Resilience Evaluation and Simulation for Green Supply Chains: A Case Study of Customized Furniture Industry Using Hybrid Partial Least Squares Structural Equation Modeling and System Dynamics Methods

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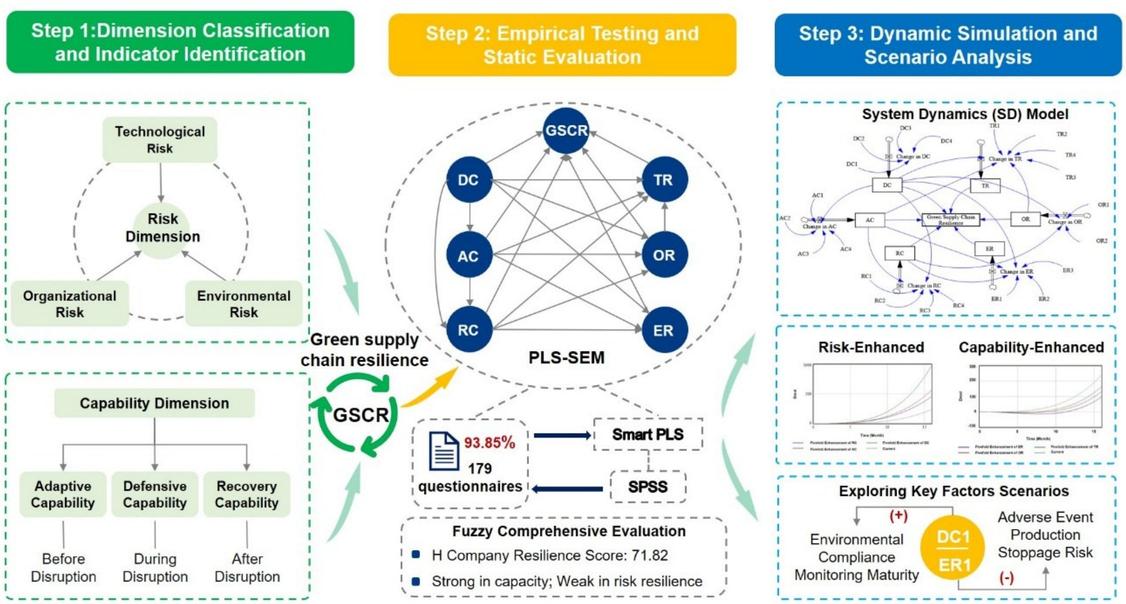
GRAPHICAL ABSTRACT



Resilience Evaluation and Simulation for Green Supply Chains: A Case Study of Customized Furniture Industry Using Hybrid Partial Least Squares Structural Equation Modeling and System Dynamics Methods

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Analytical and simulation models were used to investigate the formation mechanism and enhancement pathways of green supply chain resilience (GSCR) in customized home furnishing enterprises. A mixed-methods research approach was employed, incorporating both quantitative and qualitative data collection. For the qualitative component, anchored in resilience theory and the Technology-Organization-Environment (TOE) framework, a resilience indicator system was developed that integrates both capability and risk factors, proposing 21 mechanistic hypotheses. For the quantitative component, 179 targeted questionnaires were collected, and partial least squares structural equation modeling (PLS-SEM) was applied using SmartPLS software for factor analysis and hypothesis testing. This was followed by a fuzzy comprehensive evaluation of the case enterprise's resilience level. Furthermore, a system dynamics model was constructed to simulate resilience development trends under four distinct scenarios. The results indicate that factors such as environmental compliance monitoring maturity and production disruption risks due to adverse events exert the most significant influence on the GSCR of customized home furnishing enterprises.

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Keywords: Customized home furnishing enterprise supply chain; Green supply chain resilience; Resilience evaluation; PLS-SEM; System dynamics

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INTRODUCTION

As one of the oldest industries, the furniture manufacturing sector contributes significantly to global economic growth, particularly in emerging economies (Cai *et al.* 2022; Sakib *et al.* 2024). The international furniture market demonstrates a steady growth trend, with its scale reaching $490 billion in 2019 and projected to expand to $650.7 billion by 2027 (Zhu *et al.* 2023). However, the environmental impact of the furniture manufacturing industry is concerning. It involves severe pollution, the felling of an average of 15 billion trees annually, contributes 8 to 10% of global greenhouse gas emissions, and results in a staggering ecological footprint (Bianco *et al.* 2021). This underscores the urgent need to drive supply chain transformation. A green furniture supply chain emphasizes the sustainable development of a product throughout its entire lifecycle, covering stages from raw material extraction and processing to manufacturing and recycling. This relies on the support of industry policies and emerging technologies. Customized furniture, which occupies a significant share of the furniture market, primarily uses materials such as wood and bamboo. Their natural, eco-friendly, renewable, and low-carbon emission characteristics (Jungmeier *et al.* 2002; Nambiar 2015) contribute to the industry's sustainable development and help mitigate climate change.

The concept of resilience comes from the ability of an object to recover its original state after deformation. In the early 1970s, ecologist Holling introduced it into the study of system ecology, which pioneered the interdisciplinary application of resilience theory (Ponomarov and Holcomb 2009; Chowdhury and Quaddus 2016). With the depth of interdisciplinary research, it was expanded to many disciplines, such as management and engineering, and evolved into an important analytical framework that emphasizes the dynamic adaptation process of a system rather than the static outcome. Its core is to reveal the adaptive capacity that a system exhibits under perturbation scenarios rather than focusing on the stability characteristics of the system only (Carpenter *et al.* 2001).

In the field of supply chain management, Christopher first introduced the concept of resilience, defining it as the intrinsic property of a system to recover to its original or better state after suffering a disturbance (Christopher and Peck 2004). The green supply chain of customized furniture is particularly vulnerable in practice to various disturbances. These include biophysical disruptions such as pest outbreaks or extreme weather that impede the harvesting of certified timber; market and regulatory shocks such as sharp price fluctuations of key green materials (*e.g.*, low-formaldehyde adhesives) or sudden tightening of environmental export regulations; and operational failures at core technology suppliers, including accidents involving photovoltaic panels or wastewater treatment system providers. Addressing various disruptions requires supply chains to not only possess risk-buffering capabilities but also agile response and recovery mechanisms, which precisely embody the core characteristics of resilience.

According to industry reports, global manufacturing experiences a major supply chain disruption lasting over one month on average every 3.7 years, with a systemic shock comparable to the COVID-19 pandemic occurring approximately every five years (Lund *et al.* 2020). Currently, the custom furniture sector primarily focuses on enhancing flexible production capabilities, with insufficient recognition of supply chain resilience management. This results in a reactive stance when confronting uncertainties such as recurring pandemics, international raw material price fluctuations, and geopolitical conflicts, potentially constraining corporate sustainability (Cohen and Kouvelis 2021). Strengthening supply chain resilience has thus become a pressing necessity. Against the backdrop of global value chain restructuring and escalating geopolitical-climate risks, building supply chains that are both resilient and sustainable has become a core strategic priority for the manufacturing sector (Zhao *et al.* 2023).

However, the root causes and focal points of resilience challenges vary systematically across different manufacturing models. For bulk material processing industries, represented by chromium, pulp, and paper, the challenges are primarily upstream-oriented and scale-driven (Xiang *et al.* 2025; Del Rio *et al.* 2022). In contrast, for complex assembly industries, exemplified by automotive manufacturing, the challenges stem from collaborative complexity, with resilience strategies focusing on managing cascading disruption risks within globalized, multi-tier supplier networks (Jum'a *et al.* 2024). The customized furniture industry faces intricate and unique green supply chain resilience (GSCR) challenges. It must simultaneously address material-criticality risks akin to those in bulk industries, operational agility requirements similar to those in assembly industries, and its own distinct challenge of communicating lifecycle green value in personalized products (Xiong *et al.* 2017; Arabi *et al.* 2023).

Despite these pressing challenges, academic attention to the strategic level of green supply chain resilience in the custom furniture industry remains insufficient. Existing research largely fails to systematically integrate capacity-building with risk control mechanisms, and lacks theoretical frameworks and practical solutions that directly support the achievement of sustainable development goals. Therefore, establishing an assessment system for the resilience of green supply chains in the custom furniture sector requires transcending traditional single-dimensional approaches. It demands a holistic lifecycle perspective that integrates capacity enhancement (*e.g.*, carbon footprint tracking, renewable energy utilization) with risk prevention (*e.g.*, ecological material quality, policy compliance), while incorporating key concepts such as flexibility, maturity, and policy volatility (Jüttner and Maklan 2011; Singh *et al.* 2019; Pettit *et al.* 2013).

Although the conceptual definition of supply chain resilience has not been unified in academia, a systematic research paradigm has emerged, focusing on its measurement through influencing factors, dynamic modeling (Qi *et al.* 2022), and decision optimization (Majumdar *et al.* 2021). However, extant studies often lack integration between static assessment and dynamic simulation, particularly within the context of green supply chains. This gap motivates the present study, which aims to develop a hybrid assessment framework that quantifies resilience levels statically and projects their evolution dynamically, thereby offering more actionable insights for the customized furniture industry.

The Technology-Organization-Environment (TOE) framework, which was originally proposed by Tornatzky and Fleischer as a model for analyzing technology adoption drivers, has since evolved into a comprehensive analytical tool incorporating organizational and environmental dimensions (Awa *et al.* 2016; Ullah *et al.* 2021). Technological factors, such as infrastructure readiness, perceived comparative advantages, and security concerns are critical to this framework, while organizational factors typically include structural characteristics, firm size, and partnership dynamics (Chatterjee *et al.* 2021; Chittipaka *et al.* 2023). Environmental influences further encompass policy support mechanisms, industry competition pressures, and market volatility (Awa *et al.* 2016). Recent applications in supply chain management demonstrate the framework's versatility, evidenced by its use in studies ranging from blockchain adoption to multi-level risk mitigation strategies (Ullah *et al.* 2021; Chittipaka *et al.* 2023). Despite its broad utility, a significant gap persists in adapting the TOE framework to industry-specific contexts. This limitation is particularly pronounced in the customized home furnishing sector, where conventional TOE analyses often overlook unique challenges, such as production system flexibility demands, nonlinear material flow dependencies, and demand-side uncertainty, factors that fundamentally reshape traditional resilience paradigms.

To overcome the limitations of static assessments and capture the dynamic interactions among factors within the TOE framework, this study introduces a system dynamics approach. System Dynamics (SD) is a mathematical modeling approach pioneered by Professor Forrester at the Massachusetts Institute of Technology in 1956, designed to analyze and address complex time-evolving systems (Ma *et al.* 2021). Through constructing feedback loops and dynamic equations, SD effectively captures nonlinear interactions among system components (Sun *et al.* 2020). Its dynamic simulation capabilities are particularly well-suited for evaluating the evolution of supply chain resilience under various scenarios (Ma *et al.* 2021). However, existing research has paid limited attention to supply chain resilience in customized home furnishing enterprises. Despite the growing interest in supply chain resilience, the authors' systematic review of the literature found no qualitative studies that specifically address resilience enhancement strategies in the context of customized furniture supply chains under disruptions. There remains a lack of empirical case studies incorporating industry-specific data and quantitative system dynamics analysis tailored to this sector.

This study conducted an empirical analysis of Company H to systematically assess and enhance green supply chain resilience in customized furniture manufacturing. Building on resilience theory and the TOE framework, a six-dimensional evaluation system based on 21 measured indicators was developed. The methodology combined PLS-SEM for causal analysis with fuzzy comprehensive evaluation to quantify resilience levels, supplemented by system dynamics simulations to model future scenarios. The scenario analyses of capacity-building and risk-mitigation factors yielded predictive insights into resilience dynamics, along with tailored improvement strategies. The research provides both a novel analytical framework and practical management tools specifically designed for customized furniture supply chains.

EXPERIMENTAL

Research Design and Data Collection

Research subjects

This study focuses on the custom panel furniture sector, a segment that holds a significant and steadily growing share within the furniture market. Typical products include custom wardrobes, bookcases, and kitchen cabinets. Engineered wood panels serve as the primary structural material for such furniture due to their stability, cost-effectiveness, and compliance with environmental certification requirements. Surface treatments predominantly utilized low-volatile organic carbon (VOC) decorative laminates or coatings. Responding to industry sustainability demands, this study also examined the application trend of bamboo-based composites as alternative green materials. It is important to note that green furniture in this research does not exclusively refer to products made entirely from plant-based materials. Its green attributes reflect supply chain characteristics, emphasizing sustainable practices throughout the product lifecycle.

The custom furniture supply chain is an integrated system that prioritizes customer personalization as its value proposition. This system encompasses not only the physical lifecycle from raw material procurement to recycling, but more crucially, it transforms the traditional linear chain into a dynamically responsive value co-creation network. This is achieved through customer involvement in the design phase and flexible collaboration between manufacturers and suppliers. The customized furniture green supply chain model proposed in this study (Fig. 1) highlights key risk challenges affecting system resilience at each stage. Due to the limited availability of alternative suppliers meeting green certification standards, environmental violations by raw material suppliers may cause production disruptions. Addressing pollution incidents requires substantial emergency funds and management resources, thereby weakening the enterprise's long-term development potential and resilience to disturbances. Unreasonable packaging severely hampers product recycling efficiency, impedes the effective operation of closed-loop circular economy systems, and undermines overall sustainability. Distributors and retailers, serving as inventory buffers and customer touchpoints, play a critical role in the supply chain's overall green resilience through their ability to adapt to evolving environmental regulations and effectively communicate green product information.

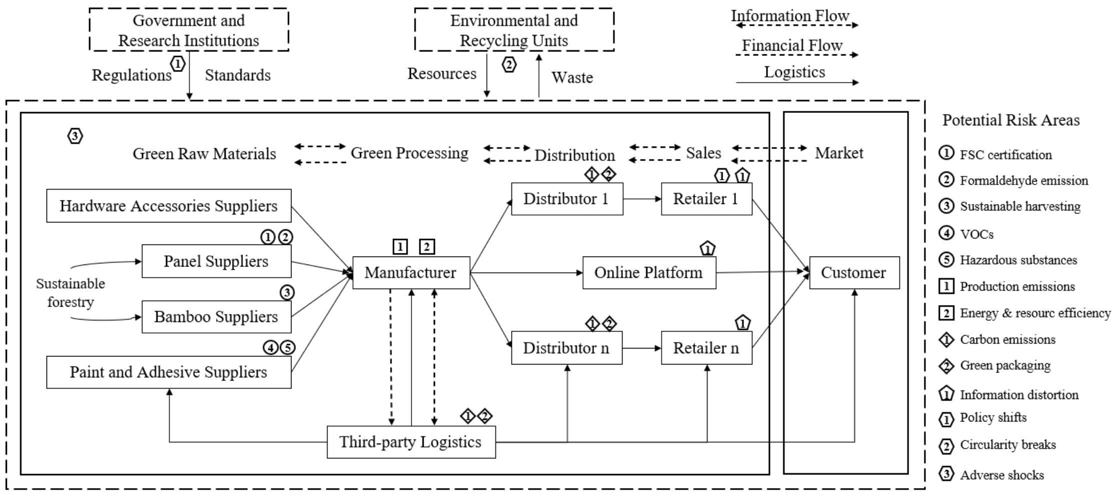

Fig. 1. Supply chain structure of customized home furnishing enterprises

Data sources and case background

Enterprise H is a representative listed company in China's customized home furnishing industry, focusing on the R&D and production of whole-house customized products, with intelligent production bases in South China and East China. The company and has built a marketing network covering distributors, directly-managed stores, and e-commerce platforms. Based on field research, the company's supply chain consists of upstream raw material suppliers, midstream design service providers, outsourced processing plants, H enterprises, and downstream distributor networks and end consumers (Fig. 2). In recent years, its supply chain has faced significant challenges: the supply side is subject to import dependence on key raw materials and supplier concentration risks, while the market side is under the dual pressure of raw material price volatility and declining industry margins.

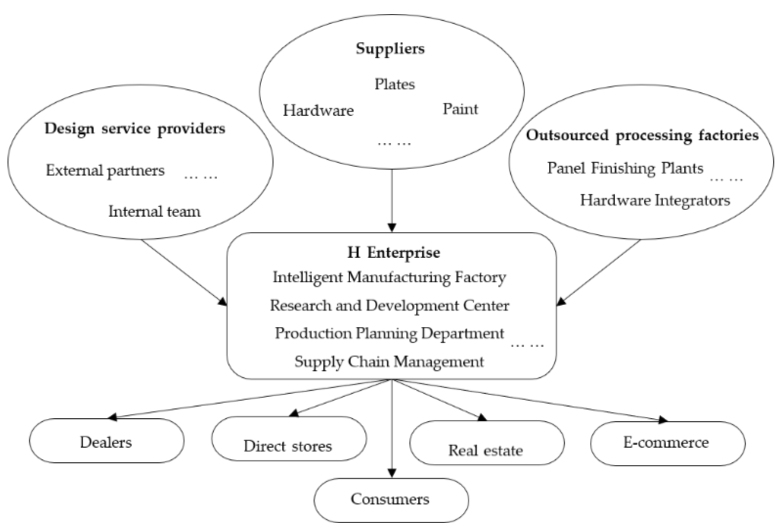

Fig. 2. Supply chain model of H customized furniture enterprise

Green Supply Chain Resilience Evaluation Framework

Supply chain resilience is the property of a system to resist internal and external perturbations, adapt to disruptions, and recover to the original state or reach a new stable state in a dynamic environment. Based on the resilience theory and the dynamic capability theory, this study classifies the green supply chain capability of customized home furnishing enterprises into defensive capability (DC), adaptive capability (AC), and recovery capability (RC), which correspond to vulnerability before disturbance, real-time adjustment during disturbance, and performance restoration after disturbance, respectively (Raubenheimer and Conradie 2002; Jüttner and Maklan 2011; Macdonald *et al.* 2018). Based on the TOE theoretical framework and the characteristics of the customized home furnishing industry, this study identifies the key risk influencing elements from the three dimensions of technological risk (TR), organizational risk (OR), and environmental risk (ER).

Following the principles of science, feasibility, and comprehensiveness, an indicator system of green supply chain resilience factors for customized home furnishing enterprises was constructed, including 6 dimensions and 21 indicators (Christopher and Peck 2004; Erol *et al.* 2010; Fan and Stevenson 2018; Bartolini *et al.* 2019; Han *et al.* 2020; Tukamuhabwa *et al.* 2015). The complete framework is presented in Table 1.

Table 1. Green Supply Chain Resilience Influencing Factors Indicator System

Perspectives	Dimension	Indicators
Capabilities	DC	Environmental Compliance Monitoring Maturity (DC1)
		Green Material Stock Reliability (DC2)
		Renewable Energy Backup Readiness (DC3)
		Carbon Footprint Traceability Clarity (DC4)
	AC	Low-carbon Logistics Adaptability (AC1)
		Clean Supplier Geographic Diversity (AC2)
		Cleaner Production Flexibility (AC3)
		Green Partner Collaboration Level (AC4)
	RC	Technology Improvement Capital Reserve (RC1)
		Waste Recycling Contingency Preparedness (RC2)
		Clean Production Knowledge Accessibility (RC3)
		Resource Recycling Mechanism Maturity (RC4)
Risk	TR	Information Security Exposure (TR1)
		Green Technology Readiness Gap (TR2)
		ESG Talent Shortage (TR3)
		Eco-material Quality Risk (TR4)
	OR	Clean Energy Access Constraints (OR1)
		Green Financing Gap Severity (OR2)
	ER	Adverse Event Production Stoppage Risk (ER1)
		Carbon Tariff Policy Volatility (ER2)
		Green Demand Shift (ER3)

Adhering to the exploratory principle, 21 path hypotheses were proposed based on the index system of green supply chain resilience influencing factors of customized home furnishing enterprises, from the driving mechanism of capability dimension (H1 to H6), the inhibiting mechanism of risk dimension (H7 to H12), and the regulating mechanism of capability to risk (H13 to H21); refer to Table 2 for more information.

Table 2. Summary of Research Hypotheses

Hypotheses	Conceptual Relationship	Statistical Expectation
H1	Defensive capability → Green Supply Chains resilience	$\beta 1 > 0$, $p < 0.05$
H2	Adaptive capability → Green Supply Chains resilience	$\beta 2 > 0$, $p < 0.05$
H3	Recovery capability → Green Supply Chains resilience	$\beta 3 > 0$, $p < 0.05$
H4	Defensive capability → Adaptive capability	$\beta 4 > 0$, $p < 0.05$
H5	Defensive capability → Recovery capability	$\beta 5 > 0$, $p < 0.05$
H6	Adaptive capability → Recovery capability	$\beta 6 > 0$, $p < 0.05$
H7	Technological risk → Green Supply Chains resilience	$\beta 7 < 0$, $p < 0.05$
H8	Organizational risk → Green Supply Chains resilience	$\beta 8 < 0$, $p < 0.05$
H9	Environmental risk → Green Supply Chains resilience	$\beta 9 < 0$, $p < 0.05$
H10	Environmental risk → Technological risk	$\beta 10 > 0$, $p < 0.05$
H11	Environmental risk → Organizational risk	$\beta 11 > 0$, $p < 0.05$
H12	Organizational risk → Technological risk	$\beta 12 > 0$, $p < 0.05$
H13	Defensive capability → Technological risk	$\beta 13 < 0$, $p < 0.05$
H14	Defensive capability → Organizational risk	$\beta 14< 0$, $p < 0.05$
H15	Defensive capability → Environmental risk	$\beta 15 < 0$, $p < 0.05$
H16	Adaptive capability → Technological risk	$\beta 16 < 0$, $p < 0.05$
H17	Adaptive capability → Organizational risk	$\beta 17 < 0$, $p < 0.05$
H18	Adaptive capability → Environmental risk	$\beta 18 < 0$, $p < 0.05$
H19	Recovery capability → Technological risk	$\beta 19 < 0$, $p < 0.05$
H20	Recovery capability → Organizational risk	$\beta 20 < 0$, $p < 0.05$
H21	Recovery capability → Environmental risk	$\beta 21 < 0$, $p < 0.05$

Table 3. Descriptive Statistics of Respondent Demographics

Category	Options	Count	Percentage
Position	Senior Management	16	9.52%
	Middle Management	32	19.05%
	Junior Staff	120	71.43%
Company Size	Small Enterprise (<50 employees)	27	16.07%
	Medium Enterprise (50-300 employees)	95	56.55%
	Large Enterprise (>300 employees)	46	27.38%
Work Experience (Years)	Less than 1 year	54	32.14%
	1-5 years	68	40.48%
	6-10 years	33	19.64%
	More than 10 years	13	7.74%
Education Level	Master's degree or above	26	15.48%
	Bachelor's degree	107	63.69%
	Associate degree or below	35	20.83%

Data collection was conducted online using purposive sampling, targeting professionals in the wooden and bamboo custom furniture sector. A total of 200 five-point Likert-scale questionnaires on green supply chain resilience factors were distributed, with 179 valid responses collected. After excluding incomplete or contradictory information, 168 valid questionnaires were retained, achieving a response rate of 93.85%. The final sample size exceeded the minimum threshold required for robust Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis (Hair *et al.* 2019). Respondent demographics, including job title, company size, work experience, and education level, are presented in Table 3. These characteristics indicate that the sample adequately represents key industry stakeholders, thereby supporting the external validity of the findings.

Descriptive statistics, along with reliability and validity tests were conducted using SPSS software to ensure data quality. Subsequently, PLS-SEM model construction and evaluation were performed in SmartPLS. Ultimately, non-significant paths (ER→TR; ER →OR; AC→OR; RC→TR) were removed, resulting in the revised mechanism model for green supply chain resilience in customized furniture (Fig. 3).

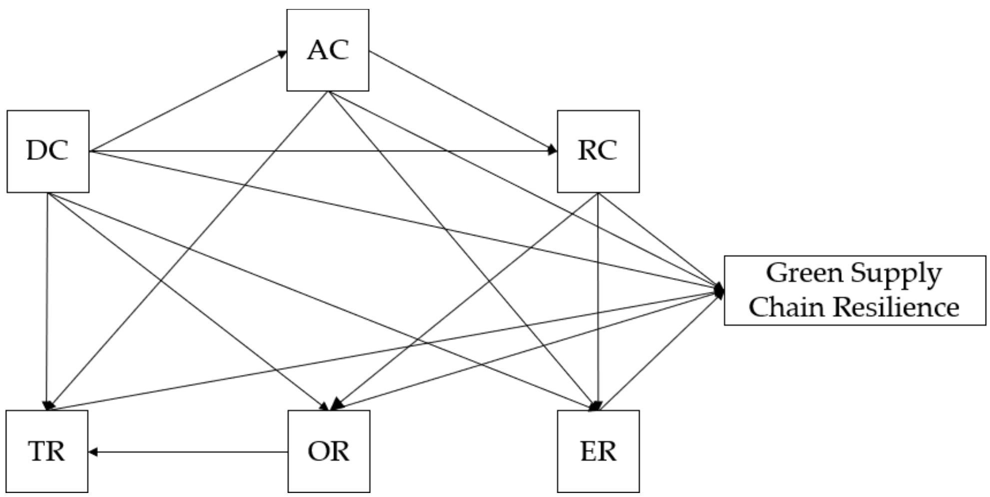

Fig. 3. Green supply chain resilience mechanism model

Weight and Effect Calculation Based on PLS-SEM Results

The relative contribution (weight) of each significant observed variable to its corresponding latent construct was determined based on the standardized factor loadings from the validated PLS-SEM measurement model. To obtain the relative weights within each construct, these loadings were normalized using the Eq. 1,

$$W_i = \frac{F_i}{\sum_{i=1}^{n} F_i} \quad (1)$$

where W_i is the weight coefficients of variables and F_i is the normalized path coefficients or normalized factor loadings.

The calculated weights for all indicators are presented in Table 4 and were used as the factor weights in the subsequent fuzzy comprehensive evaluation. The calculation results are shown in Table 4. Furthermore, the analysis of the PLS-SEM structural model yielded the total effects of each green supply chain resilience dimension on the target variable. The decomposition of effects into direct and indirect components is summarized in Table 5.

Table 4. Normalized Weights for Fuzzy Evaluation Derived from PLS-SEM

Dimension	Direct Effect	Measurement Indicator	Factor Loading	Normalized Weight
DC	0.208	DC1	0.932	0.269
		DC2	0.898	0.259
		DC3	0.787	0.227
		DC4	0.850	0.245
AC	0.219	AC1	0.888	0.250
		AC2	0.883	0.249
		AC3	0.891	0.251
		AC4	0.887	0.250
RC	0.204	RC1	0.884	0.252
		RC2	0.882	0.251
		RC3	0.867	0.247
		RC4	0.877	0.250
TR	-0.181	TR1	0.834	0.245
		TR2	0.859	0.252
		TR3	0.865	0.255
		TR4	0.845	0.248
OR	-0.089	OR1	0.926	0.512
		OR2	0.882	0.488
ER	-0.151	ER1	0.893	0.337
		ER2	0.870	0.329
		ER3	0.884	0.334

Table 5. Total Effect and Path Decomposition of Resilience Dimensions

Dimension	Mediated Path	Indirect Effect	Total Effect	Normalized Weight
DC	DC→AC→AHSCR	0.202	0.654	0.351
	DC→RC→AHSCR	0.084		
	DC→TR→AHSCR	0.080		
	DC→OR→AHSCR	0.028		
	DC→ER→AHSCR	0.052		
AC	AC→RC→AHSCR	0.113	0.481	0.258
	AC→TR→AHSCR	0.077		
	AC→ER→AHSCR	0.071		
RC	RC→OR→AHSCR	0.024	0.274	0.147
	RC→ER→AHSCR	0.047		
TR	-	-	-0.122	0.065
OR	OR→TR→AHSCR	-0.033	-0.181	0.097
ER	-	-	-0.151	0.082

Fuzzy Evaluation of Green Resilience Indicators

This study establishes a fuzzy comprehensive evaluation framework to quantify the level of green supply chain resilience of customized home furnishing enterprises, combining with the affiliation function ground to transform qualitative indicators into quantitative measures. Based on the established supply chain resilience indicator system, the first step is to define the first-level evaluation dimensions as the main factor set (U_1 to U_6). Then each dimension is decomposed into specific second-level measurements to construct hierarchical subfactor sets.

The assessment framework employed a five-level linguistic evaluation set V = (fully met, better met, basically met, partially not met, and seriously not met), with corresponding numerical scores V = (100, 80, 60, 40, and 20) for quantitative analysis. Through expert scoring, the degree of affiliation was determined for each indicator and constructed six fuzzy evaluation matrices (R_1 to R_6). These matrices were processed through the comprehensive evaluation model $B = W \times R$, where W represents the weight vector derived from PLS-SEM analysis. The final resilience score F was calculated as $F = B \times V^T$, which allows for a standardized evaluation of the case companies.

The PLS-SEM-based indicator system identifies six core dimensions of green supply chain resilience for customized home furnishing enterprises: U = (AC, RC, TR, OR, ER), with respective weights W = (0.351, 0.258, 0.147, 0.065, 0.097, 0.082). Each dimension contains specific measurable elements:

DC (U_1 = (DC1, DC2, DC3, DC4), W_1 = (0.269, 0.259, 0.227, 0.245));
AC (U_2 = (AC, AC2, AC3, AC4), W_2 = (0.250, 0.249, 0.251, 0.250));
RC (U_3 = (RC1, RC2, RC3, RC4), W_3 = (0.252,0.251,0.247,0.250);
TR (U_4 = (TR1, TR2, TR3, TR4), W_4 = (0.245, 0.252, 0.255, 0.248));
OR (U_5 = (OR1, OR2), W_5 = (0.512, 0.488));
ER (U_6 = (ER1, ER2, ER3), W_6 = (0.337, 0.329, 0.334)).

System Dynamics (SD) Simulation

Model construction

The supply chain resilience system of customized home furnishing enterprises comprised six interconnected subsystems—defensive capability, adaptive capability, recovery capability, technological risk, organizational risk, and environmental risk—collectively forming a complex adaptive system. Based on the system's theoretical framework and structural characteristics, this study established fundamental modeling assumptions: statistically validated internal elements sufficiently characterize resilience dynamics, while external boundary effects exhibited negligible influence. To balance mathematical robustness with industrial relevance, the model retained only statistically significant pathways ($p < 0.05$). Through analyzing causal feedback mechanisms among key variables, a system dynamics model was constructed using Vensim PLE software, featuring 7 state variables, 6 rate variables, and 21 auxiliary variables (Fig. 4).

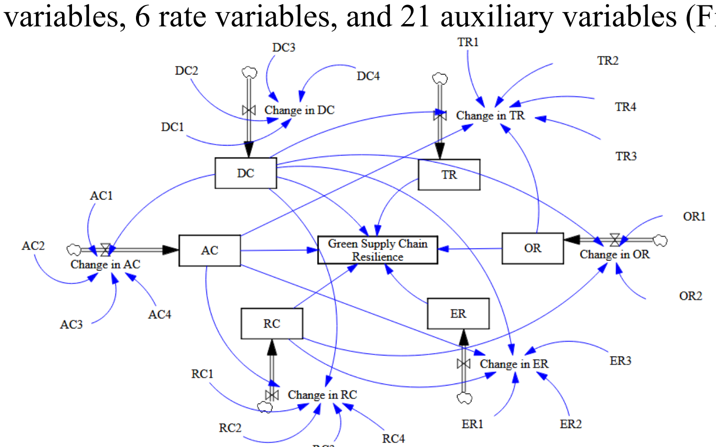

Fig. 4. Green supply chain resilience mechanism model

Parameter configuration

The key equation structure and parameters of the system dynamics model were directly derived from the PLS-SEM empirical analysis and fuzzy comprehensive evaluation results, ensuring consistency between the simulation model and the static analysis. To maintain computational consistency within the model and facilitate cross-variable comparisons, all variables were uniformly defined in dimensionless units (Dmnl). The equations explicitly retain positive and negative signs to accurately reflect promoting or inhibiting causal relationships between variables. Based on the above principles, examples of the main system dynamics equations constructed were as follows:

DC = INTEG (Change in DC, Initial DC)

Change in DC = 0.269*DC1 + 0.259*DC2 + 0.227*DC3 + 0.245*DC4

AC = INTEG (Change in AC, Initial AC)

Change in AC = 0.206*DC + 0.794* (0.250*AC1 + 0.249*AC2 + 0.251*AC3 + 0.250*AC4)

RC = INTEG (Change in RC, Initial RC)

Change in RC = 0.092*DC + 0.124*AC + 0.784* (0.252*RC1 + 0.251*RC2 + 0.247*RC3 + 0.250*RC4)

TR = INTEG (Change in TR, Initial TR)

Change in TR = 0.764* (0.245*TR1 + 0.252*TR2 + 0.254*TR3 + 0.248*TR4) + 0.041*OR – 0.099*DC – 0.096*AC

OR = INTEG (Change in OR, Initial OR)

Change in OR = 0.755* (0.512*OR1 + 0.488*OR2) – 0.134*DC – 0.111*RC

ER = INTEG (Change in ER, Initial ER)

Change in ER = 0.701* (0.337*ER1 + 0.328*ER2 + 0.335*ER3) – 0.091*DC – 0.126*AC – 0.082*RC

Green supply chain resilience = 0.351*DC + 0.258*AC + 0.147*RC – 0.065*TR – 0.097*OR – 0.082*ER

RESULTS AND DISCUSSION

Resilience Evaluation of H Enterprise's Green Supply Chain

To ensure the authority and reliability of the assessment, this study employed purposive sampling when forming the expert panel. This approach selected evaluators possessing over five years of research or practical experience in furniture manufacturing, supply chain management, or sustainability, alongside in-depth knowledge of the bespoke furniture sector. Ultimately, eight experts were invited to assess Company H's green supply chain resilience. This cohort comprised six supply chain management specialists from the furniture industry and two academics engaged in related research. Prior to the formal assessment, all experts were provided with the background to the present research, an explanation of the indicator system, and detailed scoring guidelines. In the questionnaire design, to avoid the understanding bias caused by negative indicators, the risk dimension indicators were described in reverse.

According to the results of expert scoring, the fuzzy judgment matrix for each dimension of Enterprise H was derived as follows:

Fuzzy judgment matrix R_1 for the DC:

$$R_1 = \begin{pmatrix} 0.375 & 0.375 & 0.250 & 0.000 & 0.000 \\ 0.500 & 0.375 & 0.125 & 0.000 & 0.000 \\ 0.125 & 0.500 & 0.250 & 0.125 & 0.000 \\ 0.250 & 0.500 & 0.250 & 0.000 & 0.000 \end{pmatrix}$$

Fuzzy judgment matrix R_2 for the AC:

$$R_2 = \begin{pmatrix} 0.375 & 0.500 & 0.125 & 0.000 & 0.000 \\ 0.125 & 0.375 & 0.375 & 0.125 & 0.000 \\ 0.250 & 0.500 & 0.125 & 0.125 & 0.000 \\ 0.250 & 0.625 & 0.125 & 0.000 & 0.000 \end{pmatrix}$$

Fuzzy judgment matrix R_3 for the RC:

$$R_3 = \begin{pmatrix} 0.500 & 0.250 & 0.250 & 0.000 & 0.000 \\ 0.250 & 0.500 & 0.125 & 0.125 & 0.000 \\ 0.250 & 0.375 & 0.250 & 0.125 & 0.000 \\ 0.125 & 0.250 & 0.500 & 0.125 & 0.000 \end{pmatrix}$$

Fuzzy judgment matrix R_4 for the TR:

$$R_4 = \begin{pmatrix} 0.000 & 0.250 & 0.500 & 0.250 & 0.000 \\ 0.000 & 0.125 & 0.625 & 0.250 & 0.000 \\ 0.000 & 0.250 & 0.500 & 0.250 & 0.000 \\ 0.000 & 0.125 & 0.500 & 0.375 & 0.000 \end{pmatrix}$$

Fuzzy judgment matrix R_5 for the OR:

$$R_5 = \begin{pmatrix} 0.000 & 0.125 & 0.375 & 0.250 & 0.125 \\ 0.000 & 0.125 & 0.500 & 0.375 & 0.000 \end{pmatrix}$$

Fuzzy judgment matrix R_6 for the ER:

$$R_6 = \begin{pmatrix} 0.000 & 0.125 & 0.375 & 0.375 & 0.125 \\ 0.000 & 0.000 & 0.500 & 0.500 & 0.250 \\ 0.000 & 0.125 & 0.250 & 0.500 & 0.125 \end{pmatrix}$$

Since the weight vector $W_1 = (0.269, 0.259, 0.227, 0.245)$, $B_1 = W_1 \times R_1 = (0.320, 0.435, 0.217, 0.028, 0.000)$. Combined with $V = (100, 80, 60, 40, 20)$, it can be seen that $F_1 = B_1 \times V^T = 80.9$. Similar calculations were carried out in order to obtain $F_2 = B_2 \times V^T = 78.5$; $F_3 = B_3 \times V^T = 73.4$; $F_4 = B_4 \times V^T = 58.2$; $F_5 = B_5 \times V^T = 49.9$; $F_6 = B_6 \times V^T = 45.8$; $F(\text{total}) = B(\text{total}) \times V^T = 71.82$.

The evaluation results showed that Enterprise H's green supply chain resilience had a comprehensive score of 71.82, indicating that its overall resilience level was basically compliant, which is in line with its status as a leading enterprise in green practices in the industry. The results also verified the applicability of the evaluation system. Specifically, the resilience level of Enterprise H's capability dimension was relatively good. The readiness capability was more prominent, which is mainly attributed to the enterprise's continuous investment in the construction of an intelligent warehousing system and the layout of a regionalized logistics network. However, the score of the risk management dimension was relatively low, especially the environmental risk realized as a key shortcoming that restricts sustainable development. This characterization of strong operations and weak risk resistance suggests that, despite its strengths in supply chain capacity building, Enterprise H is in dire need of systematically strengthening its risk resilience to ensure sound long-term development.

Scenario-based Simulation

Historical data test

After the system dynamics model had undergone logic testing and quantitative consistency validation, Vensim software was employed to conduct dynamic simulations of green supply chain resilience. The scores obtained from the fuzzy comprehensive evaluation for each dimension were set as the initial values for the state variables to ensure that the simulation commenced from the current resilience level of the case enterprise. The simulation results of Vensim software showed that the resilience level had a slow and then fast exponential growth trend (Fig. 5) within the 16-month simulation cycle, which was consistent with the performance of the actual program of Enterprise H. In the early stage, the growth was slow due to the coordination of multiple factors such as design and market fluctuation, material supply, and production cost. Design changes, market fluctuations, material supply and production costs, and other factors led to a slow toughness growth at the beginning. With the program determined and production implementation, the supply chain stability was enhanced, and the toughness level accelerated, which verified the effectiveness of the model.

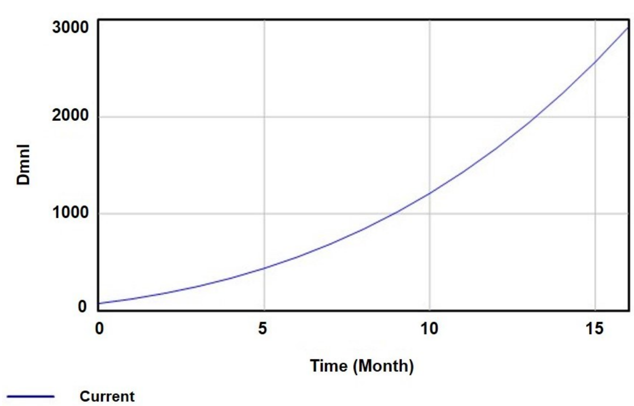

Fig. 5. Green simulation of supply chain resilience development trends

Scenario setting and results analysis

(1) Scenario 1: Capability Enhancement

In this scenario, the initial values of the factors DC, AC, and RC were increased by a factor of five, and the results were analyzed in comparison with the original state (current), as shown in Fig. 6.

The simulation trend under this scenario shows that the enhancement of readiness, responsiveness, and resilience all were able to promote the growth of resilience, with decreasing degrees of influence. The toughness evolution presented the characteristics of stabilization in the early stage, steady growth in the middle stage, and accelerated enhancement in the late stage, in which the positive effect of readiness capability was the most significant.

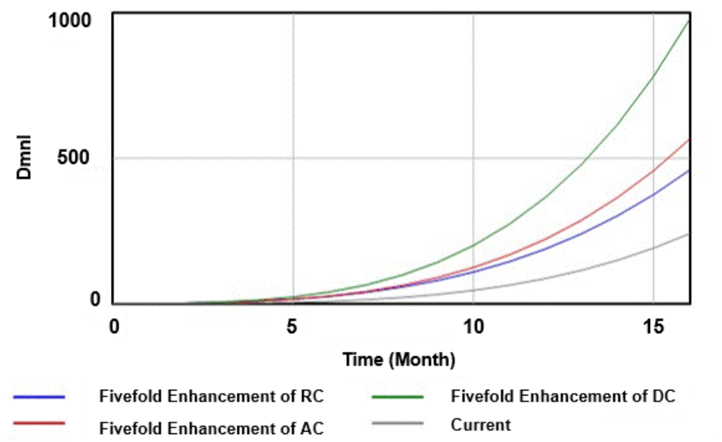

Fig. 6. Comparison of green supply chain resilience under the capacity-enhancing scenario

(2) Scenario 2: Critical Capability Exploratory

To explore the impact of capability factors on resilience, the simulation experiment elevated the initial values of key factors to ten times the baseline level. Results indicated (as shown in Figure 7) that under the capability enhancement scenario, environmental compliance monitoring maturity contributed most significantly to resilience improvement, followed by green material inventory reliability, carbon footprint traceability clarity, and renewable energy backup readiness.

The simulation results described above further confirmed, from a dynamic evolution perspective, that the complex equilibrium between achieving supply chain sustainability goals and operational economic viability was profoundly shaping its resilience structure within the current ESG-driven regulatory and market environment (Mirzaee *et al.* 2024). Within the context of green supply chains, macro-environmental regulations do not merely constitute constraints. Rather, they drive custom home furnishing enterprises to establish and refine management systems centered on carbon reduction, thereby achieving a structural enhancement of supply chain resilience.

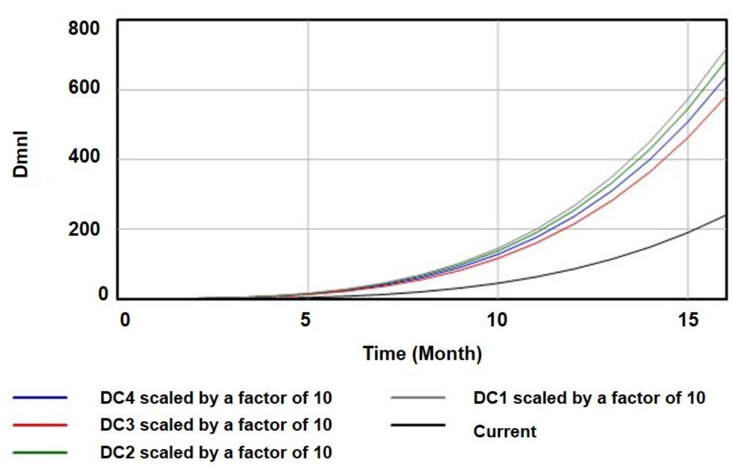

Fig. 7. Comparison of toughness under the key capability exploratory scenario

(3) Scenario 3: Risk-enhanced

In this scenario, the initial values of the factors affecting TR, OR, and ER were enhanced by 5 times, and compared with the original state (current), and the results are shown in Fig. 8.

The simulation trend under this scenario shows that all three types of risks weakened the resilience level. However, the observed recovery pattern aligns with complex adaptive system theory; in the long-term trend, the green supply chain resilience level can eventually recover or even exceed the initial state. The level of impact of each dimension of risk was in the order of environmental, organizational, and technological risk.

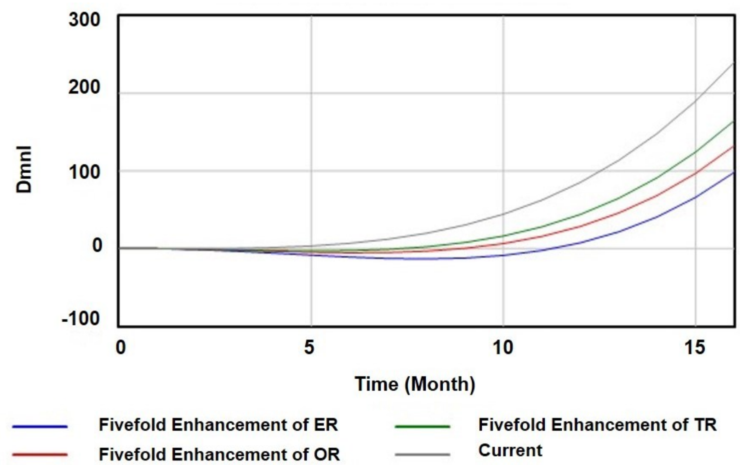

Fig. 8. Comparison of resilience under the risk-enhanced scenario

(4) Scenario IV: Critical Risk Exploratory

Three key environmental risk factors were simulated at ten times their baseline levels (Fig. 9). Results indicate that under heightened environmental risk scenarios, different risk types exert markedly divergent impacts on supply chain resilience. Among these, production shutdown risks triggered by extreme unforeseen events proved most devastating to resilience, exerting greater influence than shifts in green demand or carbon tariff policy volatility.

This key finding reveals that the vulnerability of make-to-order supply chains is rooted in their operational model, reflecting the low inventory levels and high dependence on production continuity characteristic of the custom furniture industry (Xiong *et al.* 2020). Production disruptions trigger value chain ruptures and generate multiple cascading consequences, a phenomenon prevalent across broader manufacturing sectors. For instance, in the chromium supply chain, which is highly sensitive to external raw materials, widening supply-demand gaps may further impact pricing, production capacity, capacity utilization, and demand, thereby drastically undermining overall resilience.

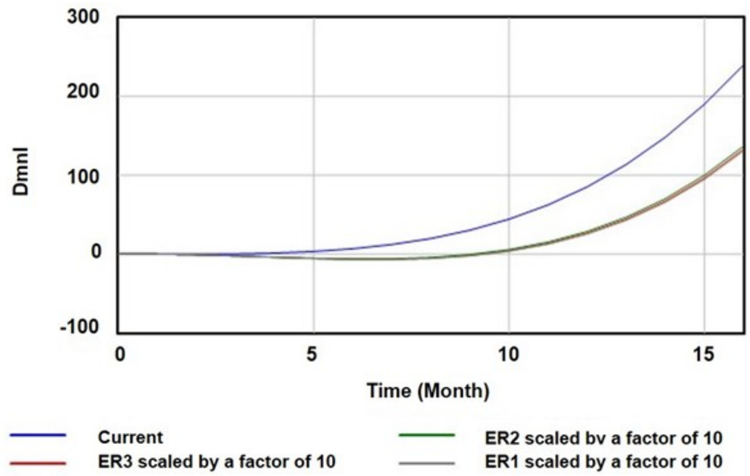

Fig. 9. Comparison of resilience under the key risk-exploratory scenario

Limitations and Future Prospects of Simulation Research

The system dynamics model in this study treated external factors such as carbon tariff policy volatility and shifts in green market demand as static or unidirectional inputs. This simplification failed to capture the bidirectional dynamic feedback between macro-environmental factors and enhanced corporate supply chain resilience, limiting the model's ability to explore long-term environment-system interactions under evolving external conditions. Future research may employ hybrid simulation methods to model the interactions among policy signal transmission, market preference evolution, and corporate resilience investment decisions. Such approaches will more realistically depict the emergence and co-evolution of supply chain resilience under external shocks.

CONCLUSIONS

1. This study focused on identifying the core factors that enhance the resilience of green supply chains in customized furniture enterprises. An evaluation index system was constructed from the dual perspectives of capability enhancement and risk prevention, with data collected through targeted questionnaires. Through integrating resilience theory and the Technology-Organization-Environment (TOE) framework for qualitative analysis, six key dimensions and 21 evaluation indicators were identified. Combining existing literature and industry practices, a theoretical model comprising 21 resilience mechanism hypotheses was ultimately developed.
2. Further system dynamics simulations under multiple scenarios revealed the following trends in resilience evolution: (1) In capability-enhancement scenarios, supply chain resilience showed a monotonically increasing trend, with preparedness capability exerting the strongest positive effect, followed by response and recovery capabilities. Environmental compliance monitoring maturity contributed the most to resilience improvement. (2) In risk-escalation scenarios, resilience initially stagnated, and then it declined rapidly in the medium term before slowly recovering. Environmental risk demonstrated the most severe negative impact, followed by organizational and technological risks, with adverse event production stoppage risk emerging as the most detrimental factor.

3. Based on these findings, strategic recommendations for manufacturers include: (a) developing a digital control platform for supply chain resilience and establishing dynamic capability cultivation mechanisms; and (b) optimizing supply chain operations through financial policy innovation and supplier management to enhance cost efficiency. These strategies provide both theoretical foundations and practical guidance for customized furniture enterprises to strengthen green supply chain resilience.
4. Practically, the research has delivered actionable strategies for home furnishing enterprises to align supply chain optimization with sustainable development objectives, effectively balancing waste reduction, risk mitigation and sustainability targets. The proposed framework shows particular relevance for resource-intensive industries; cross-sector applications ranging from textile waste upcycling in apparel to e-waste hub integration in electronics illustrate its potential to simultaneously resolve material deficits and circular economy challenges, offering tangible sustainable development goals implementation pathways.
5. Through comparison and discussion with existing literature, the findings of this study have not only been partially validated in other contexts but also reveal the unique resilience mechanisms of custom furniture green supply chains under the dual constraints of personalization and environmental sustainability. This provides contextualized supplementation and deepening to relevant theories.

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REFERENCES CITED

Arabi, A., Tajdini, A., Pourmousa, S., Imani, M. N., and Lashgari, A. (2023). "Sustainable supply chain management and performance in Iran's wooden furniture industry," *Wood Material Science & Engineering* 18(4), 1192-1201. https://doi.org/10.1080/17480272.2022.2116995

Awa, H. O., Ukoha, O., and Emecheta, B. C. (2016). "Using TOE theoretical framework to study the adoption of ERP solution," *Cogent Business & Management* 3(1), article 1196571. https://doi.org/10.1080/23311975.2016.1196571

Bartolini, M., Bottani, E., and Grosse, E. H. (2019). "Green warehousing: Systematic literature review and bibliometric analysis," *Journal of Cleaner Production* 226, 242-258. https://doi.org/10.1016/j.jclepro.2019.04.055

Bianco, I., Thiébat, F., Carbonaro, C., Pagliolico, S., Blengini, G. A., and Comino, E. (2021). "Life Cycle Assessment (LCA)-based tools for the eco-design of wooden furniture," *Journal of Cleaner Production* 324, article 129249. https://doi.org/10.1016/j.jclepro.2021.129249

Cai, Y., Zhu, H., Chen, Z., and Geng, Y. (2022). "Country risk and wooden furniture export trade: Evidence from China," *Forest Products Journal* 72(3), 180-189. https://doi.org/10.13073/fpj-d-22-00019

Carpenter, S., Walker, B., Anderies, J. M., and Abel, N. (2001). "From metaphor to measurement: resilience of what to what," *Ecosystems* 4, 765-781. https://doi.org/10.1007/s10021-001-0045-9

Chatterjee, S., Rana, N. P., Dwivedi, Y. K., and Baabdullah, A. M. (2021). "Understanding AI adoption in manufacturing and production firms using an integrated TAM-TOE model," *Technological Forecasting and Social Change* 170, article 120880. https://doi.org/10.1016/j.techfore.2021.120880

Chittipaka, V., Kumar, S., Sivarajah, U., Bowden, J. L.-H., and Baral, M. M. (2023). "Blockchain Technology for Supply Chains operating in emerging markets: An empirical examination of technology-organization-environment (TOE) framework," *Annals of Operations Research* 327(1), 465-492. https://doi.org/10.1007/s10479-022-04801-5

Chowdhury, M. M. H., and Quaddus, M. (2016). "Supply chain readiness, response and recovery for resilience," *Supply Chain Management: An International Journal* 21(6), 709-731. https://doi.org/10.1108/SCM-12-2015-0463

Christopher, M., and Peck, H. (2004). "Building the resilient supply chain," *International Journal of Logistics Management* 15(2), 1-14. https://doi.org/10.1108/09574090410700275

Cohen, M. A., and Kouvelis, P. (2021). "Revisit of AAA excellence of global value chains: Robustness, resilience, and realignment," *Production & Operations Management* 30(3), 633-643. https://doi.org/10.1111/poms.13305

Dev, N. K., Shankar, R., Zacharia, Z. G., and Swami, S. (2021). "Supply chain resilience for managing the ripple effect in Industry 4.0 for green product diffusion," *International Journal of Physical Distribution & Logistics Management* 51(8), 897-930. https://doi.org/10.1108/IJPDLM-04-2020-0120

Erol, O., Sauser, B. J., and Mansouri, M. (2010). "A framework for investigation into extended enterprise resilience," *Enterprise Information Systems* 4(2), 111-136. https://doi.org/10.1080/17517570903474304

Fan, Y., and Stevenson, M. (2018). "A review of supply chain risk management: Definition, theory, and research agenda," *International Journal of Physical Distribution & Logistics Management* 48(3), 205-230. https://doi.org/10.1108/IJPDLM-01-2017-0043

Hair, J. F., Risher, J. J., Sarstedt, M., and Ringle, C. M. (2019). "When to use and how to report the results of PLS-SEM," *European Business Review* 31(1), 2-24. https://doi.org/10.1108/EBR-11-2018-0203

Han, Y., Chong, W. K., and Li, D. (2020). "A systematic literature review of the capabilities and performance metrics of supply chain resilience," *International Journal of Production Research* 58(15), 4541-4566. https://doi.org/10.1080/00207543.2020.1785034

Iritani, D. R., Silva, D. L., Saavedra, Y., Grael, P. F. F., and Ometto, A. R. (2015). "Sustainable strategies analysis through Life Cycle Assessment: A case study in a furniture industry," *Journal of Cleaner Production* 96, 308-318. https://doi.org/10.1016/j.jclepro.2014.05.029

Jum'a, L., Qamardin, S., and Ikram, M. (2024). "Development resilience strategies amid supply chain risks in the automotive industry: A stakeholder theory perspective," *Business Strategy & the Environment 33*(8), 9197-9213. https://doi.org/10.1002/bse.3977

Jungmeier, G., Werner, F., Jarnehammar, A., Hohenthal, C., and Richter, K. (2002). "Allocation in lca of wood-based products experiences of cost action E9 part i. methodology," *The International Journal of Life Cycle Assessment* 7(5), 290-294. https://doi.org/10.1007/bf02978890

Jüttner, U., and Maklan, S. (2011). "Supply chain resilience in the global financial crisis: An empirical study," *Supply Chain Management: An International Journal* 16(4), 246-259. https://doi.org/10.1108/13598541111139062

Lund, S., Manyika, J., Woetzel, J., Barriball, E., Krishnan, M., Alicke, K., Birshan, M., George, K., Smit, S., Swan, D., and Hutzler, K. (2020). *Risk, Resilience, and Rebalancing in Global Value Chains*, McKinsey Global Institute. https://www.mckinsey.com/~/media/mckinsey/business%20functions/operations/our%20insights/risk%20resilience%20and%20rebalancing%20in%20global%20value%20chains/mgi-risk-resilience-and-rebalancing-in-global-value-chains-full-report-vh.pdf

Ma, L., Ma, X., Zhang, J., Yang, Q., and Wei, K. (2021). "A methodology for dynamic assessment of laboratory safety by SEM-SD," *International Journal of Environmental Research and Public Health* 18(12), article 6545. https://doi.org/10.3390/ijerph18126545

MacDonald, J. R., Zobel, C. W., Melnyk, S. A., and Griffis, S. E. (2018). "Supply chain risk and resilience: Theory building through structured experiments and simulation," *International Journal of Production Research* 56(12), 4337-4355. https://doi.org/10.1080/00207543.2017.1421787

Majumdar, A., Sinha, S. K., and Govindan, K. (2021). "Prioritising risk mitigation strategies for environmentally sustainable clothing supply chains: Insights from selected organisational theories," *Sustainable Production and Consumption* 28, 543-555. https://doi.org/10.1016/j.spc.2021.06.021

Mirzaee, H., Samarghandi, H., and Willoughby, K. (2024). "Comparing resilience strategies for a multistage green supply chain to mitigate disruptions: A two-stage stochastic optimization model," *Journal of Cleaner Production* 471, article 143165. https://doi.org/10.1016/j.jclepro.2024.143165

Nambiar AO, E. S. (2015). "Forestry for rural development, poverty reduction and climate change mitigation: We can help more with wood," *Australian Forestry* 78(2), 55-64. https://doi.org/10.1080/00049158.2015.1050776

Pettit, T. J., Croxton, K. L., and Fiksel, J. (2013). "Ensuring supply chain resilience: development and implementation of an assessment tool," *Journal of Business Logistics* 34(1), 46-76. https://doi.org/10.1111/jbl.12009

Ponomarov, S. Y., and Holcomb, M. C. (2009). "Understanding the concept of supply chain resilience," *The International Journal of Logistics Management* 20(1), 124-143. https://doi.org/10.1108/09574090910954873

Qi, F., Zhang, L., Zhuo, K., and Ma, X. (2022). "Early warning for manufacturing supply chain resilience based on improved grey prediction model," *Sustainability* 14(20), article 13125. https://doi.org/10.3390/su142013125

Raubenheimer, A., and Conradie, P. J. (2002). "Using a new supply chain planning methodology to improve supply chain efficiency," *South African Journal of Industrial Engineering* 13(2), 53-70. https://doi.org/10.7166/13-2-308

Sakib, M. N., Kabir, G., and Ali, S. M. (2024). "A life cycle analysis approach to evaluate strategies in the furniture manufacturing industry," *Science of the Total Environment* 907, article 167611. https://doi.org/10.1016/j.scitotenv.2023.167611

Singh, C. S., Soni, G., and Badhotiya, G. K. (2019). "Performance indicators for supply chain resilience: review and conceptual framework," *Journal of Industrial Engineering International* 15(Suppl 1), 105-117. https://doi.org/10.1007/s40092-019-00322-2

Sun, J., Wang, H., and Chen, J. (2020). "Decision-making of port enterprise safety investment based on system dynamics," *Processes* 8(10), article 1235. https://doi.org/10.3390/pr8101235

Tukamuhabwa, B. R., Stevenson, M., Busby, J., and Zorzini, M. (2015). "Supply chain resilience: Definition, review and theoretical foundations for further study," *International Journal of Production Research* 53(18), 5592-5623. https://doi.org/10.1080/00207543.2015.1037934

Ullah, F., Qayyum, S., Thaheem, M. J., Al-Turjman, F., and Sepasgozar, S. M. (2021). "Risk management in sustainable smart cities governance: A TOE framework," *Technological Forecasting and Social Change* 167, article 120743. https://doi.org/10.1016/j.techfore.2021.120743

Wu, X., Zhu, J., and Wang, X. (2021). "A review on carbon reduction analysis during the design and manufacture of solid wood furniture," *BioResources* 16(3), 6212-6230. https://doi.org/10.15376/biores.16.3.6212-6230

Xiang, Y., Li, X., Liu, W., Luo, F., and Wang, M. (2025). "Enhancing chromium supply chain security through resilience strategies: Decision support based on system dynamics simulations." *Journal of Cleaner Production* 493, article 144981. https://doi.org/10.1016/j.jclepro.2025.144981

Xiong, X., Guo, W., Fang, L., Zhang, M., Wu, Z., Lu, R., and Miyakoshi, T. (2017). "Current state and development trend of Chinese furniture industry," *Journal of Wood Science* 63, 433-444. https://doi.org/10.1007/s10086-017-1643-2

Xiong, X., Ma, Q., Wu, Z., and Zhang, M. (2020). "Current situation and key manufacturing considerations of green furniture in China: A review," *Journal of Cleaner Production* 267, article 121957. https://doi.org/10.1016/j.jclepro.2020.121957

Zhao, N., Hong, J., and Lau, K. H. (2023). "Impact of supply chain digitalization on supply chain resilience and performance: A multi-mediation model," *International Journal of Production Economics* 259, article 108817. https://doi.org/10.1016/j.ijpe.2023.108817

Zhu, L., Yan, Y., and Lv, J. (2023). "A bibliometric analysis of current knowledge structure and research progress related to sustainable furniture design systems," *Sustainability* 15(11), 8622. https://doi.org/10.3390/su15118622

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