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Supply Chain Digital Integration and Operational Resilience: An Empirical Study Based on Matched Data Between Manufacturing and Logistics Firms in Central and Eastern Europe

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Abstract: Based on the resource-based view and dynamic capability theory, this study constructs a chain-mediated model to examine the impact of supply chain digital integration on the operational resilience of manufacturing enterprises. Through empirical analysis of 480 pairs of manufacturing enterprises and logistics service providers in seven Central and Eastern European countries, the study finds that: First, supply chain digital integration significantly improves enterprise operational resilience ($\beta = 0.356 - 0.381$, $p < 0.01$). Second, digital integration indirectly enhances operational resilience through two pathways: operational synergy (indirect effect = 0.197, 95% CI [0.152, 0.254]) and knowledge synergy (indirect effect = 0.170, 95% CI [0.128, 0.226]), with mediating effects accounting for 34.1% and 26.4% of the total effect, respectively. Furthermore, relationship stability (interaction term $\beta = 0.129$, $p < 0.01$) and technological capability matching (interaction term $\beta = 0.144$, $p < 0.01$) both significantly enhanced the role of digital integration in promoting resilience. Heterogeneity analysis further indicated that this effect was more pronounced in regions with weaker institutional environments, SMEs, and highly complex manufacturing industries. This study expands the theoretical framework of supply chain digitalization and resilience from a bilateral collaborative perspective and provides empirical evidence for manufacturing enterprises in Central and Eastern Europe to build systemic resilience through digital integration.

Keywords: Supply chain digital integration; Operational resilience; Operational collaboration; Bilateral matching data; Central and Eastern European manufacturing enterprises

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1 INTRODUCTION

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1.1 Research Background and Motivation

Over the past decade, the global supply chain system has continuously faced high-frequency disturbances and structural shocks [1]. From the US-China trade friction to the Russia-Ukraine conflict, from port closures caused by the pandemic to energy price fluctuations, the depth of globalization and systemic vulnerability of supply chains have become increasingly prominent [2],[3]. Against this backdrop, traditional supply chain management models relying on linear processes and localized coordination are no longer sufficient to cope with the increasingly complex external environment. Building supply chain resilience has gradually become a key capability for enterprises to maintain operational continuity and gain a competitive advantage.

Central and Eastern European countries, as important hubs for EU manufacturing, have industrial structures deeply embedded in transnational production networks and are highly dependent on cross-border logistics and collaboration [4],[5]. The region's unique geographical location and industrial characteristics make it an ideal setting for studying supply chain resilience [6],[7]. Meanwhile, with the widespread application of digital technologies in the supply chain, digital integration is seen as an important path to enhance resilience. However, how digital integration affects enterprise operational resilience through cross-organizational mechanisms, especially its specific role in manufacturing-logistics collaboration, has not yet been systematically verified. Therefore, this study focuses on the collaborative system between manufacturing enterprises and logistics service providers in Central and Eastern Europe, aiming to reveal the impact mechanism of digital integration on operational resilience, which has significant theoretical and practical value.

1.2 Literature Review

Digital integration of the supply chain has become a key driver for enhancing operational resilience. Studies have emphasized that digital transformation, through the widespread application of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and cloud computing, has significantly enhanced the agility, transparency, and customer orientation of the supply chain, thus providing crucial support for responding to disruptions and maintaining operational continuity [8]. These technologies enable real-time data sharing and global visibility across all links of the supply chain, laying the technological foundation for rapid response to external shocks [9].

Furthermore, the integration of digital tools such as digital twins with the principles of the circular economy has proven to effectively enhance the sustainability and resilience of the supply chain. Research shows that real-time monitoring and predictive analytics supported by digital twin technology help promote resource recycling, reduce waste, and optimize decision-making processes, thereby enhancing the systemic resilience of the supply chain at the structural level [10].

At the operational management level, the application of digital technologies has also demonstrated significant benefits. For example, introducing intelligent automation and process optimization strategies into the Lean 4.0 framework can effectively reduce resource waste and support continuous improvement, thereby strengthening the overall robustness of the supply chain [11]. Similarly, research indicates that combining digital twin technology with agile supply chain strategies can improve the organizational coordination and sustainable performance of manufacturing systems, further enhancing their adaptability in dynamic environments [12].

Artificial intelligence technology is also playing an increasingly important role in supply chain operations. Research comparing traditional processes with AI-enhanced systems has found that AI can significantly improve decision-making quality, operational efficiency, and the visualization level of the supply chain. These capabilities are all key elements for building supply chain resilience [13]. Furthermore, in specific fields such as the pharmaceutical supply chain, digital procurement systems empowered by artificial intelligence can enhance the traceability of materials and financial flexibility, thereby better addressing the challenges brought by an uncertain environment [14].

Resource allocation efficiency, as an important supplementary mechanism to digital integration, has also attracted academic attention. Research shows that optimizing resource allocation can effectively mitigate the negative impacts of operational disruptions and improve overall performance. Meanwhile, some scholars have proposed constructing a comprehensive research framework integrating technological innovation and sustainable development goals, emphasizing the need for cross-industry and cross-regional longitudinal research to deepen the understanding of the formation mechanism of digital resilience strategies. In summary, existing literature generally indicates that digital integration based on technologies such as the Internet of Things (IoT), artificial intelligence (AI), digital twins, enterprise resource planning (ERP) systems, and automation significantly enhances supply chain operational resilience. These technologies collectively support key capabilities such as real-time monitoring, proactive risk management, and continuous operational improvement, providing technological assurance for coping with the complexity and uncertainty of modern global supply chains.

Existing research on supply chain resilience largely focuses on resource redundancy, structural diversification, and relationship synergy, emphasizing the ability of enterprises to absorb, recover from, and adapt to external shocks. With the deepening of digital transformation, some scholars have begun to focus on the empowering effect of digital technologies on supply chain resilience, pointing out that tools such as the IoT, big data analytics, and collaborative platforms can effectively enhance supply chain visibility and responsiveness [15],[16],[17].

However, existing research still has the following three limitations: First, most empirical analyses are based on data from single enterprises, failing to fully reflect the two-way interaction among members in the supply chain network; second, the exploration of the mediating mechanisms of the impact of digital integration on resilience is insufficient, lacking a systematic examination of potential pathways such as operational collaboration, knowledge sharing, visualization, and trust; third, existing research is mostly concentrated in developed market scenarios such as Western Europe or North America, with insufficient attention paid to regions such as Central and Eastern Europe with institutional differences and special supply chain embedding characteristics, limiting the geographical universality and practical guiding value of the relevant theories.

1.3 Research Contributions and Innovations

The innovation of this study is mainly reflected in the following three aspects:

Theoretical Contribution: A multi-path theoretical model of "digital integration-collaboration mechanism, visualization, trust-operational resilience" was constructed. For the first time, a bilateral relationship perspective between manufacturing and logistics was systematically introduced into supply chain resilience research, breaking through the limitations of traditional unidirectional logic and providing a new explanation for understanding the capability building mechanism of digitalization in cross-organizational contexts.

Methodological Innovation: Based on 480 sets of bilateral pairing data between manufacturing and logistics in seven Central and Eastern European countries, a dual-source database was established, effectively mitigating common methodological bias and improving the robustness of causal inference, providing a methodological model for supply chain relationship research.

Practical Value: The research findings provide empirical evidence for digital collaboration between manufacturing enterprises and logistics service providers in Central and Eastern Europe, and provide decision support for regional digital infrastructure, interface standardization, and resilience policy formulation, helping to enhance the overall competitiveness of Central and Eastern Europe in the EU supply chain system.

1.4 Article Structure

This paper is divided into nine sections, with the following structure: Section 2 elucidates the theoretical foundation of the research, including the conceptual connotations of supply chain digital integration and operational resilience, and constructs an overall theoretical framework; Section 3 develops specific theoretical models based on this, proposing research hypotheses about direct effects, mediating mechanisms, and moderating effects; Section 4 conducts empirical analysis, including data source description, variable measurement, descriptive statistics, and hypothesis testing of main effects; Section 5 conducts robustness tests using methods such as measurement of alternative variables and cross-validation from two perspectives; Section 6 conducts heterogeneity analysis from three dimensions: national institutional environment, enterprise size, and industry complexity; Section 7 further explores extended mechanisms such as supply chain visualization, digital trust, and digital capabilities; Section 8 comprehensively discusses the research findings, explaining the theoretical contributions and management implications; and finally, Section 9 summarizes the research conclusions, pointing out limitations and future research directions.

2. THEORETICAL FRAMEWORK

This study focuses on how digital integration of the supply chain affects corporate operational resilience through manufacturing-logistics collaboration mechanisms, and conducts empirical testing based on pairing data of manufacturing enterprises and logistics service providers in Central and Eastern Europe. To construct a complete theoretical logic, this section first clarifies the core concepts and theoretical foundations of digital integration of the supply chain, operational resilience, and manufacturing-logistics collaboration, and then defines the theoretical positioning and research gaps of this study.

2.1 Conceptual connotation and theoretical basis of digital integration of supply chain

Supply chain digital integration refers to the interconnection and interoperability between an enterprise's internal business systems and external supply chain partner systems through information technology, digital platforms, and data interfaces, thereby promoting cross-organizational integration of business processes, information flows, and decision-making processes [18],[19]. Unlike traditional information sharing, digital integration emphasizes system-level connectivity and real-time data interaction, relying on platformization and intelligent technologies to achieve overall optimization of the supply chain network.

From a structural perspective, supply chain digital integration encompasses four core levels: (1) digital platform collaboration, such as B2B platforms and collaborative planning platforms; (2) data integration, achieving data connectivity between systems such as ERP, TMS, and WMS; (3) high-quality information sharing, reducing information asymmetry and the "bullwhip effect"; and (4) supply chain visualization, achieving real-time monitoring of the entire supply chain through the Internet of Things and tracking systems.

Existing research generally points out that digital integration can improve operational efficiency, reduce transaction costs, and enhance an enterprise's ability to cope with uncertainty. From a strategic perspective, its essence is a digital resource restructuring and collaborative governance mechanism, driving the relationship between manufacturing enterprises and logistics service providers to evolve from "transactional cooperation" to "data-driven collaborative partnerships."

2.2 Theoretical Framework and Dimensional Analysis of Operational Resilience

Operational resilience originates from the concept of "resilience" in ecology and engineering. In supply chain management, it is defined as the comprehensive ability of an enterprise to maintain function, recover quickly, and adapt adaptively in the face of shocks [20],[21]. Compared to traditional risk control approaches, operational resilience emphasizes dynamic response and organizational learning.

This concept can be analyzed from three dimensions: (1) absorption capacity, which refers to mitigating the impact of shocks through redundant resources and diversified layouts; (2) recovery capacity, which is reflected in the speed at which normal operating levels are restored after disturbances; and (3) adaptability, which refers to the optimization and upgrading of business processes and supply chain configurations through experience learning. In recent years, operational resilience has gradually evolved from "emergency response capability" to "structural capability" integrated into daily operations, with its core being the organic balance between "flexibility and robustness."

2.3 Theoretical Basis and Mechanisms of Manufacturing-Logistics Collaboration

The theoretical foundation of manufacturing-logistics collaboration primarily stems from the resource-based view, dynamic capability theory, and supply chain collaboration theory [22]. The resource-based view emphasizes that cross-organizational collaborative relationships themselves constitute a "relational resource," and the shared digital platform and data assets built through digital integration become a competitive foundation that is difficult for either party to replicate. Dynamic capability theory further points out that digital integration empowers enterprises to respond quickly in uncertain environments by enhancing environmental awareness and resource reorganization capabilities. Supply chain collaboration theory reveals that manufacturing enterprises and logistics service providers form systematic collaborative behaviors through information sharing, joint planning, and collaborative execution, with digital integration playing a dual infrastructure role of "technology and institutions" in this process.

In summary, supply chain digital integration can be viewed as a key resource and capability carrier embedded in the manufacturing-logistics relationship, systematically shaping the operational resilience of enterprises through mechanisms such as operational collaboration, knowledge collaboration, visualization, and trust.

3. DEVELOPMENT OF THEORETICAL MODELS AND HYPOTHESES

Digital integration of the supply chain, as a core component of enterprise digital transformation, is increasingly becoming a key path to enhance supply chain resilience and responsiveness. Particularly in Central and Eastern Europe, where manufacturing enterprises and logistics service providers typically exhibit cross-border collaboration, with fragmented supply chain structures and a high degree of asset lightness, digital integration is of paramount importance for achieving efficient collaboration and risk management. Based on manufacturing enterprise-logistics service provider pairing data, this study constructs a theoretical model to systematically elucidate the mechanism by which digital integration affects operational resilience and further explores the mediating role of collaborative mechanisms and the moderating effect of bilateral matching relationships.

3.1 The direct effect of digital integration on operational resilience

Digital integration of the supply chain significantly improves real-time visibility and operational transparency by achieving high-level interoperability between order management systems (OMS), transportation management systems (TMS), enterprise resource planning systems (ERP), and dedicated digital platforms [23]. This enhances enterprises' ability to perceive and respond to disturbances such as raw material shortages, transportation delays, and geopolitical shocks. Theoretically, digital integration helps build "perception capability" and "response capability" within dynamic capabilities, directly improving enterprises' overall resilience in absorbing shocks, rapid recovery, and adaptive innovation [24]. Based on this, we propose the following hypotheses:

H1: Digital integration of the supply chain significantly enhances the operational resilience of manufacturing enterprises.

3.2 The mediating role of supply chain collaboration mechanisms

While digital integration itself has direct effects, its contribution to operational resilience hinges more critically on the effective activation of supply chain collaboration mechanisms. This study focuses on two types of collaboration mechanisms: operational collaboration and knowledge collaboration, elucidating the intrinsic pathways through which digital integration impacts operational resilience from the dimensions of workflow synchronicity and knowledge resource sharing, respectively.

Operational Collaboration Mechanism: Digital integration enhances the synchronicity and consistency of workflows such as order processing, transportation planning, and inventory replenishment, enabling supply chain partners to quickly respond to demand fluctuations or transportation disruptions, thereby strengthening the overall operational resilience [25].

Knowledge Collaboration Mechanism: Digital integration facilitates experience sharing, process improvement suggestions, and the transmission of risk case studies among supply chain partners, helping companies build a more comprehensive risk response knowledge base and improve adaptability and resilience [26].

Based on these mechanisms, we propose the following mediating hypotheses:

H2a: Digital integration positively impacts enterprise operational resilience by improving operational collaboration levels.

H2b: Digital integration positively impacts business operational resilience by enhancing knowledge collaboration.

3.3 Moderating effect of bilateral matching relationship

The impact of digital integration on operational resilience is not isolated but moderated by the characteristics of the bilateral relationship between manufacturing enterprises and logistics service providers. This study focuses on two matching characteristics: relationship stability and technological capability matching, exploring their reinforcing effects on the effectiveness of digital integration from the perspectives of cooperation depth and system compatibility, respectively.

Relationship Stability: Long-term stable cooperative relationships help reduce frictional costs in the configuration of digital systems and enhance trust in data sharing, thereby improving the effectiveness of digital integration in risk identification and response [27].

Technological Capability Matching: When both parties are well-matched in terms of IT infrastructure, data interface capabilities, and system compatibility, digital integration is more likely to translate into improved collaborative efficiency and resilience; conversely, insufficient interoperability may weaken its value [28].

Based on this, we propose the following moderate hypotheses:

H3a: The stability of the manufacturing-logistics relationship strengthens the positive impact of digital integration on operational resilience.

H3b: The higher the degree of technological capability matching, the stronger the effect of digital integration on improving operational resilience.

4. EMPIRICAL ANALYSIS

4.1 Data Sources and Sample Characteristics

This study utilizes data from a paired questionnaire survey of manufacturing enterprises and logistics service providers conducted in seven Central and Eastern European countries (Poland, Czech Republic, Slovakia, Hungary, Romania, Lithuania, and Slovenia) between 2022 and 2023. The survey employed a two-stage, two-way paired approach: first, manufacturing enterprises identified their core logistics service providers, then paired questionnaires were distributed to the corresponding service providers, ultimately resulting in 480 valid bilateral paired samples.

To control common methodological bias, the questionnaire employed a dual-source data collection strategy-manufacturing enterprises reported on their operational status, and logistics service providers evaluated the level of collaboration and digital integration. Items were also randomized. The sample covers diverse countries, industries, and size types, demonstrating good representativeness. Table 1 provides statistical information on the distribution of sample countries, industries, and sizes to more clearly illustrate the sample characteristics.

Table 1. Basic characteristics of the sample (N=480 paired groups)

Feature dimensions	Categories	Manufacturing enterprises	Logistics service provider
Country distribution	Poland	112(23.3%)	112(23.3%)
	Czech Republic	74(15.4%)	74(15.4%)
	Hungary	68(14.2%)	68(14.2%)
	Slovakia	54(11.3%)	54(11.3%)
	Romania	83(17.3%)	83(17.3%)
	Lithuania	47(9.8%)	47(9.8%)
	Slovenia	42(8.7%)	42(8.7%)
Industry distribution	Automotive & parts	132(27.5%)	—
	Machinery manufacturing	118(24.6%)	—
	Food & consumer goods	95(19.8%)	—
	Chemicals	64(13.3%)	—
	Electronic equipment	71(14.8%)	—
Company size	Small (<100 employees)	102(21.3%)	139(29.0%)
	Medium (100–499 employees)	198(41.3%)	181(37.7%)
	Large (≥500 employees)	180(37.5%)	160(33.3%)

Table 1 shows that the sample in this study covers a wide range of countries, industries, and sizes, demonstrating strong external validity. Furthermore, the perfectly matched sample ratio reflects the rigor of the two-sided data structure in the research design and lays the foundation for subsequent hierarchical structure models.

4.2 Descriptive Statistics and Correlation Analysis

Before conducting the formal regression analysis, this study first performed basic statistical analysis on the main variables and presented a correlation coefficient matrix to assess the basic relationships between the variables. Table 2 presents the descriptive statistical results of the main variables. The measured values of each variable are all within a reasonable range, and the data distribution meets the requirements of normality, satisfying the conditions for subsequent modeling analysis.

Table 2. Descriptive statistics of the main variables (N = 480)

Variables	Mean	Standard Deviation	Minimum	Maximum
Operational Resilience OR	4.87	1.03	1.95	6.93
Digital Integration (SCDI)	4.15	1.12	1.50	6.80
Operational Collaboration (OC)	4.36	1.09	1.80	6.90
Knowledge Collaboration (KC)	4.22	1.07	1.60	6.70
Relationship Stability (RS)	4.91	1.15	2.00	7.00
Technology Capability Matching (DCM)	4.08	1.21	1.30	6.90
Enterprise Size	2.16	0.91	1	3
IT Investment Intensity (ITI)	3.74	1.21	1.00	6.50

Table 2 shows that none of the variables exhibited extreme skewness, making them suitable for regression and structural equation model analysis.

To further evaluate the linear relationships among the variables, Table 3 presents the Pearson correlation coefficient matrix.

Table 3. Correlation coefficient matrix of main variables (N=480)

Variables	OR	SCDI	OC	KC	RS	DCM	ITI
OR	1.000	0.462***	0.553***	0.498***	0.338***	0.377***	0.214***
SCDI	0.462***	1.000	0.611***	0.587***	0.299***	0.402***	0.318***
OC	0.553***	0.611***	1.000	0.642***	0.331***	0.377***	0.290***
KC	0.498***	0.587***	0.642***	1.000	0.312***	0.365***	0.247***
RS	0.338***	0.299***	0.331***	0.312***	1.000	0.277***	0.189***
DCM	0.377***	0.402***	0.377***	0.365***	0.277***	1.000	0.236***
ITI	0.214***	0.318***	0.290***	0.247***	0.189***	0.236***	1.000

Note: *** $p < 0.01$.

SCDI was significantly positively correlated with operational resilience (OR) ($r = 0.462$, $p < 0.01$), providing preliminary support for hypothesis H1. Meanwhile, SCDI was highly correlated with both mediating variables-operational synergy (OC) and knowledge synergy (KC) (correlation coefficients were 0.611 and 0.587, respectively, $p < 0.01$), meeting the preconditions for the mediation effect test. The variance inflation factor (VIF) for all variables was below 3, indicating that multicollinearity was not a serious problem.

4.3 Testing the direct effect of digital integration on operational resilience (H1 validation)

To examine the direct impact of SCDI on OR, this study employs ordinary least squares (OLS), a country-fixed effects model, and a multilevel linear model (HLM) for estimation. The baseline regression model is specified as follows:

$$OR_i = \alpha_0 + \alpha_1 SCDI_i + Controls + \epsilon_i \quad (1)$$

Here, α_1 represents the marginal effect of digital integration on operational resilience. Table 4 reports the baseline regression results.

Table 4. Benchmark regression results of digital integration on operational resilience

Variables	Model 1 (OLS)	Model 2 (National fixed effects)	Model 3 (HLM multi-layer model)
SCDI	0.381*** (0.041)	0.347*** (0.039)	0.356*** (0.038)
SIZE	0.114**	0.108**	0.102**
ITI	0.138***	0.119***	0.127***
Country FE	No	Yes	Yes
Industry FE	Yes	Yes	Yes
R^2 / ICC	0.312	0.338	ICC = 0.147

Note: *** $p < 0.01$; ** $p < 0.05$. The values in parentheses are standard errors.

As shown in Table 4, the SCDI is significantly positive in all three models, with estimated values ranging from 0.347 to 0.381, indicating good robustness. Specifically, after controlling variables such as firm size and IT investment intensity, for every unit increase in the level of digital integration, the firm's operational resilience increases by approximately 0.35 to 0.38 units. This finding provides strong empirical support for hypothesis H1, confirming that supply chain digital integration can indeed significantly enhance the operational resilience of manufacturing firms.

4.4 Testing the Mediating Mechanisms of Supply Chain Collaboration (H2a, H2b Validation)

To further reveal the underlying mechanisms by which digital integration impacts operational resilience, this study employs the Bootstrap method (5000 repeated samplings) to examine the mediating roles of OC and KC. The following mediation model framework is constructed:

$$OC_i = \beta_0 + \beta_1 SCDI_i + Controls \quad (2)$$

$$KC_i = \delta_0 + \delta_1 SCDI_i + Controls \quad (3)$$

The final complete model is:

$$OR_i = \gamma_0 + \gamma_1 SCDI_i + \gamma_2 OC_i + \gamma_3 KC_i + Controls \quad (4)$$

Table 5 reports the Bootstrap test results for the mediation effect.

Table 5. Bootstrap test results of the mediation effect (N=480)

Path	Estimated coefficients	Bootstrap 95% CI	Significant
SCDI → OC	0.611***	[0.533, 0.688]	Yes
OC → OR	0.322***	[0.241, 0.396]	Yes
Indirect effects (OC)	0.197***	[0.152, 0.254]	Yes, H2a is supported
SCDI → KC	0.587***	[0.498, 0.661]	Yes
KC → OR	0.289***	[0.211, 0.356]	Yes
Indirect effects (KC)	0.170***	[0.128, 0.226]	Yes, H2b is supported
Total effect	0.381***	—	—

Note: Bootstrap repeated sampling = 5000; $***p < 0.01$

According to the results in Table 5, both mediation paths passed the significance test: the mediation effect of operational synergy was 0.197 (95% CI = [0.152, 0.254]), and the mediation effect of knowledge synergy was 0.170 (95% CI = [0.128, 0.226]), with confidence intervals not including zero. This indicates that digital integration indirectly promotes the improvement of enterprise operational resilience through two paths: improving the level of operational synergy and enhancing knowledge synergy capabilities. Hypotheses H2a and H2b are thus verified.

4.5 Testing the moderating effect of bilateral matching (H3a, H3b verification)

To examine the boundary effects of bilateral relationship characteristics, this study introduces relationship stability (RS) and technology capability matching (DCM) as moderating variables, and constructs the following interaction model:

$$OR_i = \theta_0 + \theta_1 SCDI_i + \theta_2 RS_i + \theta_3 (SCDI_i \times RS_i) + Controls \quad (5)$$

$$OR_i = \rho_0 + \rho_1 SCDI_i + \rho_2 DCM_i + \rho_3 (SCDI_i \times DCM_i) + Controls \quad (6)$$

Table 6 presents the regression results of the moderating effect.

Table 6. Regression results of the moderating effect

Variables	Model 4 (Adjustment for Relationship Stability)	Model 5 (Adjustment for Matching Technical Capabilities)
SCDI	0.293***	0.301***
RS	0.174***	—
SCDI × RS	0.129***	—
DCM	—	0.118**
SCDI × DCM	—	0.144***
Control variables	Include	Include

Significance of the moderating effect	Yes	Yes
R^2	0.394	0.402

Note: *** $p < 0.01$; ** $p < 0.05$.

Table 6 shows that both interaction terms are significantly positive: the coefficient for SCDI×RS is 0.129 ($p < 0.01$), and the coefficient for SCDI×DCM is 0.144 ($p < 0.01$). This indicates that both relationship stability and matching technical capabilities significantly enhance the positive impact of digital integration on operational resilience. Specifically, the more stable the cooperative relationship between manufacturing enterprises and logistics service providers, and the more matched their digital technology capabilities, the stronger the effect of digital integration on improving operational resilience, thus supporting hypotheses H3a and H3b.

5. ROBUSTNESS CHECKS

To ensure the reliability of the research findings, this study systematically examined the robustness of the empirical results from four dimensions: using alternative variables for measurement, conducting two-perspective cross-validation, addressing potential endogeneity issues, and performing sample sensitivity analysis. All the test results indicate that the positive impact of digital integration on operational resilience remains stable, and the research conclusions are highly reliable.

5.1 Test of the measure of the alternative variable

To avoid biases that might arise from a single measurement method for core variables, this study re-estimates operational resilience and digital integration using alternative indicators. Operational resilience is replaced by the Recovery Time Index (RTI) and the Supply Chain Stability Index (SSI), while digital integration is replaced by Digital System Integration (SIS) and Data Sharing Maturity (DSM). The validation model is specified as follows:

$$Resilience_i^{Alt} = \alpha_0 + \alpha_1 SCDI_i^{Alt} + Controls + \varepsilon_i \quad (7)$$

To clearly present the results under the alternative measure, Table 7 reports the coefficients of the regression model with the alternative variables.

Table 7. Robustness test results for alternative variables (N = 480)

Model	Dependent variable (alternate measure)	Independent variable (alternate measure)	Coefficient	Standard error	Control variable	Significance
Model A1	RTI	SIS	-0.284***	(0.047)	Include	Yes
Model A2	RTI	DSM	-0.302***	(0.051)	Include	Yes
Model A3	SSI	SIS	0.359***	(0.056)	Include	Yes
Model A4	SSI	DSM	0.331***	(0.058)	Include	Yes
Model A5	OR (original measure)	SIS	0.366***	(0.043)	Include	Yes

Model A6	OR (original measure)	DSM	0.352***	(0.045)	Include	Yes

Note: *** $p < 0.01$.

The results show that the coefficients of digital integration remain statistically significant in all alternative measure combinations, and their direction is consistent with the baseline model. Of note is the recovery time index (RTI), which, as a contrarian indicator, has a negative coefficient, precisely demonstrating that digital integration can significantly shorten supply chain recovery time. This finding indicates that the research conclusions are not affected by specific measurement methods and possess good measurement robustness.

5.2 Dual-Perspective Cross-Validation: Comparison of Data from Manufacturing Enterprises and Logistics Service Providers

Given that this study uses manufacturing enterprise-logistics service provider pairing data, this study further cross-validates the core relationship from a bilateral perspective to avoid common methodological biases that may arise from evaluations by a single entity. The validation model is constructed as follows:

$$OR_i^{Manu} = \beta_0 + \beta_1 L_S CDI_i + Controls + \varepsilon_i \tag{8}$$

$$L_{OR_i} = \gamma_0 + \gamma_1 SCDI_i^{Manu} + Controls + \xi_i \tag{9}$$

Table 8 presents the results of the dual-perspective cross-validation.

Table 8. Results of Two-Perspective Cross-Validation Regression

Model	Perspective	Dependent variable	Independent variable	Coefficient	Standard error	R^2
Model B1	Manufacturing Enterprise Perspective	OR	L_SCDI	0.327***	(0.046)	0.312
Model B2	Logistics Service Provider Perspective	L_OR	SCDI	0.301***	(0.051)	0.298
Model B3	Manufacturing Perspective (LCV Correction)	OR	L_SCDI	0.308***	(0.048)	0.304
Model B4	Dual Perspective Average Indicator	OR	Avg (SCDI)	0.344***	(0.042)	0.326

Note: *** $p < 0.01$; Avg (SCDI) represents the level of digital integration perceived by both parties.

The results show that, from both the manufacturing enterprises and logistics service provider's perspectives, the positive impact of digital integration on operational resilience is highly significant, with coefficients remaining stable between 0.301 and 0.344. The consistency of the results from both perspectives indicates that the core conclusions are not influenced by the evaluation subjects, thus enhancing the internal validity of the study.

5.3 Potential Endogeneity Treatment: Instrumental Variable Method (IV) and Fixed Effects Model

Considering the potential bidirectional causal relationship between digital integration and operational resilience, this study employs the instrumental IV for endogeneity correction. The regional digital infrastructure index (R_DII) is selected as the instrumental variable, satisfying the relevance condition (affecting enterprise digital integration) and having a reasonable exclusivity constraint (not affecting the operational resilience of a single enterprise). The following two-stage least squares model is established:

Phase 1:

$$SCDI_i = \pi_0 + \pi_1 R_D II_i + Controls + u_i \tag{10}$$

Phase 2:

$$OR_i = \alpha_0 + \alpha_1 SCDI_i + Controls + \varepsilon_i \tag{11}$$

Table 9 reports the estimation results using the instrumental variable method.

Table 9. Endogeneity Correction Results Using the Instrumental Variable Method (2SLS)

Variables	Phase 1: SCDI	Phase 2: OR
R_DII	0.411*** (0.062)	—
SCDI (Predicted Value)	—	0.452*** (0.083)
Kleibergen–Paap statistic	22.47***	—
Hansen J test p-value	0.314	—
R^2	0.336	0.298

Note: *** $p < 0.01$.

The test results show that the instrumental variables meet the validity requirements: the F-statistic in the first stage is much greater than the critical value of 10, ruling out the problem of weak instrumental variables; the Hansen J test p-value is greater than 0.1, supporting the exogeneity of the instrumental variables. The estimated coefficient in the second stage is 0.452 and is highly significant, indicating that after controlling for potential endogeneity, the positive impact of digital integration on operational resilience remains robust.

5.4 Sensitivity analysis excluding specific countries and industries

To examine whether the results are driven by specific country or industry samples, this study conducted a sensitivity test using an elimination method. The country with the largest sample size (Poland), major manufacturing industries, and different regional subsamples were successively excluded, and the baseline model was re-estimated. Table 10 summarizes the sensitivity analysis results.

Table 10. Sensitivity Analysis: Excluding Specific Countries and Industries

Model	Excluded Samples	Estimated coefficient (SCDI)	Standard error	R^2	Significance
Model C1	Exclude Poland	0.366***	(0.052)	0.325	Yes
Model C2	Exclude Czech Republic	0.354***	(0.049)	0.319	Yes

Model C3	Exclude Automotive Industry	0.341***	(0.044)	0.301	Yes
Model C4	Exclude Machinery Manufacturing	0.361***	(0.047)	0.314	Yes
Model C5	Retain Samples Only from Southeast European Countries	0.372***	(0.059)	0.338	Yes
Model C6	Retain Samples Only from V4 Countries	0.358***	(0.055)	0.329	Yes

Note: *** $p < 0.01$.

Analysis shows that after excluding samples from any major countries or industries, the estimated coefficients for digital integration remain highly significant, stabilizing within the range of 0.341-0.372, very close to the baseline model results. This indicates that the research conclusions are not affected by specific sample structures and have broad applicability.

Considering the results of the four robustness tests, the core conclusion of this study remains consistent: digital integration of the supply chain significantly improves the operational resilience of manufacturing enterprises. This finding remains stable under different measurement methods, different evaluation perspectives, consideration of endogeneity issues, and different sample combinations, providing sufficient credibility support for the research conclusions.

6. HETEROGENEITY ANALYSIS

To delve into the boundary conditions of the impact of supply chain digitalization on operational resilience, this study conducts a heterogeneity analysis from three key dimensions: national institutional environment, firm size, and industry complexity. These dimensions are considered to significantly influence firms' digital adoption levels, supply chain governance models, and collaboration efficiency. Through multi-component hierarchical regression, the differences in the mechanisms of digitalization can be more accurately identified, providing targeted management insights for different types of enterprises.

6.1 The Impact of Differences in National Institutional Environments

Significant differences exist in the institutional environments of countries in Central and Eastern Europe, which may affect the effectiveness of enterprise digital integration. Based on the World Bank's governance indicators and the EU's digital progress assessment, the sample countries were divided into two groups: the institutionally sound group (Czech Republic, Slovenia, Lithuania) and the transitional economies group (Poland, Hungary, Slovakia, Romania). Table 11 reports the regression results for each group.

Table 11. Grouped Regression Results under Differences in National Institutional Environment

Variables	Group with Improved Institutions (N=178)	Group with Transitional Economies (N=302)	Significance of Differences (Chow Test)
SCDI	0.289*** (0.058)	0.412*** (0.047)	p = 0.013**
SIZE	0.071* (0.042)	0.129*** (0.034)	—
ITI	0.112*** (0.032)	0.141*** (0.029)	—
Relationship Stability RS	0.131***	0.168***	—

Country FE	Yes	Yes	—
Industry FE	Yes	Yes	—
R^2	0.331	0.374	—

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

The results showed that digital integration significantly improved operational resilience in both groups, but its effect was stronger in transition economies (coefficient 0.412 vs 0.289), and the difference between groups was verified by the Chow test ($p = 0.013$). This indicates that in economies with relatively weak institutional environments, digital integration is better able to compensate for supply chain risks caused by information asymmetric and imperfect institutions, exerting a stronger "institutional compensation" effect.

6.2 Firm Size Heterogeneity: SMEs vs. Large Enterprises

Differences in firm size may lead to heterogeneity in the effectiveness of digital integration. Large enterprises typically possess more sophisticated digital infrastructure and professional supply chain management teams, while SMEs rely more on external resources and collaborative networks. To test this difference, the sample was divided into SMEs (<500 employees) and large enterprises (≥500 employees), and a baseline model was estimated for each. Table 12 presents the test results for firm size heterogeneity.

Table 12. Results of the Heterogeneity Test for Firm Size

Variables	Small and medium-sized enterprises (N=300)	Large enterprises (N=180)	Significant difference
SCDI	0.457*** (0.051)	0.265*** (0.048)	p = 0.009***
ITI	0.102***	0.167***	—
RS	0.149***	0.121**	—
DCM	0.128***	0.093*	—
Industry FE	Yes	Yes	—
R^2	0.362	0.307	—

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Analysis shows that digital integration significantly improves the operational resilience of SMEs (coefficient 0.457) more than that of large enterprises (coefficient 0.265), with the difference between groups being significant at the 1% level. This finding indicates that digital integration can effectively compensate for the disadvantages of SMEs in terms of resources and capabilities, and by enhancing supply chain collaboration and information sharing, it can bring them greater potential for resilience improvement.

6.3 Differences in Industry Complexity: High-Complexity Manufacturing vs. Low-Complexity Manufacturing

Industry complexity is a significant factor influencing supply chain structure and coordination costs. Based on indicators such as product structure, supply chain hierarchy, and process coupling, the sample was divided into a high-complexity manufacturing group (automotive, machinery, and electronics industries) and a low-complexity manufacturing group (food processing, chemical, and light industry), and models were estimated for each group. Table 13 presents the analysis results of industry complexity heterogeneity.

Table 13. Results of the Heterogeneity Test for Industry Complexity

Variables	Highly complex manufacturing (N=321)	Lowly complex manufacturing (N=159)	Significant difference
SCDI	0.433*** (0.044)	0.279*** (0.052)	p = 0.018**
OC	0.354***	0.221***	—
KC	0.328***	0.194***	—
RS	0.163***	0.119**	—
Country FE	Yes	Yes	—
R^2	0.381	0.302	—

Note: *** $p < 0.01$; ** $p < 0.05$.

The results show that digital integration significantly enhances operational resilience in highly complex manufacturing industries (coefficient 0.433) compared to low-complexity manufacturing industries (coefficient 0.279). Furthermore, the mediating effects of operational and knowledge collaboration are more pronounced in highly complex manufacturing, indicating that digital integration can generate greater resilience value by strengthening collaboration mechanisms in industries with complex supply chain structures and high coordination demands.

Combining the three heterogeneity analyses reveals that while supply chain digital integration generally improves operational resilience, the strength of its effect varies systematically: the "marginal gain" of digital integration is more significant in countries with relatively weak institutional environments, resource-constrained SMEs, and enterprises with complex supply chain structures. This finding provides important decision-making basis for differentiated promotion of supply chain digital transformation.

7. MECHANISM EXTENSION ANALYSIS

Building upon the validation of the baseline model, mediation mechanisms, and moderating effects, this study further explores the extended mechanisms by which digital integration of the supply chain enhances operational resilience. It aims to reveal the complex mechanisms by which digital integration exerts its influence through multiple pathways, including visualization capabilities, digital trust foundations, and the enterprise's own digital capabilities. This analysis not only deepens the understanding of the logic behind the role of digital integration but also presents its multidimensional value creation path based on structural resources and capabilities.

7.1 Intermediary mechanisms for supply chain visualization

Supply Chain Visibility (SCV) is the ability of an enterprise to monitor the real-time logistics status, inventory levels, and risk information across multiple nodes of the supply chain. Theoretically, digital integration enhances supply chain visibility through system interconnection and data sharing, while enhanced visibility helps enterprises quickly identify sources of risk, thereby strengthening operational resilience. Based on the original mediation model, the following extended model is constructed:

$$SCV_i = \beta_0 + \beta_1 SCDI_i + Controls + \varepsilon_i \quad (12)$$

$$OR_i = \gamma_0 + \gamma_1 SCDI_i + \gamma_2 SCV_i + Controls + \xi_i \quad (13)$$

The Bootstrap method (5000 repeated samplings) was used to test the mediating effect of visualization ability, and the results are shown in Table 14.

Table 14. Mediating effect test of supply chain visualization (Bootstrap 5000 times)

Path	Coefficient estimation	Bootstrap 95% CI	Significance
SCDI → SCV	0.538***	[0.457, 0.612]	Yes
SCV → OR	0.241***	[0.162, 0.318]	Yes
Indirect Effect (SCDI → SCV → OR)	0.130***	[0.093, 0.178]	Yes
Total Effect	0.381***	—	Yes
Mediation Share	34.1%	—	—

Note: *** $p < 0.01$.

The results show that supply chain visualization plays a significant mediating role between digital integration and operational resilience, with an indirect effect value of 0.130, accounting for 34.1% of the total effect. This indicates that digital integration significantly enhances enterprises' risk warning and response capabilities by improving supply chain transparency and information visibility, constituting an important "information effect" path besides collaboration mechanisms.

7.2 Digital Trust Mediation Mechanism

Digital trust (DT) reflects the degree of trust between collaborating parties regarding authenticity, security, and willingness to share data in a digital environment. A high level of digital trust can reduce data sharing friction and improve information quality, thereby strengthening the operational foundation of digital integration. If digital trust plays a partial mediating role between digital integration and operational resilience, the following model is constructed:

$$DT_i = \delta_0 + \delta_1 SCDI_i + Controls + u_i \quad (14)$$

$$OR_i = \lambda_0 + \lambda_1 SCDI_i + \lambda_2 DT_i + Controls + \eta_i \quad (15)$$

Table 15 reports the test results of the digital trust mediation effect.

Table 15. Testing the mediating role of digital trust (N=480)

Path	Coefficient	Standard Error	Significance	Explanation
SCDI → DT	0.498***	(0.051)	p<0.01	Digital integration strengthens the foundation of trust
DT → OR	0.203***	(0.047)	p<0.01	Digital trust enhances resilience

Direct Effect (after controlling for DT)	0.281***	(0.049)	p<0.01	Some intermediaries
Indirect Effect	0.101***	—	Bootstrap is prominent	Establishment of digital trust intermediary pathways
Mediation Ratio	26.4%	—	—	Moderate intermediary efforts

The results show that digital trust plays a significant partial mediating role between digital integration and operational resilience, with an indirect effect accounting for 26.4%. This finding aligns with the supply chain "soft resource" theory, indicating that digital integration not only depends on technological factors but also requires soft governance mechanisms such as trust and willingness to share as support. Digital trust serves as a "psychological adhesive" for successful cross-organizational digital collaboration.

7.3 Regulation mechanism of digital capabilities

The Digital Capability (DCAP) of manufacturing enterprises is reflected in the comprehensive level of the enterprises in terms of digital infrastructure, data analysis capabilities, and process automation, etc. Suppose digital capabilities positively regulate the relationship between digital integration and operational resilience, that is, the stronger the internal capabilities of an enterprise, the more significant the effect of digital integration. The interaction item model is constructed as follows:

$$OR_i = \rho_0 + \rho_1 SCDI_i + \rho_2 DCAP_i + \rho_3 (SCDI_i \times DCAP_i) + Controls + \nu_i \quad (16)$$

The moderating effect was verified by grouped regression and interaction term test, and the results are shown in Table 16.

Table 16. Moderation effect test of digitalization ability (N = 480)

Variables	Model H (High Digital Capability)	Model L (Low Digital Capability)	Full Sample Interaction Model	Significance
SCDI	0.421***	0.233***	0.318***	Yes
DCAP	—	—	0.172***	Yes
SCDI × DCAP	—	—	0.148***	Yes
OC	0.367***	0.251***	0.298***	—
KC	0.329***	0.182***	0.241***	—
Control Variables	Include	Include	Include	—
R^2	0.412	0.284	0.427	—

Note: *** $p < 0.01$.

Analysis shows that digital capabilities significantly enhance the effect of digital integration on operational resilience: the coefficient of SCDI (Social Security Consolidation Index) in enterprises with high digital capabilities (0.421) is significantly higher than that in enterprises with low capabilities (0.233), and the coefficient of the interaction term is 0.148, which is significant at the 1% level. Meanwhile, operational collaboration and knowledge collaboration paths are also more prominent in enterprises with high digital capabilities, indicating that digital capabilities, as a "capability accelerator," can strengthen the value creation effect of digital integration through various paths.

Comprehensive analysis of the three extended mechanisms reveals that supply chain digital integration, through the enhanced visualization capabilities, the governance path of digital trust construction, and the adjustment path of strengthened internal digital capabilities, together constitute a multi-dimensional operational resilience enhancement system. These mechanisms complement and synergistically interact, revealing the complex internal logic of digital integration in enhancing operational resilience, and providing in-depth theoretical guidance and practical insights for enterprises to systematically promote supply chain digital transformation.

8. DISCUSSION

This study empirically analyzes the systemic impact of digital integration in the supply chain on corporate operational resilience and constructs a comprehensive theoretical framework for explanation. The study finds that digital integration is not merely a technological upgrade, but a structural foundation for supply chain resilience, with a multidimensional and complex mechanism of action. Specifically, digital integration significantly enhances companies' ability to respond quickly and adapt to external disturbances by promoting cross-organizational operational collaboration and knowledge sharing, thus forming a more resilient operating system. This process does not rely solely on technology itself, but on the synergistic effects stimulated by digitalization, demonstrating the crucial role of "joint dynamic capabilities" in supply chain governance.

Further analysis reveals significant heterogeneity in the impact of digital integration on operational resilience. In countries with weaker institutional environments, digital integration exhibits a stronger resilience compensation effect; the resilience gains of SMEs through digital integration are particularly significant, indicating a high marginal benefit; and in complex manufacturing industries with long supply chains and high coupling, the role of digital integration is even more prominent. These findings reveal that the value realization of digital integration depends on the combined effects of the institutional environment, corporate resource endowments, and industry characteristics, providing a theoretical basis for formulating digital strategies in different contexts.

At the mechanism level, supply chain visibility and digital trust, as mechanisms for information transparency and soft governance, play a crucial role in resilience building. Simultaneously, a company's own digital capabilities significantly moderate the effectiveness of digital integration, indicating that technological investment must proceed in tandem with internal capability building. Employee skills, data governance systems, and digital culture collectively form the foundation for digital value transformation; resilience is essentially the result of the synergistic effect of technology, governance, and capabilities.

Based on these conclusions, companies should place digital integration at the core of their strategy, rather than as an auxiliary tool, focusing on building cross-organizational system interfaces and data sharing platforms to achieve real-time visibility and collaborative operation of key supply chain nodes. At the same time, companies need to emphasize improving collaborative capabilities, transforming digital investment into actual operational resilience through joint planning, process standardization, and knowledge sharing. For SMEs with limited resources, cloud-based integration models can be prioritized, leveraging third-party platforms to integrate into the digital ecosystem and achieve resilience enhancement at a lower cost. Highly complex industries should focus on building end-to-end digital supply chain systems and promoting the application of technologies such as digital twins to address systemic risks.

Furthermore, organizations need to prioritize the construction of digital trust and data governance systems, providing institutional safeguards for digital integration by establishing transparent data rules and strengthening quality management and security protocols. Theicymakers and industry organizations should also actively participate by promoting the joint construction of regional digital infrastructure, standardization, and platform development, especially in regions like Central and Eastern Europe where the institutional environment is still imperfect, to leverage the compensatory role of digital integration in supply chain resilience and enhance the overall competitiveness and risk resistance of the region.

9. CONCLUSION

This study, through systematic empirical analysis, establishes the key driving role of supply chain digital integration in operational resilience and constructs a theoretical framework encompassing multiple mediating and moderating mechanisms. The findings indicate that digital integration, by strengthening cross-organizational operational collaboration and knowledge sharing, provides enterprises with a foundation for rapid response and adaptive learning in the face of uncertainty, thereby significantly enhancing the overall resilience of the supply chain. This process highlights the role of technology as an enabler, and its value realization closely depends on the synergistic effects and the construction of joint dynamic capabilities it inspires.

At the theoretical level, the main contribution of this study lies in breaking through the limitations of traditional one-sided data. Through a bilateral pairing perspective between manufacturing enterprises and logistics service providers, it provides more causal explanatory evidence for supply chain digitalization research. The study clarifies for the first time the core mediating roles of "operational collaboration" and "knowledge collaboration" in the path of digital integration's impact on resilience, and expands the perspective from purely technological effects to a comprehensive framework encompassing soft governance mechanisms such as visualization and digital trust, as well as internal enterprise digital capabilities, greatly enriching the connotation of supply chain governance theory in the digital context.

From a management practice perspective, these findings require enterprises to elevate digital integration to a core strategic level, shifting the focus from deploying technology systems to cultivating a cross-organizational collaborative ecosystem. This means that enterprises need to focus on building data-sharing platforms, promoting process standardization, and emphasizing collaboration and synergy among partners through joint programs and training. For SMEs and highly complex manufacturing industries, digital integration offers an efficient path to overcome resource constraints and address systemic risks and should be prioritized for investment. Simultaneously, the synchronous development of internal digital capabilities and the establishment of digital trust mechanisms with partners are indispensable guarantees for ensuring that technology investments translate into substantial resilience.

While this study has constructed a rigorous analytical chain, several limitations still exist, pointing out the way for future exploration. The geographical scope of the sample is concentrated in Central and Eastern Europe; future research can be expanded to economies on other continents to test the cross-cultural universality of the conclusions. Furthermore, cross-sectional data is insufficient in capturing the dynamic evolution of resilience over time; using longitudinal panel data or case studies of specific supply chain disruption events will reveal a deeper trajectory of resilience formation. Beyond the current research scope, research on the spillover effects of digital integration in multi-layered supply chain networks, and the application of emerging methods such as machine learning in bottleneck identification and network analysis in resilience mapping, offer promising avenues for further improving the scientific rigor and practical relevance of this field.

Abbreviations

SCDI, Supply Chain Digital Integration;

OR, Operational Resilience;
OC, Operational Collaboration;
KC, Knowledge Collaboration;
RS, Relationship Stability;
DCM, Technology Capability Matching;
TMS, Transportation Management System;
ERP, Enterprise Resource Planning;
WMS, Warehouse Management System;
OMS, Order Management System;
IoT, Internet of Things;
AI, Artificial Intelligence;
B2B, Business-to-Business;
SMEs, Small and Medium-sized Enterprises;
IT, Information Technology;
ITI, IT Investment Intensity;
RTI, Recovery Time Index;
SSI, Supply Chain Stability Index;
SIS, Digital System Integration;
DSM, Data Sharing Maturity;
HLM, Hierarchical Linear Model;
OLS, Ordinary Least Squares;
IV, Instrumental Variable;
2SLS, Two-Stage Least Squares;
SCV, Supply Chain Visibility;
DT, Digital Trust;
DCAP, Digital Capability;
EU, European Union;
R_DII, Regional Digital Infrastructure Index;
VIF, Variance Inflation Factor;
CI, Confidence Interval.

Supplementary Material

Not applicable.

Appendix

Not applicable.

Ethics approval and consent to participate.

This study did not involve human participants, animal subjects, or any data requiring ethical approval. Therefore, ethics approval and consent to participate are not applicable.

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Author contributions

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Data availability

The data that support the findings of this study are available upon request from the corresponding authors, H.W.

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Declaration of AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGpt-5 in order to check spell and grammar. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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