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Digital adoption and supply chain collaboration in a volatile, uncertain, complex and ambiguous business environment: Mediating roles of visibility and risk

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Background: The study was conducted in response to the challenges of a volatile, uncertain, complex and ambiguous (VUCA) business environment that pressures firms to enhance collaboration and resilience within their supply chains.

Objectives: This study examined how the business environment and the degree of digital technology adoption influenced supply chain collaboration (SCC), while also assessing the mediating roles of supply chain visibility (SCVI) and supply chain risk management (SCRM).

Method: A quantitative survey was performed with 180 manufacturing enterprises in Vietnam. The proposed model was tested using the partial least squares structural equation modelling (PLS-SEM) technique to evaluate direct and indirect relationships among variables.

Results: The business environment positively affected technology adoption, SCVI, SCRM and SCC ($p < 0.05$). Technology adoption directly and indirectly influenced SCC through SCVI and SCRM. Both SCVI and SCRM significantly enhanced SCC, and the overall model explained 43.1% of the variance in SCC ($R^2 = 0.431$).

Conclusion: The findings indicated that while environmental dynamism stimulated digital transformation, SCVI remained the key driver that translated environmental pressures and technological capabilities into effective SCC.

Contribution: Theoretically, the study extends the dynamic capability perspective by jointly considering environmental and digital determinants and by identifying SCVI as a catalyst for collaborative practice and performance in supply chains. Practically, it offers recommendations for policymakers and managers on fostering SCC through coordinated technical and managerial solutions, including digital adoption, enhanced visibility and integrated SCRM.

Keywords: supply chain collaboration; business environment; digital technology; supply chain visibility; supply chain risk management; VUCA.

Introduction

The business world today operates in a VUCA (volatility, uncertainty, complexity, ambiguity) context, where heightened volatility and uncertainty increase the risk of supply chain disruption (Grzybowska & Tubis 2022).

Recent shocks, such as the coronavirus disease 2019 (COVID-19) pandemic, have exposed the vulnerability of global supply networks, while geopolitical tensions have further constrained the supply of energy and raw materials, amplifying risk along supply chains (Chowdhury & Quaddus 2017; Queiroz et al. 2022). Through resource coordination, planning synchronisation and information exchange, supply chain collaboration (SCC) has emerged as a crucial tool for preserving flow and operating efficiency in such settings (Cao & Zhang 2011).

Alongside these VUCA pressures, supply chain management is being transformed by a wave of digital technologies such as big data (BD), artificial intelligence (AI), the Internet of Things (IoT) and enterprise resource planning systems (ERPs) that make supply chains more intelligent and connected (Zhao, Hong & Lau 2023).

The Internet of Things facilitates real-time tracking of inventories and shipments, increasing transparency and enabling early risk detection (Taj et al. 2023), while BD and AI enhance the capacity to forecast demand and risks, optimise processes and strengthen resilience (Dubey et al. 2021). In emerging markets, the ability to apply these technologies has proved critical for maintaining operations and recovering from shocks, thereby reinforcing collaboration between supply chain partners (Balakrishnan & Ramanathan 2021). Taken together, these developments highlight the central role of digital technology in supporting SCC and maintaining continuity of flows under VUCA conditions.

However, the specific mechanisms through which VUCA pressures and digital technologies influence SCC remain insufficiently understood. Prior work suggests that intermediary elements should be taken into account (Ali & Gölgeci 2019). Two important capabilities are supply chain visibility (SCVI) and supply chain risk management (SCRM). Supply chain visibility captures how well actors access and share timely information on supply and demand, inventories and transportation, thereby facilitating efficient coordination (Frederico, Garza-Reyes & Kumar 2023; Srinivasan & Swink 2018).

Digital technologies such as IoT and data platforms enable instant access to order information and early detection of incidents (Qader et al. 2022), and evidence shows that information transparency improves collaboration, flexibility and efficiency (Baah et al. 2022). Supply chain risk management, in turn, includes identifying, assessing and addressing systemic risks in the supply chain (Fan & Stevenson 2018). In a VUCA environment, proactive risk management reduces losses and enhances performance and resilience (Fan & Stevenson 2018), while close cooperation supports risk-information sharing and good SCRM strengthens trust and promotes long-term collaboration (Li et al. 2023). Supply chain visibility and SCRM can therefore be considered the 'bridge' through which the effects of VUCA and digital technology are translated into more effective SCC.

Despite this, the current research has several important shortcomings. Firstly, most earlier studies have concentrated on two separate areas: evaluating the advantages of digital adoption or examining how supply chain operations are affected by environmental instability. This fragmented approach has led to a lack of an integrated perspective on how the business environment and technology jointly shape supply chain practices, particularly SCC. Secondly, most existing empirical evidence has been collected in developed countries, whereas emerging markets with their specific institutional, infrastructural and capability constraints remain under-studied (Balakrishnan & Ramanathan 2021). As a result, we still know relatively little about how firms in emerging economies respond to VUCA and leverage digital technologies for effective chain collaboration.

To address these gaps, the present study develops an integrated analytical framework that simultaneously examines the impact of the VUCA business environment and the adoption of digital technologies (BD, AI, IoT, ERP) on SCC, taking into account the mediating roles of SCVI and SCRM. In other words, we propose and test the hypothesis that VUCA pressures and firms' digital capabilities positively affect SCC through enhanced visibility and more effective risk management.

Our research model is grounded in several complementary theoretical perspectives. Dynamic capability and resource-based theories emphasise the importance of developing internal capabilities to adapt to changing environments (Barney 1991; Teece, Pisano & Shuen 1997). The technology-organisation-environment (TOE) framework and institutional theory highlight how technological contexts and external institutional forces drive firms to adopt innovations and strengthen collaboration (DiMaggio & Powell 1983; Tornatzky & Fleischer 1990). Information-processing theory argues that firms must enhance their capacity to gather and disseminate information to make effective decisions under uncertainty (Galbraith 1974). The relational view stresses that collaborative competencies such as trust and information sharing can become a shared competitive advantage for entire supply chains (Dyer & Singh 1998). Taken together, these perspectives provide a comprehensive analytical lens for explaining how external factors (business environment) interact with internal capabilities (digital technologies, SCVI, SCRM) to shape SCC outcomes.

On this theoretical basis, we propose an integrated research model and test it using empirical survey data. Specifically, the model hypothesises that the VUCA business environment (BENV) and the level of digital technology adoption (TECH) positively influence SCC, both directly and indirectly, through SCVI and SCRM. To test this model, we surveyed 180 manufacturing enterprises in Vietnam, an emerging economy.

The collected data were analysed using partial least squares structural equation modelling (PLS-SEM), which enables the simultaneous estimation of relationships and the evaluation of the mediating roles of SCVI and SCRM in transmitting the effects of BENV and TECH to SCC.

Literature review and hypotheses development

Part 2 presents an overview of recent research to clarify the role of VUCA, digital technology, SCVI and SCRM for SCC. On that basis, research hypotheses are developed to test the proposed model.

Literature review

The influence of a volatile, uncertain, complex and ambiguous environment on supply chain management

The VUCA environment, defined by volatility, uncertainty, complexity and ambiguity, compels firms to enhance flexibility and strengthen supply chain capabilities to sustain a competitive edge (Koç, Delibaş & Anadol 2022). Rising uncertainty has encouraged organisations to embrace digital technologies that increase information-processing capacity and partner connectivity, thereby augmenting SCVI and real-time data exchange (Troise et al. 2022; Zhou et al. 2024). Volatile, uncertain, complex and ambiguous conditions also highlight the importance of proactive SCRM: empirical evidence shows a shift from reactive to proactive risk practices that improve resilience to disruptions such as COVID-19 and geopolitical crises (El Baz & Ruel 2021). However, the realisation of SCVI and SCRM is uneven. Delphi research points to barriers such as limited data transparency and weak technology integration that keep many supply chains vulnerable to shocks (Grzybowska & Tubis 2022). This suggests that the effectiveness of firms' responses to VUCA depends on how far they can develop and align their technology use, SCVI, SCRM and collaborative capabilities.

The impact of digital technology on supply chain management

Modern digital technologies can help supply chains become more efficient and adaptable. The adoption of digital tools improves the ability to collect and interpret information, allowing firms to react faster to market changes and become more resilient to disruptions (Ivanov & Dolgui 2020; Yu et al. 2025). The Internet of Things and cloud computing systems provide real-time data sharing on inventory and transportation, thereby enhancing SCVI (Delgado, Garrido & Bezerra 2025). Big data and AI applications support early risk identification and timely response, thus strengthening SCRM capabilities (Oubrahim, Sefiani & Happonen 2023; Singh & Singh 2019). Technology-enabled platforms and online collaboration tools further support SCC by facilitating information-sharing and joint planning across partners (Ning & Yao 2023).

Overall, there is a broad consensus that digital technologies enhance information processing and inter-firm connectivity, thereby supporting faster coordination and more responsive supply chains (Ning & Yao 2023; Yu et al. 2025). However, findings remain contested regarding whether collaboration gains materialise uniformly, because benefits often depend on prior integration readiness and data governance, while high costs, infrastructure gaps and trust concerns can constrain adoption and data sharing (Delgado et al. 2025; Yu et al. 2025; Zhou et al. 2023b). This also implies heterogeneous effects by digital maturity, where more advanced inter-organisational deployment is more likely to translate into SCC than partial or pilot implementation (Delgado et al. 2025; Marinagi, Trivellas & Sakas 2023).

At the same time, the literature shows that the impact of digitalisation is contingent. Some studies report that digital transformation significantly improves recovery and performance only when the underlying level of supply chain integration and process alignment is already high (Yu et al. 2025). In many contexts, deploying new technologies still faces substantial barriers related to cost, infrastructure and trust; a lack of common data standards or fear of sharing information can hinder transparency and limit collaboration benefits (Delgado et al. 2025). These mixed findings indicate that the collaboration value of technology is realised primarily through the development of enabling capabilities, especially SCVI and SCRM, rather than through technology adoption per se, which motivates a closer examination of their mediating roles in the TECH–SCC relationship.

Visibility, risk management and supply chain collaboration

Supply chain visibility is widely seen as a crucial element for enhancing collaboration and responsiveness to variability. By reducing information asymmetry, SCVI fosters mutual understanding and trust among partners and thus facilitates SCC (Agrawal et al. 2024; Montecchi, Plangger & West 2021). Supply chain risk management represents a central pillar of supply chain stability in volatile environments: firms with effective SCRM detect risks early, control them efficiently and recover more quickly when disruptions occur (Fan & Stevenson 2018). Risk management can itself become a collaborative process through activities such as risk-information sharing, joint response planning and joint investment in contingency measures (Scholten & Schilder 2015). Yet these capabilities are only fully effective when implemented under appropriate conditions and in a coordinated manner. Supply chain visibility is valuable only if partners are willing and able to provide timely, reliable data, whereas SCRM is more efficacious when supported by a culture of cooperation and trust among stakeholders (Kim & Kim 2024). Hence, to build flexible and reliable supply chains, SCVI and SCRM need to be integrated with SCC competencies instead of functioning as separate, stand-alone practices.

Supply chain collaboration as a dynamic capability

Supply chain collaboration is not only a management approach but also a dynamic capability that enables firms to adapt, optimise resources and increase resilience to fluctuations (Abou Kamar et al. 2023; Chowdhury & Quaddus 2017). It encompasses activities such as data sharing, planning synchronisation and collaborative product development (Simatupang & Sridharan 2005), which have been shown to lower costs, enhance efficiency and strengthen crisis resilience (Ivanov & Das 2020). Supply chain collaboration therefore plays a pivotal role in fostering flexibility, resilience and integration, key elements for high performance in a VUCA environment (Scholten & Schilder 2015). The effectiveness of SCC, however, depends on the depth and quality of coordination: more intensive and balanced collaboration yields greater value than superficial cooperation (Lee & Choi 2021). Trust and a balanced distribution of power are also essential conditions for sustaining collaboration over time; without them, SCC is difficult to maintain (Oyedijo et al. 2022). Firms thus need to develop SCC both in technological terms (information systems and integration) and relational terms (trust, shared goals) to fully realise its benefits.

Summary and research gap

Synthesising dynamic capability and resource-based perspectives (Barney 1991; Teece et al. 1997), the TOE framework and institutional theory (DiMaggio & Powell 1983; Tornatzky & Fleischer 1990), information-processing theory (Galbraith 1974) and the relational view (Dyer & Singh 1998), this study argues that a VUCA business environment pushes firms to adopt digital technologies, expand SCVI and strengthen SCRM.

These three capabilities reinforce SCC and thereby improve adaptability and operational performance across the chain. More specifically, prior studies often examined visibility and risk management in separate streams (Fan & Stevenson 2018; Montecchi et al. 2021), leaving limited evidence on their simultaneous mediating roles and their relative importance in translating digital adoption into SCC under VUCA conditions. Although previous studies have examined many of the individual relationships among VUCA, digital adoption, visibility, risk management and collaboration, there is still a lack of integrated testing of these links within a single model, particularly regarding the indirect effects of BENV and TECH on SCC via SCVI and SCRM.

The proposed integrated model (Figure 1) addresses this gap by simultaneously considering SCVI and SCRM as mediating mechanisms, thereby clarifying how internal capabilities transform external pressures into sustainable collaborative advantages.

Hypotheses development

Based on the literature review presented in the section *Literature review*, the section *Hypotheses development* develops nine research hypotheses as follows:

Impact of the volatile, uncertain, complex and ambiguous business environment

Volatile, uncertain, complex and ambiguous conditions increase uncertainty, making businesses tend to demand higher supply chain transparency to minimise risk when making decisions. When the environment is unpredictable, businesses often increase information sharing with partners to detect changes early and react quickly to events (Christopher & Lee 2004). In fact, businesses that operate in highly uncertain environments attain higher SCVI levels because they make proactive investments in information systems that efficiently track the movement of commodities (Zhou et al. 2023a). Thus, the following is the proposed as follows:

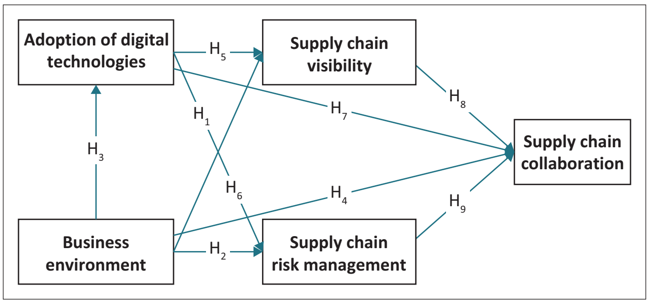


FIGURE 1: Proposed research model.

H1: The business environment positively impacts supply chain visibility.

The supply chain is more likely to be disrupted because of the VUCA, so companies must concentrate on SCRM.

Actually, companies invest more in SCRM to respond quickly and keep operations stable when there is more uncertainty. According to the findings, organisations in high-risk environments typically have faster chain resilience and better SCRM than those that are less vulnerable to VUCA (Fan & Stevenson 2018; Piprani et al. 2022). The second hypothesis, then, is put out as follows:

H2: The business environment positively impacts supply chain risk management.

Several studies indicate that companies are encouraged to use digital technology more in chain management to promote adaptation in a volatile and unpredictable environment like VUCA (Ivanov & Dolgui 2020). A Chinese survey indicates that when managers perceive an unpredictable environment, they are more inclined to spend heavily in inter-organisational digital systems to enhance supply chain integration and monitoring (Zhou et al. 2023a). The suggested theory is as follows:

H3: The business environment has a positive impact on the level of adoption of digital technology in supply chain management.

The VUCA environment, characterised by numerous uncertainties, heightens interdependence among firms, compelling them to collaborate more intimately in resource and risk sharing, aligning with the dynamic capabilities framework (Teece et al. 1997). Vietnamese businesses must forge stronger connections with suppliers and consumers to stabilise supply amid the nation's significant volatility (Hieu, Nguyen & Hoai 2024). The hypothesis is thus put forth:

H4: The business environment exerts a positive influence on supply chain collaboration.

The role of the adoption of digital technology

The degree of digital technology adoption indicates how extensively organisations implement advanced Industry 4.0 technologies in supply chain management. These technologies facilitate the digitisation of processes, enabling the automatic collection and processing of real-time data, thus markedly enhancing the capacity for transparent information tracking across the chain (Qader et al. 2022). In practice, real-time data sharing among partners facilitated by IoT, cloud computing and RFID enables all parties to concurrently access information regarding demand, inventory and orders, thereby markedly enhancing transparency and coordination across stages (Marinagi et al. 2023; Qader et al. 2022). Therefore, the hypothesis is proposed:

H5: The level of digital technology adoption has a positive impact on supply chain visibility.

The application of digital technology is also expected to improve the risk management capacity of the supply chain. Technologies such as AI and BD help businesses forecast demand more accurately, detect anomalies in the chain early and proactively respond before risks escalate (Ivanov & Dolgui 2020). Empirical study demonstrates that organisations with advanced technical capabilities can markedly mitigate the effects of disruption and enhance supply chain resilience (Qader et al. 2022). Therefore, the H6 hypothesis is proposed:

H6: The level of adoption of digital technology has a positive impact on supply chain risk management.

The application of digital technology is expected to promote closer cooperation between partners in the supply chain. Inter-organisational information systems automate information exchange, making interactions between businesses and partners more frequent and transparent (Marinagi et al. 2023). Online planning and collaboration tools also allow parties to participate in the forecasting and planning process, thereby synchronising operations across the chain (Zhou et al. 2023a). Many practical studies confirm that businesses that develop digital collaboration capabilities often achieve a higher level of cooperation with partners (Alshawabkeh, Abu Rumman & Al Abbadi 2024). Therefore, the hypothesis is proposed:

H7: The level of digital technology application has a positive impact on supply chain collaboration.

Relationship between supply chain visibility, risk management and supply chain collaboration

According to Simatupang and Sridharan (2005), the foundation of SCC is information sharing, and the more transparent the relationship, the more cohesive and trustworthy the partners are. In addition, the ability to share real-time data helps chain members coordinate more flexibly and synchronously, thereby improving collaboration efficiency (Alshawabkeh et al. 2024). Therefore, the hypothesis is proposed:

H8: Supply chain visibility positively impacts supply chain collaboration.

When businesses proactively share risk information and work with partners to plan responses, the relationship between them becomes more cohesive (Scholten, Scott & Fynes 2014). Coordination of risk responses builds confidence and understanding between parties, laying the groundwork for long-term cooperation.

Consequently, the hypothesis is posited:

H9: Supply chain risk management exerts a positive influence on supply chain collaboration.

On the basis of theoretical arguments and typical research results presented, we expect to determine the direct impact of VUCA and the degree of adoption of digital technology on SCC, and clarify the intermediary role of the level of adoption of digital technology, SCVI and SCRM in these relationships. The main hypotheses that have been formulated (H1–H9) will be tested quantitatively in later parts of the study.

Research methods and design

Research sample and data collection

The study targeted manufacturing enterprises operating in Vietnam that manage relatively complex supply chains and therefore have a stronger need for formal SCC than typical service firms.

Given resource and time constraints and the impracticality of surveying all manufacturing firms nationwide, we adopted a cluster sampling strategy. Vietnam has experienced rapid growth in industrial and export-processing zones with a diverse mix of foreign-invested and domestic manufacturers; accordingly, three representative industrial clusters were selected in Hanoi, Hung Yen and Bac Ninh.

Questionnaires were distributed to manufacturing firms via the management boards of these industrial zones.

In each enterprise, the research team approached two to three senior managers responsible for supply chain or digital technology. The questionnaire was pre-tested through semantic checking and a small pilot before the full survey. In total, 400 questionnaires were sent out, 196 responses were received, and after screening for completeness and consistency, 180 valid firm-level responses were retained for analysis. The raw response rate was 49% (196/400), and the usable rate was 45% (180/400). Data collection took place during October 2024–February 2025.

The sample is heterogeneous in terms of ownership and market participation. Private firms account for the largest share (92/180; 51.1%), and 81.1% of firms have been in operation for at least 10 years. Moreover, 145 out of 180 firms (80.6%) are involved in global supply chains, defined as having either main markets or core suppliers that are international or both domestic and international.

The sample size is adequate for PLS-SEM. Following the ‘10-times rule’, the minimum required sample equals at least ten times the largest number of arrows pointing at any latent construct. In our model, the maximum number of predictors for a construct is four, implying a minimum of 40 observations. With 180 firms, the actual sample size comfortably exceeds this threshold and is considered sufficient for complex PLS-SEM applications (Hair et al. 2019).

Questionnaire and scale design

The questionnaire consisted of two main parts: (1) general information about the firm and the respondent, and (2) items measuring the constructs in the research model. All latent variables, business environment (BENV), digital technology adoption (TECH), supply chain visibility (SCVI), supply chain risk management (SCRM) and supply chain collaboration (SCC), were operationalised as reflective constructs.

Business environment, SCVI, SCRM and SCC were measured using a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree), capturing the degree of agreement with each statement. TECH was measured using a five-level adoption scale ranging from 1 = 'not applied', 2 = 'pilot testing', 3 = 'applied in some activities', 4 = 'applied in most related activities' to 5 = 'widely deployed with both supply-side and demand-side partners', reflecting the extent of digital transformation in the firm's supply chain activities.

All measurement scales were adapted from established international studies and adjusted to the Vietnamese manufacturing context to ensure content validity. Table 1 summarises the constructs, number of items, retained indicator codes and the main original sources of the scales; Table 1-A1 (see Appendix 1) provides the full wording of all items.

Partial least squares structural equation modelling data analysis and model evaluation

Data were analysed using PLS-SEM with SmartPLS 4.0. Partial least squares structural equation modelling is appropriate for this study because the research model is relatively complex, the sample size is moderate, and the main aim is to explain and predict key endogenous constructs rather than to reproduce a full covariance structure (Hair et al. 2019).

The analysis followed three main steps: (1) evaluation of the measurement model, including assessments of indicator reliability, internal consistency, convergent validity and discriminant validity (section *Evaluating the measurement model*); (2) evaluation of the structural model, examining path coefficients, coefficients of determination (R^2), effect sizes (f^2) and predictive relevance (Q^2) (section *Evaluation of the structural model*); and (3) assessment of mediating effects, testing the indirect roles of TECH, SCVI and SCRM in transmitting the influence of BENV and TECH on SCC (section *Intermediary role testing*).

Because all constructs were measured using a single self-reported questionnaire, we also considered common method variance (CMV). Procedural remedies were implemented by assuring respondents of anonymity and confidentiality and emphasising that there were no right or wrong answers. In addition, CMV was assessed using a full collinearity test. Following Kock (2015), the variance inflation factors (VIFs) for all latent variables should be below 3.3 to indicate that the model is free of CMV. As reported in Table 2, all VIF values ranged from 1.450 to 2.944 (for BENV1-3, TECH1-5, SCVI1-3, SCRM1-3 and SCC1-6), suggesting that CMV is unlikely to pose a serious threat to the findings.

Ethical considerations

Ethical clearance to conduct this study was obtained from the Ethics Research Committee at the School of Economics and Management, Hanoi University of Science and Technology on 16 October 2025.

Research results

Evaluating the measurement model

Firstly, we assessed the reliability and convergent validity of the scales. As reported in Table 3, most factor loadings exceeded 0.70; only SCC1 had a slightly lower loading (0.67) but was retained because of its content relevance, which is still acceptable in exploratory settings (Hair et al. 2019). All Cronbach's α and composite reliability (CR) values were above 0.70, and all AVEs exceeded 0.50, indicating satisfactory internal consistency and convergent validity (Fornell & Larcker 1981; Hair et al. 2019).

Secondly, discriminant validity was assessed using the Fornell–Larcker criterion and the heterotrait–monotrait (HTMT) ratio. Table 4 reports the correlation matrix and the square roots of AVE (bold values on the diagonal). In all cases, the square roots of AVE (0.82–0.87) were higher than the correlations between constructs, satisfying the Fornell–Larcker criterion (Fornell & Larcker 1981). As shown in Table 5, all HTMT values ranged from 0.274 to 0.622 and were clearly below the conservative threshold of 0.85, indicating that the constructs were empirically distinct (Henseler, Ringle & Sarstedt 2015).

TABLE 1: Measurement scales and sources.

Construct (code)	Number of items	Indicator codes	Main sources of scale
Business environment (BENV)	3	• BENV1 • BENV2 • BENV3	• Zhou et al. (2023a)
Digital technology adoption (TECH)	5	• TECH1 • TECH2 • TECH3 • TECH4 • TECH5	• Jain et al. (2017) • Qader et al. (2022) • Marinagi et al. (2023)
Supply chain visibility (SCVI)	3	• SCVI1 • SCVI2 • SCVI3	• Jain et al. (2017) • Frederico et al. (2023) • Mandal et al. (2016)
Supply chain risk management (SCRM)	3	• SCRM1 • SCRM2 • SCRM3	• Jain et al. (2017) • Piprani et al. (2022)
Supply chain collaboration (SCC)	6	• SCC1 • SCC2 • SCC3 • SCC4 • SCC5 • SCC6	• Jain et al. (2017) • Belhadi et al. (2021) • Mandal and Sarathy (2018)

Note: Please see the full reference list of the article, Nguyen, N.D., Mac, T.T. & Tran, H.T., 2026, 'Digital adoption and supply chain collaboration in a volatile, uncertain, complex and ambiguous business environment: Mediating roles of visibility and risk', *Journal of Transport and Supply Chain Management* 20(0), a1280. https://doi.org/10.4102/jtscm.v20i0.1280, for more information.

TABLE 2: Full collinearity variance inflation factors for assessing common method variance.

Items	VIF	Items	VIF	Items	VIF	Items	VIF
BENV1	1.63	TECH1	1.91	SCRM1	1.87	SCC1	1.60
BENV2	1.55	TECH2	2.83	SCRM2	2.29	SCC2	2.94
BENV3	1.45	TECH3	2.94	SCRM3	2.08	SCC3	2.60
-	-	TECH4	2.94	SCVI1	1.84	SCC4	2.61
-	-	TECH5	1.94	SCVI2	1.72	SCC5	2.58
-	-	-	-	SCVI3	1.94	SCC6	2.04

VIF, variance inflation factor; BENV, business environment; TECH, digital technology adoption; SCRM, supply chain risk management; SCC, supply chain collaboration.

Taken together, the reliability and validity tests showed that the measurement model met international standards: all constructs exhibited high internal consistency, adequate convergent validity and clear discriminant validity. BENV, TECH, SCVI, SCRM and SCC were therefore treated as distinct but related latent variables, providing a solid basis for the subsequent evaluation of the structural model in section *Evaluation of the structural model*.

Evaluation of the structural model

After confirming that the measurement model achieves reliability and differentiation value, the study conducted structural model validation according to the guidance of Hair et al. (2019). The R^2 values of the endogenous constructs ranged from 0.051 for TECH to 0.431 for SCC, indicating low to moderate explanatory power. In addition, all Q^2 values were positive, suggesting acceptable predictive relevance of the model for out-of-sample prediction (Hair et al. 2019).

A screenshot of the path coefficients and the outer loadings after the initial execution of the PLS-SEM algorithm is shown in Figure 2.

The overall conformity test of the structural model shows that the SRMR (standardised root mean square residual) of the estimated model is 0.084, which is below the threshold of 0.10 and approximately the threshold of 0.08 according to strict standards, proving that the model conforms to the data at an acceptable level. In addition, no collinear problems were detected between independent structures: all VIF variance magnification coefficients in the structure model were less than 2 (the highest VIF ≈ 1.52), which is much lower than the 3.0 threshold proposed by Hair et al. (2019). This result allows the assertion that independent variables are not collinear, so the regression estimates in the model are reliable.

Table 6 summarises the path coefficients and statistical significance levels for the H1–H9 hypotheses.

All β path coefficients were positive as expected and statistically significant at 5% or higher. In other words, the data support all 9 hypotheses. Specifically:

- The BENV variable has a positive impact on SCRM (β = 0.188; p < 0.05), TECH (β = 0.225; p < 0.01), SCVI (β = 0.365; p < 0.001) and directly to SCC (β = 0.193; p < 0.05);
- The TECH variable (technological capability) also positively affects SCRM (β = 0.302; p < 0.001), SCVI (β = 0.232; p < 0.01) and SCC (β = 0.239; p < 0.01);

TABLE 4: Correlation matrix and Fornell–Larcker discriminant validity.

Variable	Mean	s.d.	BENV	TECH	SCVI	SCRM	SCC
BENV	3.60	0.78	0.822†	0.340*	0.500*	0.350*	0.400*
TECH	3.75	0.60	0.340*	0.844†	0.400*	0.450*	0.300*
SCVI	3.90	0.70	0.500*	0.400*	0.856†	0.540*	0.500*
SCRM	3.55	0.80	0.350*	0.450*	0.540*	0.874†	0.400*
SCC	3.85	0.66	0.400*	0.300*	0.500*	0.400*	0.806†

Note: Please see the full reference list of the article, Nguyen, N.D., Mac, T.T. & Tran, H.T., 2026, 'Digital adoption and supply chain collaboration in a volatile, uncertain, complex and ambiguous business environment: Mediating roles of visibility and risk', *Journal of Transport and Supply Chain Management* 20(0), a1280. https://doi.org/10.4102/jtscm.v20i0.1280, for more information.

BENV, business environment; TECH, digital technology adoption; SCVI, supply chain visibility; SCRM, supply chain risk management; SCC, supply chain collaboration; s.d., standard deviation.

*, p < 0.05.

†, the square roots of AVE for each construct. All are greater than the corresponding inter-construct correlations, indicating that the Fornell–Larcker criterion is satisfied (Fornell & Larcker 1981).

TABLE 5: Heterotrait–monotrait ratios of constructs.

Variable	BENV	SCC	SCRM	TECH	SCVI
BENV	-	-	-	-	-
SCC	0.50	-	-	-	-
SCRM	0.32	0.53	-	-	-
TECH	0.27	0.49	0.39	-	-
SCVI	0.53	0.62	0.59	0.36	-

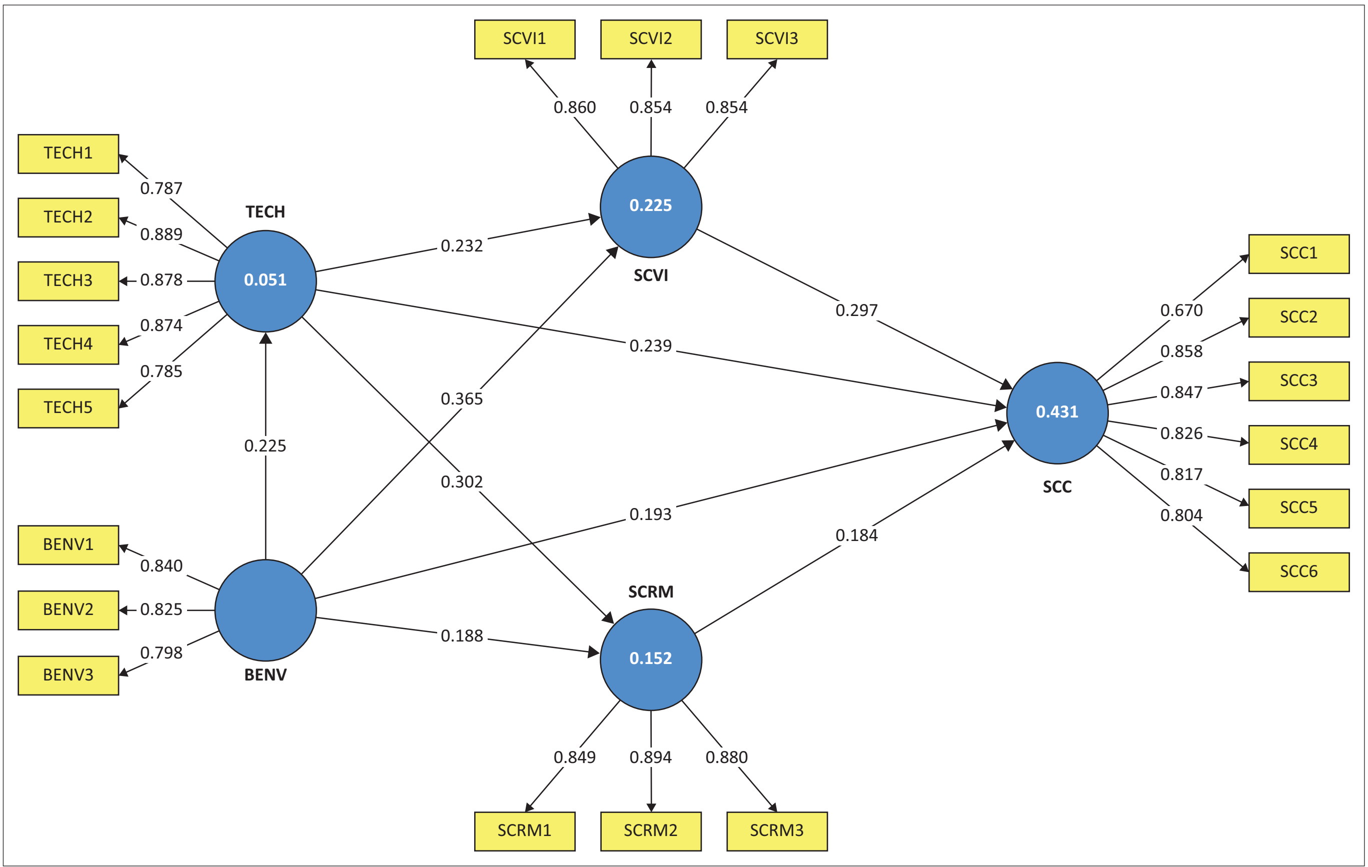
BENV, business environment; TECH, digital technology adoption; SCVI, supply chain visibility; SCRM, supply chain risk management; SCC, supply chain collaboration.

TABLE 3: Measurement model results: Reliability and convergent validity of constructs.

Construct	Cronbach's α	CR	AVE	Factor loading	Observed variables
BENV	0.76	0.86	0.67	0.84	BENV1: Our manufacturing and supply markets are constantly changing
				0.82	BENV2: Customer preferences are continuously evolving
				0.80	BENV3: Competitor actions are highly dynamic and unpredictable
TECH	0.90	0.92	0.71	0.79	TECH1: Specialised location-tracking technologies (e.g. GPS positioning systems)
				0.89	TECH2: Data analytics platforms for big data (e.g. SAS Enterprise Miner, Tableau, Apache Hadoop)
				0.88	TECH3: Artificial intelligence (AI) applications
				0.87	TECH4: Internet of Things (IoT) technologies for real-time data connectivity
				0.76	TECH5: Enterprise resource planning (ERP) systems for integrated business planning
SCVI	0.82	0.89	0.73	0.86	SCVI1: Information about inventory levels and storage is clear across our entire supply chain
				0.85	SCVI2: Information about customer demand is clear across our entire supply chain
				0.86	SCVI3: Information about orders is clear across our entire supply chain
SCRM	0.83	0.91	0.76	0.85	SCRM1: Our company uses risk assessment to predict and reduce supply chain disruption impacts
				0.89	SCRM2: Our company develops contingency plans to address potential supply chain risks
				0.83	SCRM3: Our company integrates risk management into regular supply chain activities
SCC	0.91	0.92	0.65	0.82	SCC1: We actively collaborate with supply chain partners in strategic planning
				0.86	SCC2: We cooperate with partners in managing supply chain risks and responding to market changes
				0.86	SCC3: We share data and information with supply chain partners regularly
				0.81	SCC4: Our supply chain members trust one another
				0.83	SCC5: Our supply chain members share resources during difficulties
				0.80	SCC6: We always prioritise relationships with our supply chain partners

Cronbach's α, Cronbach alpha; CR, composite reliability; AVE, average variance extracted; GPS, global positioning system; BENV, business environment; TECH, digital technology adoption; SCVI, supply chain visibility; SCRM, supply chain risk management; SCC, supply chain collaboration.

All Cronbach's α and CR values ≥ 0.758 and ≥ 0.861 (> 0.70); all AVEs ≥ 0.650 (> 0.50), indicating satisfactory reliability and convergent validity.



BENV, business environment; TECH, digital technology adoption; SCVI, supply chain visibility; SCRM, supply chain risk management; SCC, supply chain collaboration.

FIGURE 2: Partial least squares structural equation modelling structure model results (path coefficients β and R^2).

TABLE 6: Results of testing structural model hypotheses (partial least squares structural equation modelling).

Hypothesis	Relationship	β	s.e.	t	p	f^2	R^2 (%)	Conclude
H1	BENV → SCRM	0.188	0.082	2.3	< 0.050	0.07	15.2	Support
H2	BENV → TECH	0.225	0.075	3.0	< 0.010	0.05	5.1	Support
H3	BENV → SCVI	0.365	0.066	5.5	< 0.001	0.22	22.5	Support
H4	BENV → SCC	0.193	0.080	2.4	< 0.050	0.04	43.1	Support
H5	TECH → SCRM	0.302	0.072	4.2	< 0.001	0.14	-	Support
H6	TECH → SCVI	0.232	0.075	3.1	< 0.010	0.12	-	Support
H7	TECH → SCC	0.239	0.073	3.3	< 0.010	0.10	-	Support
H8	SCRM → SCC	0.184	0.087	2.1	< 0.050	0.03	-	Support
H9	SCVI → SCC	0.297	0.074	4.0	< 0.001	0.12	-	Support

Note: f^2 is the magnitude of influence according to Cohen (1988) (0.02 ~ small; 0.15 ~ medium; 0.35 ~ large). R^2 is the deterministic coefficient of the dependent variable.
BENV, business environment; TECH, digital technology adoption; SCVI, supply chain visibility; SCRM, supply chain risk management; SCC, supply chain collaboration; s.e., standard error.
*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

- At the same time, the two intrinsic capacities, SCRM and SCVI, both have a positive impact on SCC (β = 0.184; $p < 0.05$ and β = 0.297; $p < 0.001$, respectively).

Thus, the hypothetical relationships in the model are supported by observational data. Table 6 presents the PLS-SEM estimation results for each hypothesis in detail, including path coefficient, standard error (s.e.), statistical *value t*, *significance* level p, f^2 index representing the effect size and R^2 of the related dependent variable.

The results show that the business environment in the context of VUCA (BENV) has the strongest influence on SCVI ($\beta = 0.365, p < 0.001; f^2 \approx 0.22$ – medium-sized effect), implying that in the context of many fluctuations, pressure from the external environment significantly promotes information sharing and transparency in the supply chain application. This result is in line with the theoretical thesis that businesses facing a competitive and volatile environment will focus on improving transparency and visibility of the supply chain to mitigate risks. BENV also has a positive impact on the level of adoption of technology (TECH) and SCRM, although the intensity is weaker ($\beta \approx$ 0.19–0.23, $p < 0.05$; f^2 ~0.05–0.07, i.e. small effect, respectively). This suggests that environmental factors mainly indirectly affect supply chain efficiency through the promotion of intrinsic competencies such as technology, risk management and information transparency. In other words, BENV creates an incentive for businesses to develop internal capabilities, thereby improving supply chain efficiency – a thesis that is in line with the dynamic capabilities approach when businesses adapt to the environment by innovating internal capabilities.

In terms of the direct impact on SCC, intrinsic factors play a key role. Specifically, SCVI had the strongest influence on SCC ($\beta = 0.297$, $p < 0.001$) with an average impact size ($f^2 \approx 0.12$). This suggests that increasing shareability and transparency in the supply chain will contribute to significantly improving the level of collaboration between parties, which is consistent with previous studies that have emphasised the role of transparent information in promoting effective collaboration and building trust among partners in the supply chain.

In addition, the level of technology adoption (TECH) also had a positive impact on the SCC ($\beta = 0.239$, $p < 0.01$; $f^2 \approx 0.10$), reflecting the role of digital technologies in facilitating the connection and synchronisation of information, processes and goals among stakeholders – in line with the theoretical basis of technology presented in section *Literature review and hypotheses development*. Meanwhile, SCRM also had the same effect on SCC but with a weaker level ($\beta = 0.184$, $p \approx 0.05$; $f^2 \approx 0.03$) and only reached the level of statistical significance. This finding is quite surprising because, in theory, SCRM is expected to be one of the fundamental factors to promote cooperation to mitigate the impact of threats in the supply chain environment. A reasonable explanation is that the influence of SCRM on SCC is mainly promoted indirectly, through improving the level of technology adoption and SCVI. In other words, SCRM only really promotes collaboration when businesses simultaneously invest in technology and visibility to create a platform that supports risk coordination more effectively. This finding implies that businesses should not expect efficiency alone from risk management, but need to have a synchronous approach, integrating technology and information capabilities into the SCRM strategy to improve the efficiency of SCC.

Overall, the structural model results strongly support the theoretical framework: all H1–H9 are validated at a high significance level, indicating that the data are consistent with modern supply chain theory. Supply chain visibility is a key intermediary, connecting the business environment and TECH with SCC, affirming the fundamental role of information in chain coordination. Supply chain risk management's independent contribution is modest, suggesting combining SCRM with TECH and SCVI to optimise cooperation. The findings add to the empirical evidence, increasing the reliability and generality of the model in the context that VUCA and digital transformation are reshaping cooperation in the global supply chain.

These results are consistent with prior studies that highlight the role of environmental uncertainty in driving supply chain integration and collaboration (Ivanov & Dolgui 2020; Koç et al. 2022) and support the view that visibility and digital technologies are central enablers of collaborative performance (Montecchi et al. 2021; Simatupang & Sridharan 2005).

Intermediary role testing

To test the intermediate role, the study uses a bootstrapping technique with 5000 repeating patterns in PLS-SEM. This method allows for direct estimation of the indirect effects of independent variables on dependent variables through intermediate variables, and at the same time, examines the statistical significance of these effects. In addition, the study also calculates the percentage of variance explained through intermediaries (variance accounted for – VAF) to determine the type of intermediary according to the criteria of Hair et al. (2014): if VAF >80% is fully intermediate, 20% – 80% is partially intermediate, and if VAF < 20% (or indirect influence is not statistically significant), it is considered non-intermediate space.

The bootstrapping results show many indirect effects in the model that are statistically significant, suggesting the existence of intermediary mechanisms. Specifically, the BENV impacts SCC through three main intermediary channels: (1) through SCVI: β_indirect = 0.108, $p < 0.01$; (2) adoption of technology (TECH): β_indirect = 0.054, $p < 0.05$; (3) through SCRM: β_indirect = 0.035, $p < 0.05$.

All of these channels have positive and statistically significant indirect influences, suggesting that a business environment (VUCA) can drive SCC through improved transparency, enhanced technology adoption and strengthened risk management. However, the direct influence from BENV to SCC is still significant (β_direct = 0.193; $p < 0.01$). Therefore, this relationship is identified as partially intermediate. In addition, multi-level intermediate channels (consisting of two consecutive intermediate variables) such as BENV → TECH → SCRM → SCC (β_indirect ≈ 0.013, $p > 0.1$) and BENV → TECH → SCVI → SCC (β_indirect ≈ 0.016, $p > 0.1$) were not statistically significant, showing that the second-order indirect influence of BENV is negligible in the model.

In terms of the relationship between TECH and SCC, the results show that TECH influences SCC indirectly through two channels: SCRM: β_indirect = 0.056, $p < 0.05$, and SCVI: β_indirect = 0.069, $p < 0.05$.

These two indirect effects coexist with a significant direct effect from TECH to SCC (β_direct = 0.239; $p < 0.01$), indicating a partially mediated link between TECH and SCC. Between the two intermediary channels, SCVI plays a more prominent role than SCRM (β_indirect is larger and closer to β_direct), suggesting that the adoption of digital technology promotes SCC primarily through SCVI, rather than improving SCRM.

In addition, the results also show that TECH plays an intermediary role in a number of other relationships.

In particular, BENV has a strong direct effect on SCRM (β_direct = 0.188; $p < 0.01$) and, through TECH, partially affects SCRM (β_indirect = 0.068; $p < 0.01$). Accordingly, by promoting the level of technology adoption, the business environment may indirectly improve the capacity to manage risk. In contrast, the effect from BENV to SCVI is mainly direct (β_direct = 0.365; $p < 0.001$), while the indirect effect through TECH is very small (β_indirect = 0.052; $p < 0.05$), accounting for only about 12% of VAF. As a result, TECH

TABLE 7: Analysis of indirect effects and intermediary roles.

Relationships (Independent Variables → Dependent Variables)	β_indirect	β_total	VAF (%)	Intermediate type
BENV → SCC (via SCVI, TECH, SCRM)	0.200**	0.39**	50.5	Partially intermediate
TECH → SCC (via SCRM, SCVI)	0.120*	0.36**	34.3	Partially intermediate
BENV → SCRM (via TECH)	0.070**	0.26**	26.6	Partially intermediate
BENV → SCVI (via TECH)	0.052*	0.42***	12.5	No intermediaries

Note: p-values correspond to β_indirect; β_total all have corresponding meanings.
BENV, business environment; TECH, digital technology adoption; SCVI, supply chain visibility; SCRM, supply chain risk management; SCC, supply chain collaboration; VAF, variance accounted for (the percentage of impact variance passed through the intermediate variable).
*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

does not play a significant intermediary role in the relationship between BENV and SCVI. Table 7 summarises the indirect effects, total effects, VAF ratios and identifies the corresponding intermediate types for the main relationships in the study model:

The results in the table show that all meaningful intermediary relationships are partially intermediate. None of the relationships reached the 80% > VAF threshold (fully mediated), and some cases of VAF <20% (such as BENV → SCVI via TECH) were identified as significantly non-mediated. For example, the indirect influence from BENV to SCC via SCVI accounts for ~50.5% of the total influence – demonstrating a clear partial mediating role. Meanwhile, the influence from BENV to SCVI via TECH only accounts for ~12.5%, indicating that TECH is hardly intermediate in this relationship.

In terms of governance, the results show that intermediary factors such as SCVI and SCRM play an important role but cannot completely replace the direct influence of input factors (such as BENV, TECH). Therefore, enterprises not only need to develop internal capabilities but also effectively manage environmental factors and underlying technologies, thereby improving the level of SCC. This conclusion is consistent with dynamic capacity theory, which emphasises that intermediate competencies are mechanisms that transform external resources into internal outcomes, but input resources still play an important fundamental role.

Conclusion

This study empirically tested an integrated model linking the VUCA business environment (BENV), digital technology adoption (TECH), SCVI, SCRM and SCC in Vietnamese manufacturing. All nine hypotheses (H1–H9) were supported, indicating that environmental pressures and digital capabilities jointly shape collaboration both directly and through SCVI and SCRM.

The results show that firms facing stronger VUCA pressures tend to enhance visibility, adopt more digital technologies and strengthen risk management, which in turn promote SCC. Among the internal capabilities, SCVI emerged as the most influential driver of SCC, exerting a stronger effect than both TECH and SCRM. This suggests that collaboration depends first on the ability of partners to access and share transparent, timely information on demand, inventories and plans. In other words, information transparency is more critical than risk routines alone for translating environmental pressures and digital adoption into effective collaboration. TECH contributes both directly to SCC and indirectly via SCVI, reinforcing its enabling role; SCRM has a positive but comparatively weaker direct impact and appears to support collaboration mainly when combined with visibility and technology.

These findings yield several theoretical contributions. Firstly, they integrate dynamic capability, TOE, information-processing and relational perspectives into a single empirically tested framework that explains how external pressures and internal capabilities jointly affect SCC in an emerging-economy context. Secondly, they position SCVI as a central mediating capability, clarifying that visibility is the key mechanism through which VUCA and digital adoption are converted into collaborative outcomes. Thirdly, they refine the understanding of SCRM by showing that its independent contribution to SCC is modest unless embedded in a broader configuration of digital and visibility capabilities.

The study also provides clear managerial and policy implications. For managers, the results highlight that digital investments should explicitly target end-to-end visibility and shared data platforms, rather than focusing only on isolated tools. Firms should prioritise building SCVI through integrated information systems, standardised data and clear information-sharing protocols and then align SCRM practices to exploit this visibility. For policymakers, supportive instruments such as technology subsidies, tax incentives, common digital infrastructure and skills development can accelerate digital transformation and enable firms, especially SMEs, to participate more deeply in collaborative, resilient supply chains.

Finally, the study has limitations that suggest directions for future research. The cross-sectional design and focus on manufacturing firms in a single emerging economy limit causal inference and generalisability. Future studies could adopt longitudinal or event-based designs, examine moderating variables such as firm size or ownership, and test additional mediating mechanisms (e.g. resilience or innovation capability) in different countries and industries. Despite these limitations, the findings provide robust evidence that visibility-enabled, technology-supported collaboration offers a viable pathway for transforming VUCA pressures into competitive advantage in contemporary supply chains.

In practical terms, the study showed that firms facing VUCA conditions can enhance SCC by prioritising investments in visibility-enabling digital technologies and aligning SCRM practices with shared information platforms. Policymakers can support this process through targeted incentives, common digital infrastructure and capability-building programmes, particularly for SMEs. Overall, the results suggest that visibility-enabled, technology-supported collaboration is a viable pathway for improving resilience and competitive performance in uncertain environments.

Limitations and future research

This study has some limitations. Firstly, the cross-sectional design restricts causal inference; future research could use longitudinal or event-based designs. Secondly, the focus on manufacturing firms in Vietnam limits generalisability, so cross-country and cross-industry comparisons are needed. Thirdly, although procedural and statistical remedies were applied, relying on single-informant survey data means some common method bias may remain; future work could combine multiple respondents or archival data. Finally, we examined only SCVI and SCRM as mediators; subsequent studies could explore other mediators (e.g. resilience, innovation capability) and moderators such as firm size, ownership or industry segment.

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CRediT authorship contribution

Nguyen D. Nguyen: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. Thuy T. Mac: Conceptualisation, Data curation, Methodology, Project administration, Software, Supervision, Validation, Visualisation, Writing – original draft, Writing – review & editing. Huong T. Tran: Data curation, Software, Validation, Writing – original draft. All authors reviewed the article, contributed to the discussion of results, approved the final version for submission and publication, and take responsibility for the integrity of its findings.

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Data availability

The data that support the findings of this study are available on request from the corresponding author, Thuy T. Mac.

Disclaimer

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Appendix 1

TABLE 1-A1: Summary of hypotheses and reference sources.

Hypothetical code	Hypothesis content	Source
H1	BENV → SCVI	• Christopher and Lee (2004); • Zhou et al. (2023a)
H2	BENV → SCRM	• Fan and Stevenson (2018); • Piprani et al. (2022)
H3	BENV → TECH	• Ivanov and Dolgui (2020); • Zhou et al. (2023a)
H4	BENV → SCC	• Teece et al. (1997); • Hieu et al. (2024)
H5	TECH → SCVI	• Qader et al. (2022); • Marinagi et al. (2023)
H6	TECH → SCRM	• Ivanov and Dolgui (2020); • Qader et al. (2022)
H7	TECH → SCC	• Marinagi et al. (2023); • Zhou et al. (2023a); • Alshawabkeh et al. (2024)
H8	SCVI → SCC	• Simatupang and Sridharan (2005); • Alshawabkeh et al. (2024)
H9	SCRM → SCC	• Scholten et al. (2014)

H, hypothesis.

Note: Please see the full reference list of the article, Nguyen, N.D., Mac, T.T. & Tran, H.T., 2026, 'Digital adoption and supply chain collaboration in a volatile, uncertain, complex and ambiguous business environment: Mediating roles of visibility and risk', *Journal of Transport and Supply Chain Management* 20(0), a1280. https://doi.org/10.4102/jtscm.v20i0.1280, for more information.