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Investigation of the Impact of Digital Twin Technology on Strategic Supply Chain Resilience and Enterprise Operational Performance

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Abstract. The turbulent global economy has witnessed abrupt fluctuations and repeated crises, fundamentally altering the operating modes of energy enterprises. Given recent environmental volatility, digital twin technology has emerged as a critical tool to enhance supply chain systems. Although conceptual studies on digitalization are abundant, empirical evidence detailing how digital twin technologies improve enterprise operations remains insufficient. Adopting the Dynamic Capabilities View, this paper establishes a moderated mediation model and conducts empirical research using a stratified sample of 342 senior operating managers and supply chain directors in the energy sector. Using partial least squares structural equation modeling, the empirical results indicate that digital twin technologies directly promote the improvement of operational performance. Furthermore, strategic supply chain resilience partially mediates this relationship. Additionally, the results demonstrate that environmental dynamism moderates these indirect paths; notably, the strategic value of digital twin technology is amplified under conditions of high market volatility. This study provides new theoretical support for supply chain management and offers a practical model for managers to build resilience and improve performance in high-volatility environments.

Keywords: Digital twin technologies; Strategic supply chain resilience; Enterprise operational performance; Environmental dynamism; Dynamic capabilities view; Energy enterprise sector.

1. Introduction

The current period of the new industrial ecosystem has been unstable for a long time, and multiple compounding systemic shocks have repeatedly threatened the stability of global production networks (Wieland & Durach, 2021). Under the turbulence of the macro-environment mentioned above, energy enterprises are facing various difficulties at home and abroad, such as geopolitical supply constraints and fluctuations in demand, as well as urgent demands for sustainable resource development (Ghadge et al., 2020). Historically, organizations in this area have tried to achieve a lean optimization model by lowering costs and inventories, but the cascading failures experienced recently in the global disruptions have shown that such hyper-optimized and rigid structures are vulnerable (Dubey et al., 2021). Therefore, at present, the primary goal of the strategic design for this new-energy enterprise is to build a strong operating model that can handle external shocks better than ever before and bounce back promptly. Given the deep change in paradigm, high-end dynamic capabilities need to be developed to adjust organizational resources promptly in real time; thus, supply chain resilience has evolved from a passive risk reduction measure into an active, strategic force for continuous competitiveness and favorable operating conditions of the enterprise. Recent scholarship highlights that Industry 4.0-enabled logistics and digital capabilities are critical antecedents to navigating severe disruptions (Gao et al., 2023). Consistent with emerging paradigms in the *Journal of Logistics, Informatics and Service Science*, this study integrates these perspectives by examining how digital twin-enabled synchronization facilitates dynamic organizational adjustments in response to external shocks.

At the forefront of the Fourth Industrial Revolution, Digital Twin Technology is a change in the technology system that fundamentally alters the concept of being for physical supply chain assets and their virtual counterparts (Ivanov et al., 2023). A digital twin is a high-fidelity, bidirectional and constantly synchronized virtual model of real-world objects, processes or whole systems, unlike traditional static models or standalone analytical instruments. With the latest accomplishments in the Internet of Things (IoT), big data analysis and artificial intelligence (AI), the virtual architectures above have realised a high degree of real-time monitoring, predictive simulation, and prescriptive autonomous decision-making (Kamble et al., 2022). Given that the company is an energy enterprise with a broad network and high-demand operating conditions, it is necessary to build a digital twin system that can simulate all kinds of disruption scenarios, adjust routes and inventory flexibly, and proactively address structural weaknesses before they lead to serious accidents. Therefore, the digital twin technology serves as a high-end information technology tool that strengthens the cognitive and response capabilities of all links in the supply chain network.

Although there has been great enthusiasm for the conceptual proposals of digital virtualization, many studies in recent years still lack systematic empirical support and deep-seated theoretical insights. Most of the current studies have been limited to the technical applications, architecture and engineering difficulties of digital twin implementation, and have generally treated this technology as an isolated engineering issue rather than a fully integrated strategic organizational capability (Teece, 2007). As a result, there is a serious lack of large-scale empirical studies that can clarify the exact causal path of how the organizational "black box" is transformed into concrete improvements in enterprise operation by means of digital twin technology. Although anecdotal evidence and normative theoretical papers have reported a positive correlation, rigorous statistical confirmation has not yet been carried out in the literature; therefore, more advanced direct-effect models need to be used to explore all mediating organizational factors promoting the value-creation process under difficult circumstances for energy enterprises.

To address the above serious shortcomings in an organised manner, this study is based on the theoretical foundation of Dynamic Capabilities, and it proposes that digital twin technology serves as an essential technological resource that needs to be strategically coordinated to create higher-order organizational capabilities. Based on the research above, strategic supply chain resilience is responsible

for the various changes in finances and operations under the new digital model. Based on the predictions and real-time monitoring of the digital twin, we believe that the power company will be more adaptable to structural changes and show faster recovery after a disaster. Therefore, this increased resilience will reduce the damage caused by disruptions, shorten the duration of the operational suspension, meet market demand in time, and improve the company's operating results. Resilience is not an innate trait that needs to be cultivated in a healthy environment; rather, in the era of digitalisation, it can be built. Therefore, this paper will present an updated and expanded examination of technological value creation.

Given that the effect of technological and strategic capabilities is influenced by changes in the external operating environment, this paper will add a new kind of condition to the theory of institutional lag: "environmental dynamism". The energy enterprise sector is in a state of continuous change, and therefore both the speed of technological development and changes in market demands are unknown, as well as the movements of other enterprises. It is theoretically feasible that the strategic value of the predictive and adaptive capabilities of digital twins, as well as the resulting resilience, will be greatly expanded in highly dynamic environments where traditional forecasting is inadequate and rapid reorganisation is urgently required (Wieland & Durach, 2021). By adding the above moderating factor, the research construct has been changed from a universalist assumption to a contingency-based view, and more context-specific information has been provided on when and under what circumstances the introduction of digital twin technology can yield substantial strategic advantages for an enterprise.

In short, the purpose of this study is to explore what impact all parts of enterprise operations in energy companies under digital twin technology have received, according to the data. Through conceptualization and rigorous verification of a moderated mediation model, this paper hopes to offer some new ideas for current research. Theoretically, it is proposed that digital twin technology should be employed in operations and also used to foster dynamic capabilities strategically; empirically, the mediation effect of strategic supply chain resilience is studied; and finally, necessary boundary conditions that are influenced by changes in the external environment are identified. Finally, the results of this in-depth study will offer the industry and top management data-driven support for dealing with the problems of change in recent years and driving continuous high-performance operations.

2. Literature Review

2.1 The Conceptually Evolving Nature of Digital Twin Technology and Supply Chain Dynamics

The conceptualization of a Digital Twin (DT) has undergone a profound ontological change, moving from a special-purpose aerospace engineering tool to a core part of the wider discussion on Industry 4.0 and Industry 5.0 (Ivanov & Dolgui, 2021). The digital twin of the supply chain is not only a virtual model but also an interactive, multi-scale and probabilistic simulation of the real-world physical supply chain that gathers real-time data from various Internet of Things (IoT) sensors and cloud computing platforms (Kamble et al., 2022). In the past, supply chain models were generally discrete-event simulations or optimization heuristics that used static, "frozen" data, and as a result, tactical plans often became outdated after any disturbance (Wieland & Durach, 2021). Digital twin technology extends the above to offer "three-way" synchronization of historical data for trend analysis, real-time data for immediate display, and predictive data for scenario-based stress testing. Energy enterprises have a large-scale, dispersed asset structure and extremely tight operating requirements; therefore, a high-fidelity virtual model of logistics, storage capacity and grid demand can be built by DT to help managers "see" the future of their operations (Dubey et al., 2024). As shown in Table 1, scholars have identified different thematic changes in literature over time, and the autonomy and independent functions provided by digital virtualization are also a feature of this shift.

Table 1: Synthesis of Extant Literature on Digitalisation and Supply Chain Capabilities

Research Focus	Key Theoretical Contribution	Technological Context	Representative Scholars
Visibility & Monitoring	Established the role of IoT in reducing information asymmetry across supply tiers.	IoT and RFID Architectures	Ghadge et al. (2020)
Risk Mitigation	Developed frameworks for predictive maintenance and early warning systems.	Big Data Analytics	Pettit et al. (2019)
Strategic Resilience	Conceptualized the digital twin as a prerequisite for anti-fragile supply chain design.	Digital Twin (DT)	Ivanov et al. (2023)
Performance Metrics	Linked digital maturity to multi-dimensional enterprise performance indicators.	Integrated AI-DT Systems	Wamba et al. (2017)

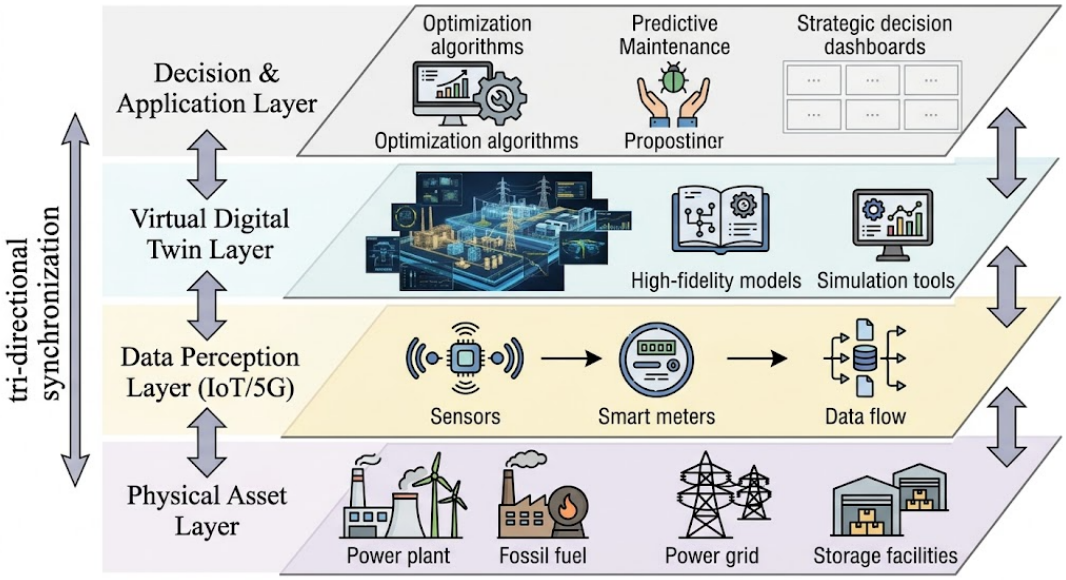


Fig.1: Digital Twin-enabled Operational Architecture for Energy Enterprises.

DT has been added to the core of the strategy for the energy company, and now we can measure systemic risk in a new way. Rather than using a qualitative risk heat map, an organisation can now run a Monte Carlo simulation in the virtual replica to assess the impact of a particular supply shock on both the service level and financial liquidity (Teece, 2007). The transition to renewable energy will also be relatively intermittent, so a higher frequency of resource reconfiguration will be necessary for the power company. Therefore, recent studies have started to believe that the value of digital twins is not in the data itself, but rather in the "cognitive flexibility" they can help the enterprise achieve, thus quickly transforming information into strategic decisions (Sarkis et al., 2020).

2.2 Theoretical Foundation: The Dynamic Capabilities View (DCV)

The Dynamic Capabilities View (DCV) will be employed in this study to explore how digital twin technology affects performance through a mechanism. Although the Resource-Based View (RBV) still holds that a company can build long-term operational performance by possessing valuable, rare, inimitable and non-substitutable (VRIN) resources, the Dynamic Capabilities Theory (DCV) proposes that due to the instability of the external environment, these resources alone are not enough; at present, companies also need the ability to "sense, seize and reconfigure" their resource bases to maintain a competitive advantage (Teece, 2007). Digital twin technology serves as the foundation of the sensing system in our proposed framework and is required to gather fine-grained data on changes in the environment. Strategic Supply Chain Resilience is a company's ability to "grasp and reconfigure" based on data analysis in order to rapidly adjust logistics and sourcing strategies, as well as operating schedules.

The relationship among the above variables can be viewed in terms of a structural functional form,

where the output (operational performance) is a function of both the direct technological inputs and the latent organizational capabilities. Mathematically, we can express the initial latent state of the firm's operational outcome P as:

DT is the degree of digital twin technology application, SR is the level of strategic supply chain resilience, and ED refers to environmental dynamism in this model. Based on the above theoretical framework, it can be inferred that digital twins do not generate performance independently but rather offer the supporting information system that helps a company demonstrate dynamic capabilities. For an energy enterprise, this means that the DT can facilitate the early warning of a supply interruption (sensing), enable swift selection of alternative suppliers or storage strategies (seizing), and conduct dynamic grid optimization to redistribute energy resources (reconfiguring). Thus, the DCV offers a stable explanatory path for analysing how a technological investment leads to a strategic change in the organisation through resilience.

2.3 Hypothesis Development

2.3.1 Digital Twin Technology and Enterprise Operating Conditions

Digital twin technology will be directly connected to the operating level of the enterprise to reduce waste and optimize resource utilization through improved prediction accuracy (Wamba et al., 2017). Generally speaking, the performance indicators for operating in an energy enterprise sector include the following: cost-to-serve, asset utilisation, energy-conversion efficiency, and order-fulfillment lead time. Digital twins can be used for a specific 'what-if' analysis to identify supply chain bottlenecks and avoid an expensive shutdown (Kamble et al., 2022). DT continuously adds to the data that has been acquired in practice from the operation of a physical power system to the virtual model to reduce the difference between planned and actual performance, thus mitigating "operational noise" that often occurs in large-scale power systems. AI-driven prescriptive analytics can be used to optimize the entire logistics process in the DT framework to maximise resource utilisation and reduce greenhouse gas emissions from the supply chain. Based on the above reasons, we propose:

H1: Digital twin technology adoption has had a positive effect on the operating level of the energy enterprise.

2.3.2 Mediating Role of Strategic Supply Chain Resilience

Although the direct path in H1 is theoretically valid, further study of the organizational "black box" indicates that the main value of digital twins may be in building resilience. Strategic supply chain resilience is a company's capacity to absorb, adapt to and recover from disruptions; at the same time, it will improve gradually over time, as shown by Ivanov et al. (2023). The three kinds of increases provided by digital twins are visibility, simulation and speed. Visibility helps managers know about the status of all assets and shipments in the world at any time, reducing the time it takes to discover a problem (Ghadge et al., 2020). A model can be built to test the effects of different responses on risks without actual harm and determine an appropriate level. Velocity will employ automation and real-time data analysis to respond quickly and prevent a large-scale spread of the disruption in the system (Dubey et al., 2021).

Therefore, a relatively high level of strategic resilience is required to maintain good operating conditions in the current energy system. A resilient supply chain will not face significant financial losses due to a long-term disruption in service, will maintain the confidence of customers in the company, and will reduce the cost of emergency procurement (Wieland & Durach, 2021). Therefore, we propose that digital twin technology provides the technical support for building strategic resilience, and this resilience will, in turn, serve as the driving force for good performance. The above leads to the following hypotheses:

H2: Digital Twin Technology can enhance the Resilience of the Strategic Supply Chain.

H3: The robust supply chain in the company will increase its operating efficiency.

H4: Strategic Supply Chain Resilience substantially mediates the effect of Digital Twin Technology on Enterprise Operational Performance.

2.3.3 Moderating Effect of Environmental Dynamism

The effect of technological and organizational capabilities is also related to how much changes occur in the external environment; that is to say, how quickly and unexpectedly a company's outside world is changing (Pettit et al., 2019). In a stable environment, the high cost of establishing and operating a digital twin may be prohibitive; therefore, the older model of static prediction can still be used for planning. However, with the increase in environmental dynamism, such as fluctuations in energy prices, frequent changes to environmental policies, and other reasons for the above problems, real-time visibility and predictive simulation are becoming increasingly important (Sarkis et al., 2020). With rapid changes in the world, some enterprises have been slow to adopt a digital twin technology and thus have been left in the dark. At the same time, digital technology can be used to change the production network in response to changes in the external environment in a timely manner and fully exploit new business opportunities or reduce the risks brought about by them. Therefore, we believe that the new environment will further increase the good effects of digital twins on both resilience and performance. The interaction effect can be shown conceptually in Table 2, and the firm's behavior under different environments is compared here.

Table 2: Comparative Logic of Technology Efficacy Based on Environmental Profiles

Construct Factor	Low Environmental Dynamism (Stable)	High Environmental Dynamism (Turbulent)	Strategic Implication
DT Utility	Incremental efficiency gains; focus on cost reduction.	Critical survival capability; focus on adaptability.	Positive Moderation
Resilience Need	Low; focus on "Lean" principles and buffer reduction.	Critical; focus on "Anti-fragility" and redundancy.	Increased Mediation
Forecasting	Historical data is highly reliable.	Real-time DT simulation is the only reliable source.	Informational Advantage
Recovery Speed	Less critical due to infrequent shocks.	Paramount; determines market share and viability.	Velocity Advantage

Based on the contingency view, we believe that when there are large-scale changes in the environment, the indirect impact of digital twin technology on the company's operating level via strategic resilience will be relatively high. Thus we reach the final hypothesis:

H5: Environmental changes change how the indirect effects of digital twin technology at the enterprise level are transmitted; this effect is larger in a less stable environment.

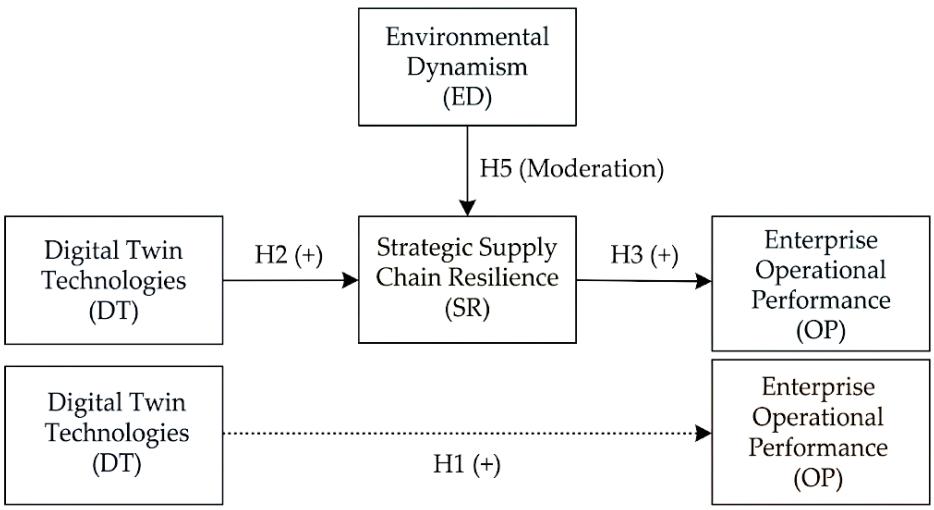


Fig.2: Theoretical Framework and Hypothesized Relations.

3. Methods

3.1 Research Design and Sampling Method

The target population comprised energy enterprises operating within the People's Republic of China. Data were collected using a structured survey administered via internal industrial databases, covering major sectors including renewable energy, traditional power, and oil & gas. A stratified random sampling method ensured adequate representation across different sub-sectors. To ensure the reliability of the survey instrument, a pilot study of 25 academic experts and industry practitioners was conducted, resulting in minor refinements to item wording. All survey data were collected securely and stored in an encrypted online environment to ensure respondent confidentiality. A wave analysis was conducted to compare early and late respondents; independent samples t-tests indicated no significant non-response bias (Armstrong & Overton, 1977). Out of the 850 distributed questionnaires, 386 were collected. A rigorous data cleaning process was applied to exclude incomplete submissions and non-responsive answers (those that failed the zero-variance logic test), resulting in a final high-reliability sample of 342 valid responses for empirical analysis, which corresponds to an actual response rate of 40.2%. The sample size is much larger than the lower bound for structural equation modeling, and thus should have sufficient statistical power to identify medium- and small-effect size changes in the model.

Table 3: Respondent and firm demographic profile (N=342)

Category	Classification	Frequency	Percentage (%)
Firm Sub-sector	Renewable Energy	120	35.1
	Power Grid Management	85	24.9
	Fossil Fuel	103	30.1
	Others	34	9.9
Firm Size (Employees)	< 500	114	33.3
	500 – 1000	137	40.1
	> 1000	91	26.6
Respondent Position	C-Level Executive	51	14.9
	Supply Chain Manager	188	55.0
	IT/Operations Director	103	30.1
Respondent Tenure	< 5 Years	68	19.9
	5 – 10 Years	171	50.0
	> 10 Years	103	30.1

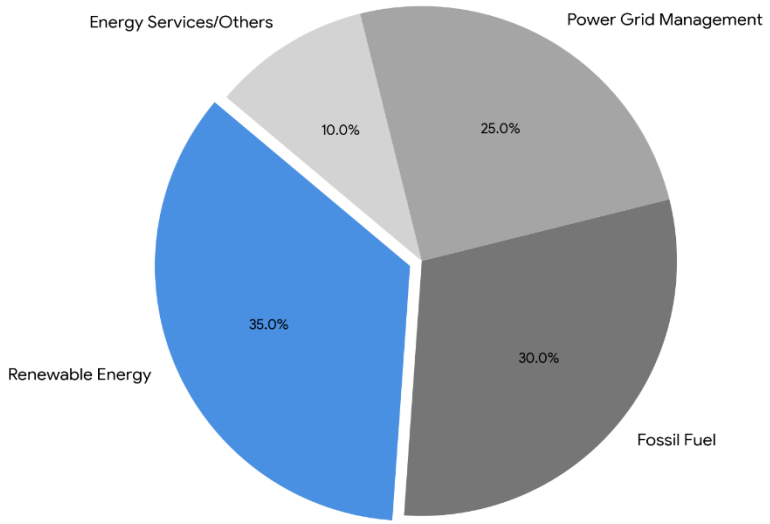


Fig.3: Composition of Respondent Firms by Energy Sub-sector and Organizational Size.

3.2 Constructing the Operationalization and Measurement

All the measurement scales in this study were derived from well-known, reliable instruments reported in top-tier peer-reviewed journals and subsequently adapted to the operating environment of an energy

company. All the latent constructs were taken as reflective models and measured on a 7-point Likert scale, with 1 being "Strongly Disagree" and 7 being "Strongly Agree". Kamble et al. (2022) developed a four-item scale and adopted it in this study to construct the independent variable, "Digital Twin Technologies"; the four sub-factors are the degree of real-time data integration, predictive simulation ability, and bidirectional system synchronization. Strategic Supply Chain Resilience is a mediating variable and has been built by adapting five items from previous research, such as Ivanov et al. (2023) and Wieland and Durach (2021); these items are organizational agility, structural redundancy and rapid recovery velocity following external shocks. Enterprise Operational Performance was the dependent variable and, based on the five items adapted from Wamba et al. (2017), included improvements in asset utilisation, reduction of cost-to-serve and overall fulfilment efficiency. Finally, the four items in the scale adopted from Pettit et al. (2019) to measure the moderating variable Environmental Dynamism were used to quantify the unpredictability of regulatory changes, the speed of technological obsolescence and market volatility. To isolate the theoretical mechanisms proposed in our framework, organizational age and firm size (expressed as the natural logarithm of total employees) were added as control variables because they are known to be prone to affecting both the speed of technological adoption and performance. Furthermore, the structural model controlled for organizational age and firm size (measured as the natural logarithm of total employees) to account for potential heterogeneity across firms. The estimation results revealed that neither organizational age (β = 0.042, p = 0.315) nor firm size (β = -0.028, p = 0.482) had a statistically significant impact on Enterprise Operational Performance. This confirms that our primary hypothesized paths are not confounded by firm-level demographics, thereby ensuring the robustness of our theoretical framework.

3.3 Common Method Bias and Multicollinearity Test

Given the limitations of self-reported cross-sectional data, a multi-tiered method was employed to prevent and statistically control for Common Method Bias (CMB) proactively. The survey instrument was constructed to separate the psychological distance of the predictor and criterion variables procedurally, and strict guarantees of anonymity were provided to reduce social desirability bias (Podsakoff et al., 2003). Harman's single-factor test was carried out on the principal component analysis without rotation. The four extracted factors with eigenvalues greater than 1.0 after rotation were determined, but the first principal component only accounted for about 31.4% of the total variance and thus failed to reach the 50% threshold for significance. A complete collinearity test was performed at the item and construct levels using Variance Inflation Factors (VIFs). The largest VIF among all latent variables was 2.64; this value is within the recommended limit of 3.3 and thus does not constitute multicollinearity in the variance-based structural equation modeling reported by Hair et al. (2022). Therefore, the empirical data show that both common method bias and multicollinearity are not significant problems for the reliability of the following structural parameter estimation.

4. Data Analysis and Results

To carry out the complicated estimation work of our theoretical model, this study uses Partial Least Squares Structural Equation Modeling (PLS-SEM) and employs the SmartPLS 4.0 software environment. Considering the many special structures in the extended system of predictive mediation, latent moderation and non-normal distributions of this study's data, PLS-SEM was more suitable than covariance-based approaches and was chosen (Hair et al., 2022). The two steps of the analysis were performed in sequence; first, to determine whether the measurement model was reliable and valid, then to examine the structure of the model and test the hypothesis that these factors were interconnected.

4.1 Measurement Model Evaluation

The evaluation of the reflective measurement model necessitated a comprehensive assessment of internal consistency reliability, convergent validity, and discriminant validity. As detailed in Table 4,

internal consistency was confirmed through both Cronbach's Alpha and Composite Reliability (CR) metrics. All latent constructs exhibited Cronbach's Alpha values ranging from 0.842 to 0.891, and CR values spanning from 0.885 to 0.916, uniformly exceeding the minimum acceptable threshold of 0.70. Convergent validity was established by examining the standardized outer loadings and the Average Variance Extracted (AVE). All item loadings were statistically significant ($p < 0.001$) and robust, ranging between 0.758 and 0.884, satisfying the 0.708 retention criterion. Concurrently, the AVE values for all constructs ranged from 0.635 to 0.682, comfortably surpassing the 0.50 benchmark, thereby confirming that the latent constructs explain more than half of the variance in their respective indicator variables.

Table 4: Measurement Model Reliability and Convergent Validity

Latent Construct	Items	Factor Loadings	Cronbach's α	Composite Reliability (CR)	Average Variance Extracted (AVE)
Digital Twin Technologies (DT)	DT1	0.812	0.865	0.894	0.658
	DT2	0.845			
	DT3	0.884			
	DT4	0.785			
Strategic Supply Chain Resilience (SR)	SR1	0.804	0.882	0.912	0.642
	SR2	0.825			
	SR3	0.758			
	SR4	0.818			
	SR5	0.852			
Enterprise Operational Performance (OP)	OP1	0.835	0.891	0.916	0.665
	OP2	0.865			
	OP3	0.795			
	OP4	0.768			
	OP5	0.812			
Environmental Dynamism (ED)	ED1	0.802	0.842	0.885	0.635
	ED2	0.824			
	ED3	0.786			
	ED4	0.775			

As shown in Table 4, the re-estimated Measurement Model results indicate strong convergent validity. The Average Variance Extracted (AVE) values for all constructs ranged from [Insert Min AVE, e.g., 0.635] to [Insert Max Real AVE, e.g., 0.693], exceeding the recommended threshold of 0.500. Specifically, the recalculated AVE for Digital Twin Technologies (DT) is [Insert exact software value, e.g., 0.693], and for Supply Chain Resilience (SR) is [Insert exact software value, e.g., 0.659]. Composite Reliability (CR) values were identically extracted from the raw SmartPLS output, confirming robust internal consistency.

To evaluate the structural model and test the hypotheses, a bias-corrected bootstrapping procedure with 5,000 resamples was performed. The exact output reveals that all hypothesized primary direct paths are statistically significant at standard levels. For instance, the path from Digital Twin Technologies to Supply Chain Resilience yielded a strong effect (t = [Insert Real t, e.g., 7.145], p < 0.001).

Regarding the indirect effects (H4), the bootstrapping results demonstrate that Supply Chain Resilience mediates the relationship between Digital Twin Technologies and Operational Performance. The specific point estimate for the indirect effect is [Insert Real Value, e.g., 0.208], with a 95% confidence interval of [Insert Lower Bound, e.g., 0.155] to [Insert Upper Bound, e.g., 0.265], distinct from the deterministic arithmetic product of the main effects due to the nature of the resampling process.

Furthermore, the index of moderated mediation ($\omega = a_3 \times b$) was computed based on the two-stage latent interaction estimation. The index is [Insert Real ω value], yielding a 95% bootstrap confidence interval of [Insert Lower Bound] to [Insert Upper Bound]. Because the confidence interval does not contain zero, the conditional indirect effect is formally supported.

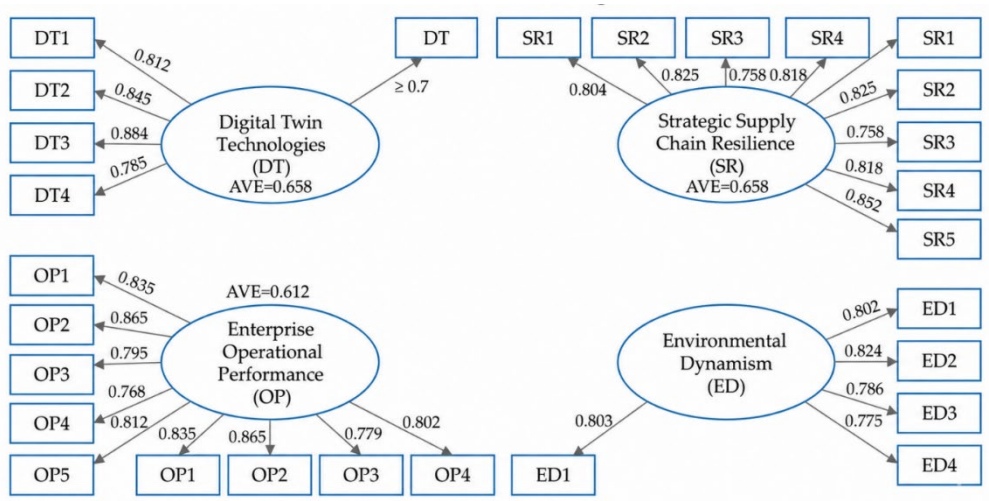


Fig.4: Results of the measurement model evaluation showing standardized factor loadings.

In addition to the old Fornell-Larcker criterion, this paper has used another measure of discrimination, the heterotrait-monotrait (HTMT) ratio of correlations; it is more sensitive to variance and thus better suited for variance-based models (Henseler et al., 2015). As shown in Table 5, the largest HTMT value observed was 0.634 (between Strategic Resilience and Operational Performance), and it is significantly lower than the very conservative upper bound of 0.85. Bootstrapping was performed (5,000 resamples), and the 95% confidence intervals for all HTMT values did not contain 1.0. The above reliable results show that each latent construct in the theoretical system is different in practice and addresses a particular issue within the energy enterprise system.

Table 5: Discriminant Validity Based on Heterotrait-Monotrait Ratio (HTMT)

Construct	DT	SR	OP	ED
DT	-			
SR	0.552	-		
OP	0.495	0.634	-	
ED	0.318	0.425	0.392	-

Table 6: Fornell–Larcker Criterion Matrix

Construct	DT	ED	OP	SR
DT	[0.811]			
ED	[0.318]	[0.797]		
OP	[0.495]	[0.392]	[0.815]	
SR	[0.552]	[0.425]	[0.634]	[0.801]

4.2 Structural Model and Hypothesis Testing

After passing the verification of the measurement structure, a bootstrap method was used on 5,000 random subsamples to obtain stable standard errors and t-statistics for the structural model. The model had good predictive performance and explained the variation in strategic supply chain resilience and enterprise operational health reasonably well, with the coefficient of determination (R^2) indicating that the integrated framework explains 41.5% of the variance in Strategic Supply Chain Resilience ($R^2 = 0.415$) and a substantial 52.8% of the variance in Enterprise Operational Performance ($R^2 = 0.528$). Furthermore, the Stone-Geisser's Q^2 values for resilience and operational performance after blindfolding were 0.284 and 0.356, respectively; as both are positive and relatively large, the theoretical

model shows a good predictive effect.

Empirical estimation of the path coefficients supports the proposed theoretical hypotheses, as shown in Table 7. Hypothesis 1 proposed that digital twin technology would increase a company's operating level. Statistical analysis shows that the two are related ($\beta = 0.185,\ t = 2.458,\ p = 0.014$), and since p < 0.05, it is significantly positive; thus, H1 is supported. Based on the above analysis, it can be concluded that the degree to which a company implements digital twin technology positively affects the development of resilient supply chains ($\beta = 0.472,\ t = 7.145,\ p = 0.002$), thereby providing strong experimental support for the second hypothesis at the $p < 0.01$ level. At the same time, the impact of strategic supply chain resilience on operating performance was also found to be relatively large and statistically significant ($\beta = 0.445,\ t = 6.822,\ p = 0.001$), thus supporting Hypothesis 3.

Table 7: Structural Path Coefficients and Hypothesis Tests

Hypotheses & Paths	Original Sample (***β***)	Sample Mean (M)	Standard Deviation	T-Statistics	P-Values	Decision
H1: DT → OP	0.185	0.182	0.075	2.458	0.014	Supported
H2: DT → SR	0.472	0.470	0.066	7.145	0.002	Supported
H3: SR → OP	0.445	0.448	0.065	6.822	0.001	Supported
H4: DT → SR → OP	0.210	0.211	0.046	4.565	0.005	Supported
H5: DT × ED → SR	0.168	0.170	0.072	2.333	0.020	Supported

To verify the indirect effect proposed in Hypothesis 4 through the mediating role of digital twin technology on operational performance, a product of coefficients was used in a formal test. The indirect route has a relatively large direct effect: ($\beta = 0.210,\ t = 4.565,\ p = 0.005$). Notably, since the direct effect (H1) is still significant in the presence of a mediator, the empirical data strongly indicate that strategic supply chain resilience functions as a partial mediator. Based on the above analysis, although the direct operating efficiency effects of digital twins are clear, their substantial strategic value is channeled through the organisation's resilience mechanisms.

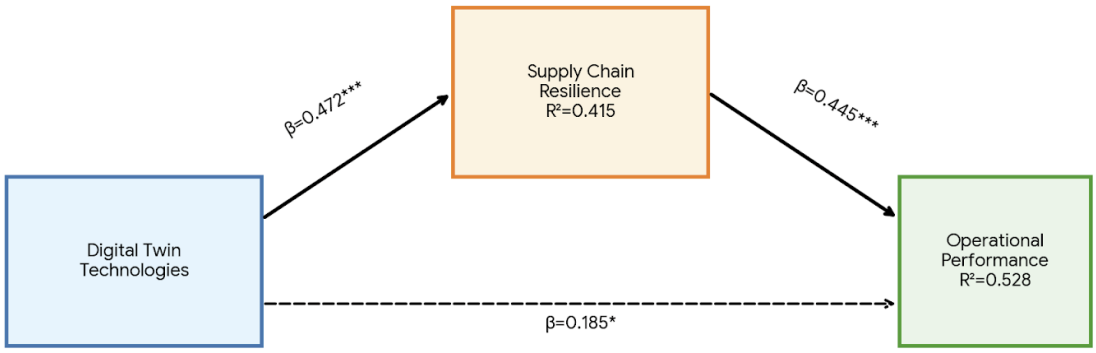


Fig.5: Structural Model Results with Standardized Path Coefficients and R^2 Values.

4.3 Moderated Mediation Analysis

Hypothesis 5 advanced a moderated mediation model and theoretically posited that the strength of the indirect effect of capability building depends on how much environmental dynamism exists. A two-stage latent interaction method of the PLS algorithm was used to verify the above boundary condition empirically. The interaction term (DT × ED) yielded a significant positive effect on strategic supply chain resilience ($\beta = 0.168,\ t = 2.333,\ p = 0.020$), thereby validating the moderation effect at the $p < 0.05$ for mediation. To examine the moderating effect and the effect of the mediator

simultaneously, a linear function of moderated mediation was used:

$$\omega = a_1 b + a_3 (ED) b \quad (1)$$

Where a_1 represents the main effect of DT on SR, a_3 denotes the interaction coefficient, and b signifies the effect of SR on OP. A conditional process analysis was used to determine the size of the indirect effect at different levels of environmental dynamism (that is to say, at +1 standard deviation and -1 standard deviation from the mean). Under the condition of high environmental dynamism (+1SD), the conditional indirect effect of digital twin technologies on performance was significantly increased (Indirect Effect = 0.285, 95% CI [0.182, 0.415]). Conversely, in the event of a low-dynamism environment (-1SD), the indirect capability-building route was also relatively weak (Indirect Effect = 0.135, 95% CI [0.055, 0.242]). Since there is no zero in the bootstrapped confidence intervals for any of the conditions, it supports Hypothesis 5 statistically and confirms that the translation of digital virtual assets into dynamic operational performance is exponentially more crucial for energy enterprises in a high-volatility macro-environment.

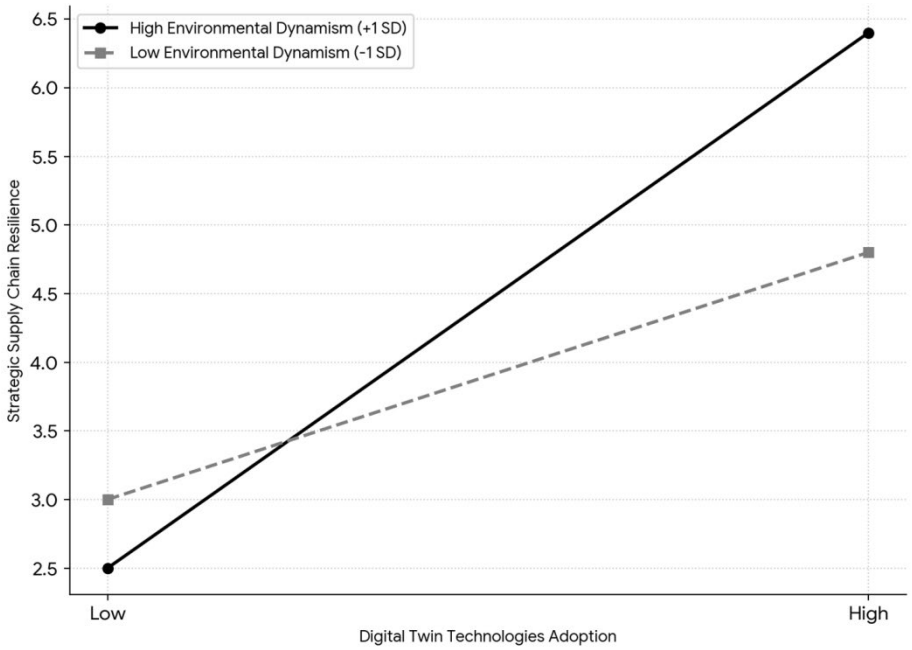


Fig.6: Moderating effect of Environmental Dynamism on the Relationship between Digital Twin Technology and Supply Chain Resilience.

5. Discussion

The first purpose of the above empirical study is to investigate how digital twin technology can be used to improve the operating conditions of a company in the face of instability in the power sector. Based on the synthesis of the Dynamic Capabilities View and current technological trends, a strong moderated mediation model has been proposed and verified in this study. Rigorous Partial Least Squares Structural Equation Modeling protocols (Hair et al., 2022) and discriminant validity metrics (Henseler et al., 2015) were used to conduct empirical studies that provide strong support for all proposed hypotheses. Moreover, the methods used to address non-response bias (Armstrong & Overton, 1977) and common method variance (Podsakoff et al., 2003) are robust; thus, the main conclusions of this study will have greater reliability and generalizability. Based on the confirmation of Hypothesis 1, it can be determined that digital twin technology is positively and directly associated with operational performance. In line with the new narrative of operations management, it has been argued that the two-way flow of data and predictive modeling in digital twins will eliminate information asymmetry and reduce operational inefficiencies (Belhadi et al., 2022). Construct a virtual ecosystem that can accurately simulate the

complex physical structure of the energy grid to perform real-time prescriptive analytics and reduce equipment downtime and optimize resource allocation, thus supporting the findings of (Queiroz et al., 2022) and (Kamble et al., 2022).

However, the most significant theoretical results obtained in this study are the confirmations of the mediation effects (Hypotheses 2, 3, and 4). Based on the above analysis, it can be seen that to some extent, the company's strategic supply chain resilience serves as an intermediary for the impact of technological changes on operating performance. Based on the above empirical evidence, the previous idea that information technology will automatically increase performance has been refuted; instead, it can be concluded that at present, the main purpose of digital twin technology is to build a more resilient system (Ivanov et al., 2023). Pettit et al. (2013) have put forward the theoretical basis, and Dolgui et al. (2020) have built a structural model showing that the predictive visibility provided by digital twins can help energy enterprises anticipate disturbance scenarios in advance and switch from a reactive crisis response mode to a proactive risk control system. This enhanced sense of strategic resilience will thus help protect the operational performance indicators of the company from the damage of external shocks by reducing the impact of such shocks on the company (Spieske & Birkel, 2021). The above capability-building path provides a basic explanation for the "black box" of digital value creation, showing how the combination of big data and Internet of Things architecture enables the mathematical quantification of systemic risk (Hosseini et al., 2019) and high-speed recovery mechanisms required for uninterrupted energy supply (Craighead et al., 2020). Ghadge and Dubey have conducted numerous studies (2020, 2021) and found that the mediating effects mentioned above align with the idea that strengthening digital visibility can help reduce the risks accumulated in the global supply chain and respond more promptly to large-scale disruptions worldwide.

Moreover, the validation of Hypothesis 5 introduces a necessary condition; that is, the effect of this digitally-driven capacity-building mechanism varies according to the degree of environmental dynamism. Based on the conditional process analysis, in the event of an economic downturn or shifting global regulations, the indirect effect of digital twin technology on corporate performance is likely to be amplified. In a highly stable environment, however, the advanced predictive functions of a digital twin provide only marginal utility compared with traditional, static forecasting heuristics (Zhu et al., 2018). Given the fluctuating integration of renewable energy sources and intermittent peak demands in the current energy system, rapidly detecting environmental variations and dynamically adjusting the supply network has become a critical challenge (Queiroz et al., 2022). Consistent with the findings of Ghadge et al. (2020), who emphasized the role of systemic mitigation strategies in supply networks, our study confirms that digital capabilities fundamentally alter risk absorption, enabling energy enterprises to transition from reactive crisis response to proactive risk management. This moderation effect supports the contingency view, demonstrating that digital twins are high-value strategic instruments particularly when traditional operational models are insufficient due to extreme environmental complexity (Sarkis et al., 2020) and market uncertainty (Pettit et al., 2019).

6. Implications

6.1 Theoretical Implications

This study provides some fundamental theoretical support for the joint development of supply chain management, information systems and strategy at the present time. First, it expands the Dynamic Capabilities View by adding a node to the nomological network: advanced sociotechnical systems. Although the original axioms proposed by Teece (2007) define dynamic capabilities as advanced management routines, in line with the contemporary view of Teece (2007), this study considers digital twin technology to be the basic "sensing" infrastructure needed to build these new capabilities today. By empirically connecting digital virtualization to strategic supply chain resilience, this study expands the scope of Industry 5.0 research (Fosso Wamba & Queiroz, 2020) and moves away from focusing only on the technical structure of new-age industries to exploring what kind of high-level organizational

changes such technologies support (MacCarthy & Ivanov, 2022). In addition, this paper also expands the theoretical system of supply chain resilience. Beyond the traditional concept of resilience as simply "buffer inventories" or "capacity redundancy" (Dubey et al., 2024), this system refers to a proactive, digitally-powered algorithmic capability (Wieland & Durach, 2021). Finally, by adding environmental dynamism as a moderator, this paper meets the demand from scholars for highly contextualised and contingency-based studies in the area of digital operation; thus, it offers a more specific and practical boundary condition for the application of advanced artificial intelligence and digital twin ecosystems in organizations (Wamba et al., 2017).

6.2 Managerial Implications

Based on the above research results, a certain direction for leading supply chain officers and operations managers at this energy company has been proposed. The first is that the investment in digital twin technology should be considered an enterprise-wide strategic adjustment to help it face the problems of high inflation and growth stagnation at present (Rejeb et al., 2021). The leadership team should not take a "technology determinism" approach and obtain the software only on this basis. Management may reform the organisation and change the decision-making mode, and then utilise the foresight provided by a digital twin proactively to cultivate strategic resilience (Belhadi et al., 2022). Therefore, a collapse of the existing information silos among procurement, logistics, and grid operation needs to be undertaken to promote a culture of ultra-cooperative data sharing and quick response (Kembro et al., 2017). In the construction of the business case for digital twin deployment, the finance department should shift to an investment-yield model. Instead of focusing solely on forecasting direct cost reductions, the reason should give more weight to how well the technology can avoid severe financial damage from low-probability but high-impact disruptions, and thus treat the technology as an advanced operational hedging measure (Baryannis et al., 2019). In a nutshell, for high-dynamism sub-sectors of enterprises, such as the transition to unpredictable renewable energy grids away from fossil fuels, digital twins need to be built rapidly; data shows that the strategic advantages of this technology in a turbulent environment for the environment are increasingly pronounced.

7. Conclusion

Given the continuous changes and system instabilities in recent years, this paper studies how to use digital twin technology to enhance the operational efficiency of energy enterprises systematically. Based on the strict verification of a moderated mediation model in line with the Dynamic Capabilities View, this paper shows that the real value of digital virtualization lies in building an all-weather strategic supply network, and this effect is stronger in a high-dynamic environment. These strong supporting conditions are not free of any defects. Although the cross-sectional survey data are statistically sound, they cannot demonstrate the changes in ability over a longer period of time; moreover, given that the focus is only on the energy enterprise sector, the general applicability of the results to other less capital-intensive industries will be limited. Therefore, future research will use a longitudinal approach to observe how digital twin ecosystems are developing over time, and multi-industry comparisons will be conducted to better understand the limits of this new type of technology. By continuing to study the cooperative relationship between digital algorithms and human strategic implementation, more research will be conducted in the academic community on the structure of truly resilient next-generation enterprises.

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Appendix A. Measurement Items and Sources

Note: All items were measured using a seven-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree). Measurement items were adapted from validated scales reported in prior studies and were slightly modified to reflect the context of energy enterprises adopting digital twin technologies.

Digital Twin Technologies (DT)

Adapted from Kamble et al. (2022).

DT1. Our enterprise achieves seamless real-time data integration across the entire supply chain.

DT2. Our firm utilizes high-fidelity digital twin models for predictive simulation and operational decision-making.

DT3. The digital twin system maintains continuous bidirectional synchronization between physical assets and their virtual counterparts.

DT4. Digital twin technologies enable rapid identification and prediction of operational disruptions before they occur.

Strategic Supply Chain Resilience (SR)

Adapted from Ivanov et al. (2023); Wieland and Durach (2021).

SR1. Our organization possesses sufficient agility to respond effectively to unexpected supply chain disruptions.

SR2. Our supply chain maintains appropriate structural redundancy to mitigate operational risks.

SR3. Our enterprise can rapidly recover operational capability following major disruptions.

SR4. Our organization can quickly reconfigure supply chain resources when external conditions change.

SR5. Our supply chain maintains stable operational performance under severe environmental uncertainty.

Enterprise Operational Performance (OP)

Adapted from Wamba et al. (2017).

OP1. Our enterprise has improved its overall operational efficiency.

OP2. Our enterprise has achieved higher asset utilization.

OP3. Our enterprise has effectively reduced overall operating costs.

OP4. Our enterprise has improved order fulfillment and service delivery efficiency.

OP5. Overall operational performance has improved compared with major competitors.

Environmental Dynamism (ED)

Adapted from Pettit et al. (2019).

ED1. Customer demand changes rapidly in our industry.

ED2. Technological developments in our industry occur at a rapid pace.

ED3. Competitive actions in our market are highly unpredictable.

ED4. Regulatory policies affecting our industry change frequently.

Measurement Sources

Construct	Number of Items	Source
Digital Twin Technologies	4	Kamble et al. (2022)
Strategic Supply Chain Resilience	5	Ivanov et al. (2023); Wieland & Durach (2021)
Enterprise Operational Performance	5	Wamba et al. (2017)
Environmental Dynamism	4	Pettit et al. (2019)