creation, delivery, and capture under twin transition conditions (Andersen, 2021; Farooque

et al., 2019). We extend circular economy literature (Amir et al., 2023; Awan et al., 2022; Chauhan et al., 2022; Fang et al., 2024) by demonstrating the positive moderating role of supply chain business model innovation in translating circular practices into firm performance.

Our results show that deliberately involving supply chain actors in the design and execution of servitized offerings enables firms to market circular solutions, customize services, and scale circular business models more effectively (Govindan and Hasanagic, 2018). Through digital platforms and adapted profit formulas, supply chain business model innovation aligns value delivery with improved value capture, while service contracts facilitate shared risk–reward arrangements and collaborative operational management (Lüdeke-Freund et al., 2019; Lahane et al., 2020). While Fang et al. (2024) show that digitalization mitigates power imbalances caused by supplier and customer concentration by reducing information asymmetry, our findings complement and extend this insight by showing how supply chain business model innovation institutionalizes transparency and alignment through process integration and outcome-based contracts. This clarifies how digital visibility is converted into realized circular value, thereby advancing understanding of the realizing mechanisms that underpin successful twin transition.

6.2. Managerial implications

This study speaks primarily to manufacturing firms' top management who are ultimately responsible for not only achieving firm performance but also resource allocation to invest in digitalization practices and circular practices. A key implication is that digitalization practices and circular practices should be tightly integrated. This challenges the traditional organizational separation where digitalization and circular or sustainability practices are organized into different departments with limited coordination, information sharing, and data integration (de Vasconcelos Gomes et al., 2023). Second, our study underscores the importance of differentiating activities with supply chain partners. Close collaboration with key partners is most effective in the enabling phase. Such collaboration is critical not only for information sharing, integrating, and joint decision-making activities but also bridges internal capability gaps. For instance, manufacturing firms can collaborate with their supply chain partners to enhance circular practices through advanced digital solutions, establishing robust digital platforms that integrate supply chain data, inventory management systems, and customer relations management to streamline circular operations and improve transparency.

Finally, our study offers practical guidance by highlighting that although many manufacturing firms succeed in establishing collaboration with supply-chain partners, the principal challenge lies in implementation and scaling. This cannot be solved only in the realization phase. Manufacturers must design orchestration mechanisms carefully, clarifying roles, data governance, KPIs, revenue/risk logic and then ensure that those mechanisms translate into business-model choices for value creation, delivery, and capture. In essence, supply chain business model innovation must remain aligned with supply chain orchestration. Suppose risk–reward sharing (e.g., uptime penalties/bonuses) was not agreed during orchestration but is introduced later in the service contract design. Partners may then resist the new terms, dispute liability for downtime, or refuse the required data sharing, stalling rollout and eroding trust. Similar issues arise if data ownership, remanufactured-parts warranties, or revenue splits are added post hoc.

7. Limitations and future directions

Our study focuses on a particular country, Sweden, and solely on the

manufacturing industry. Therefore, it is suggested that future studies explore the generalizability of our findings across different countries and industries. Utilizing a mixed-method approach can provide deeper insights into supply chain orchestration and business model adaptation. For instance, quantitative analysis could further validate or disprove our findings, while sequential qualitative research could uncover barriers and strategies for overcoming them.

The cross-sectional research design employed in this study has certain limitations. First, as data were collected at a single point in time, it is challenging to discern the exact nature of relationships between variables, and causality can never be proved. Future research would benefit from longitudinal studies, collecting data at various intervals – for example, at the initiation of twin transition implementation and when firms achieve successful transition scaling. This comparative analysis could shed light on how the dynamics of orchestration and business model adaptation assistance evolve over time. Second, while our cross-sectional design limits causal interpretation, future research could utilize lagged performance data (e.g., performance metrics from the following year) to better establish the directionality between digitalization, circular practices, and firm performance. This approach would help confirm that firm performance is indeed an outcome rather than a potential driver of circular practices.

Third, our study's multi-sectoral sample within the manufacturing industry does not fully capture sector-specific nuances that may shape the relationship between supply chain orchestration, business model innovation, and firm performance. Due to the relatively small sample size, controlling for sectoral effects was not feasible. Future studies should therefore adopt larger, sector-specific samples or comparative designs to uncover variations across industries.

Finally, there remains a need for dedicated scale development to measure the simultaneous evolution and reinforcement effects of digitalization and circular practices, reflecting how the twin transition is conceptually defined. Such a scale could better capture how firms progress in aligning digital and circular maturity over time. This is particularly relevant for SMEs and industries where digitalization is still emerging, as these firms may plan, sequence and mutually reinforce their twin transition efforts differently compared to digitally mature firms. Developing and validating such a scale would significantly enhance empirical precision and theory building in future twin transition research.

CRedit authorship contribution statement

Debadrita Panda: Conceptualization, Formal analysis, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Vinit Parida:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Johan Frishammar:** Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Conflict of 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.

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Appendices

Appendix I

Variable, items, and measurement loadings.

Variable	Code	Item	Factor loading	VIF	Average Variance Extracted (AVE)
		As an industrial firm, we are using digital technologies (such as analytics, social media, mobile, and embedded devices) to			
Digitalization practices (DP) Abou-foul et al. (2020)	DP 1	Understand supply chain and customers better.	0.634	1.786	0.529
	DP 2	Market and sell products and services.	0.594	2.477	
	DP 3	Provide supply chain and customer-oriented service.	0.810	2.323	
	DP 4	Link customer-facing and operational processes in new ways.	0.684	1.876	
	DP 5	Automate our core processes.	0.700	1.981	
	DP 6	Integrate view of key operational and customer information.	0.667	1.654	
	DP 7	Make better operational decisions.	0.747	1.997	
	DP 8	Increase the performance or added value of our existing products and services.	0.736	1.918	
Circular practices (CP) Kristoffersen et al. (2021)	DP 9	Launch a new business model.	0.756	2.003	0.599
		As an industrial firm, we are using circular practices for			
	CP 1	Providing value offerings that are decoupled from material use.	0.549	1.731	
	CP 2	Supporting products during their lifetime through providing spare parts and/or repair services as separate sales offerings.	0.667	2.057	
	CP 3	Providing the result or performance of a product as a service instead of selling the physical product.	0.582	1.582	
	CP 4	Providing the access or usage of a product as a service instead of selling the physical product.	0.627	2.802	
	CP 5	Sourcing secondary, recycled, and/or renewable materials.	0.647	2.138	
	CP 6	Running a lean and clean production.	0.563	1.786	
	CP 7	Optimizing product use and operation to extend product life, minimize energy use, and/or increase product utilization.	0.630	2.161	
	CP 8	Practicing activities to extend the existing use cycles of products and parts.	0.686	2.282	
Supply chain orchestration (SCO) Kolagar et al. (2022)	CP 9	Practicing activities to extend products and parts to new use cycles.	0.709	2.185	0.632
	CP 10	Practicing activities to extend the lifespan of materials.	0.637	1.971	
		Our firm collaborates with startups, digital service providers, network connection providers, and technology providers, suppliers, customers, and service/logistics partners to enable i.e., develop foundational capabilities and conditions for digitalization-enabled circular practices. This is operationalized by			
	SCO1	Agreeing on ecosystem performance goals (shared KPIs for all actors).	0.610	1.535	
	SCO2	Formulating governance rules and monitoring procedures.	0.653	1.564	
	SCO3	Establishing their probable roles in relation to capabilities and offerings.	0.475	1.390	
	SCO4	Negotiating responsibilities and accountabilities.	0.797	1.327	
	SCO5	Considering front/back-end role splits with a global market perspective	0.389	1.602	
	SCO6	Exploring new business opportunities.	0.564	1.325	
	SCO7	Identifying potential flow of cost and return.	0.555	1.146	
Supply chain business model innovation (SCBMI) Abou-foul et al. (2020)	SCO8	Identifying sources of potential risk and reward opportunities for creating a win-win relationship.	0.551	1.172	0.531
		Our firm works with startups, digital service providers, network connection providers, and technology providers, suppliers, customers, and service/logistics partners to realize, i.e., convert foundational capabilities into outcomes to creation, delivery and capture of value from digitalization-enabled circular practices, ultimately improving firm performance. This is practiced by			
	SCBMI 1	Aligning around the strategic importance of servitization transformation.	0.746	2.502	
	SCBMI 2	Sharing a vision of the future that involves servitized offerings with senior leaders.	0.824	2.234	
	SCBMI 3	Reviewing with the top team concerning progress on servitization transformation on a regular interval.	0.811	2.805	
	SCBMI 4	Understanding and communicating the benefits of servitization change.	0.787	2.578	
	SCBMI 5	Reconfiguring the servitized offerings by aligning revenue models and shared investment mechanisms where warranted.	0.834	2.221	
	SCBMI 6	Reviewing business cases and key performance indicators that are linked to our roadmap.	0.551	1.374	
	SCBMI 7	Integrating partners' business processes with firm's existing processes.	0.638	2.103	
	SCBMI 8	Managing the operational functions of servitized offerings.	0.675	2.045	
Firm Performance (FP) Ghasemaghahi and Calic (2020)	SCBMI 9	Sharing risk and reward through service contracts related to offerings.	0.634	1.772	0.668
	FP 1	Return on investment (ROI) is better compared to other companies in the same industry.	0.726	2.885	
	FP 2	Return on equity (ROE) is better compared to other companies in the same industry.	0.753	2.674	
	FP 3	Return on assets (ROA) is better compared to other companies in the same industry.	0.704	1.122	
	FP 4*	Perceiving firm's quality of products and services is better compared to other firms in the same industry.	0.370	3.551	
	FP 5	Having higher customer satisfaction compared to other firms in the same industry.	0.575	1.878	

(continued on next page)

Appendix I (continued)

Variable	Code	Item	Factor loading	VIF	Average Variance Extracted (AVE)
	FP 6	Having better firm image compared to other firms in the same industry.	0.526	1.613	
	FP 7	Digital products/services are breakthrough innovations.	0.757	3.092	
	FP 8	Digital products/services are technological advancements that make old technologies obsolete.	0.826	3.283	
	FP 9	Digital products/services deliver completely new benefits to customers.	0.786	3.132	

Note: Item marked with “**” has been dropped due to insufficient factor loading.

Appendix II

Welch's independent-samples t-tests (variance-robust) for common method bias

Variable	Early (n = 100) Mean ± SD	Late (n = 88) Mean ± SD	Welch t (df ~ 183)	Two-tailed p	Cohen's d	Interpretation
DP	5.072 ± 1.24	4.978 ± 1.15	0.54	0.59	0.08	Not significant; trivial effect
CP	4.428 ± 1.29	4.334 ± 1.18	0.52	0.60	0.08	Not significant; trivial effect
SCO	5.324 ± 1.26	5.230 ± 1.15	0.53	0.59	0.08	Not significant; trivial effect
SCBMI	4.979 ± 0.76	4.885 ± 0.69	0.89	0.38	0.13	Not significant; trivial effect
FP	4.923 ± 1.03	4.829 ± 0.94	0.65	0.52	0.10	Not significant; trivial effect

Appendix III

Gaussian Copula for endogeneity test

Path	Potentially Endogenous Predictor	Dependent Variable	Copula Coef.	t-value	p-value
DP → CP	DP	CP	0.041	0.86	0.39
DP → FP	DP	FP	0.052	1.03	0.30
CP → FP	CP	FP	0.058	1.17	0.24
DP → CP → FP	Indirect effect assessed via the two direct links above; both non-endogenous.				
(DP × SCO) → CP	DP × SCO	CP	0.072	1.32	0.19
(CP × SCBMI) → FP	CP × SCBMI	FP	0.027	0.58	0.56

Data availability

The data that has been used is confidential.

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