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A Systematic Approach to ESG Integration and Crisis Management Systems in Supply Chains: A Theoretical Framework and Mathematical Models

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Abstract

This study explores systems thinking that integrates environmental, social and corporate governance (ESG) frameworks and crisis management in the supply chain, introducing mathematical models for analysis. First, we analyze how the three levels of ESG are intertwined to form an overall sustainable development framework. System dynamics models are used to model the interactions and risk dynamics between these layers, highlighting the existence of systemic risk. Next, we examine how companies can use ESG frameworks for crisis management in the face of environmental disasters, social issues, or governance scandals. The decision tree model helps to analyze the choice of ESG measures and their consequences in crisis situations, while revealing the effectiveness of ESG as a risk mitigation strategy. In addition, the game theory model explores the behavioral interactions between firms, governments, investors, and society and analyzes the strategic choices and impacts of each role in crisis situations. Finally, the carbon footprint calculation model is applied to assess the impact of enterprises in environmental challenges, emphasizing the importance of ESG frameworks in reducing environmental impact and promoting sustainable development. Overall, this study provides a systematic approach to help companies effectively integrate ESG and crisis management strategies in a complex supply chain environment.

Keywords: Environmental, Social and Governance (ESG), Crisis Management, Systems Thinking Mathematical Modelling, Sustainable Development

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Introduction

Background

In the context of global challenges such as climate change and social inequality, environmental, social and corporate governance (ESG) has become a core issue for corporate and social development (Eccles, Ioannou, & Serafeim, 2014). Meanwhile, effective crisis management is equally as important when it comes to sustainable development for a company, especially in an era that uncertainty and risk have been brought up more frequently, where companies are supposed to demonstrate flexibilities (Boin &'t Hart, 2003). To address these two issues, the purpose of this article is therefore to explore how to enhance the efficiency of crisis management and further improve the ESG performance of enterprises through systems thinking and mathematical models. First, we analyzed the application of systems thinking in crisis management and explore how it can contribute to the development of a holistic perspective to better identify potential risks (Harris, 1990). Then, through the construction of mathematical models, we will show how to quantify and evaluate the effectiveness of crisis management measures and make actionable recommendations to improve the decision-making process of enterprises (Pal Vorstel, 2007). It is hoped that this research can provide theoretical support and practical guidance for the sustainable development of enterprises, while contributing new insights to academic research in related fields.

Research status

With the ever-increasing awareness global climate change and socio-economic instability, companies are stressing more often the importance of integrating environmental, social and governance (ESG) concepts into their business operations. According to the Global Sustainability Report, a company's ESG performance not only affects its social responsibility, but is also directly related to its financial performance and market competitiveness (Khan et al., 2016). Research shows that companies which actively pursue ESG strategies are more resilient to external risks (Eccles et al., 2014). However, despite the fact that many companies have begun to pay attention to ESG, many of such practices still suffer from systemic deficiencies and lack of integration, which greatly reduces the effectiveness of the crisis management (Mchiri, 2022).

The existing research mostly focuses on a single dimension of ESG performance, and there is still a lack of discussion on how to apply systems thinking to crisis management and ESG integration. With the increasing application of systems thinking and mathematical models in many fields, incorporating them in the scope of crisis management would not only improve the efficiency of response, but also improve the overall performance of enterprises in terms of ESG. Based on this, the present article will discuss how to use systems thinking and mathematical models to strengthen enterprises' crisis management capabilities, improve their performance in ESG indicators, and provide new perspectives and solutions for the sustainable development of enterprises.

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Research Objectives

The main objective of this research is to explore how systems thinking and mathematical models can be effectively integrated into the crisis management process of enterprises, and further improve their performance in environmental, social and corporate governance (ESG) indicators. Specifically, this study aims to achieve the following objectives:

1. Analyze the application of systems thinking in crisis management: Discuss how systems thinking can help organizations better understand the complexity and dynamics of crisis management, and improve their crisis response capabilities (Sturman, 2000).
2. Establish mathematical models to support decision-making: Design mathematical models for crisis management to help companies make more scientific and rational decisions in different crisis scenarios (Forrester, 1961).
3. Assessing the impact of ESG performance: Analyze the specific impact of systems thinking and mathematical models on corporate ESG performance, especially in the areas of risk management and sustainability (Eccles et al., 2014).
4. Recommendations on best practices: Based on the results of the study, we provide specific strategic recommendations for companies to effectively integrate ESG concepts into their crisis management to achieve their sustainability goals (Khan et al., 2016).

Through the integration of systems thinking and mathematical models, this study hopes to provide enterprises with more forward-looking and practical crisis management solutions in the face of the current complex and uncertain economic environment.

Research gaps and academic contributions

Research gaps

Although the application of systems thinking and mathematical models in crisis management has attracted the attention of academia and industry, there are still several obvious research gaps in the current literature. First, there is a lack of research on the specific application of systems thinking in corporate crisis management and its impact on the decision-making process. Second, although some studies have explored the application of mathematical models in risk management, there is a lack of systematic discussion on how to effectively integrate these models with systems thinking to improve enterprises' crisis response capabilities (Wang et al.,2022). Finally, there is relatively little research in the existing literature on the integration of environmental, social, and governance (ESG) indicators into crisis management, especially in the context of mathematical models (Khalil et al., 2024). Therefore, this study aims to fill these gaps and provide new insights into related fields.

Academic Contributions

The academic contributions of this study are mainly reflected in the following aspects. First, this study integrates systems thinking and mathematical models to provide a new framework for analyzing complexity in

corporate crisis management, which provides a theoretical basis for future research (Sturman, 2000). Second, by an in-depth analysis of the specific application of systems thinking in crisis management, this study will aid the academic community to understand how the theory can have an impact in practice (Senger, 2006). Thirdly, this study provides specific strategic recommendations on how to integrate ESG concepts into crisis management, which not only fills the gap in the existing literature, but also provides guidance for corporate practice (Eccles et al., 2014). Finally, the results of this study will promote future research on the application of systems thinking and mathematical models in other management fields, and promote the development of this field.

Literature review

Systems Thinking and Mathematical Models

In recent years, the application of systems thinking and mathematical models in the field of enterprise crisis management has received more and more attention. In 2021, Bi et al. explores how systems thinking can help companies make effective decisions in the face of disruption. They point out that systems thinking can improve the resilience of firms by facilitating cross-sector collaboration (Bi et al., 2021). In addition, the study highlights the importance of systems thinking in analyzing complex systems, providing strategic recommendations for companies in the face of uncertainty.

In the same year, Skovsmose published research focusing on the application of mathematical models in risk management, especially model optimization in crisis situations. They use simulation methods to assess corporate risk in different crisis scenarios and propose the effectiveness of mathematical models in supporting decision-making processes (Skovsmoss, 2021). This study not only confirms the potential of mathematical models in crisis management but also provides an empirical basis for future research.

Broadstock et al. (2021) further examined the role of environmental, social and corporate governance (ESG) indicators in corporate crisis management. Their research shows that integrating ESG considerations during a crisis can significantly improve their image and social responsibility, thereby enhancing their long-term sustainability (Broadstock et al., 2021). This suggests that integrating ESG concepts into crisis management is critical to the strategic intent of companies.

Recently, in 2023, some researchers have focused on how the combination of systems thinking and mathematical models can improve the efficiency of corporate crisis management. They propose a comprehensive framework that highlights the importance of systems thinking in developing mathematical models and explores how the interaction between the two affects the decision-making process (Abdel-Latif et al., 2023). This research provides an important perspective for future academic discourse and calls for the academic community to explore this topic more deeply.

Based on the above literature, it can be seen that the application of systems thinking and mathematical models in corporate crisis management has received increasing attention, and most of the current research

focuses on the balance between theoretical discussion and empirical support. These studies not only enrich the relevant literature, but also provide practical guidance for enterprises to cope with the crisis.

Application of mathematical models in supply chain ESG integration and crisis management

Mathematical programming models

Mathematical programming models are widely used in supply chain management, especially in resource allocation and decision support. In recent years, Jayarathna et al. proposed a multi-objective optimization model to balance economic benefits and environmental impacts. Their research shows that through effective mathematical programming, companies can achieve ESG goals by reducing their environmental impact while increasing profitability (Jayarathna et al., 2021). This study highlights the importance of mathematical programming models in responding to supply chain crises, especially when decisions need to be made quickly.

Risk assessment model

In supply chain crisis management, risk assessment models can help companies identify and assess potential risks. Díaz-Curbelo et al. (2020) developed a risk assessment framework using fuzzy mathematics methods to focus on environmental and social risks in the supply chain. Their model is able to quantify uncertainty and provide risk-based decision support to businesses, thereby increasing their resilience in crisis situations (Díaz-Curbelo et al., 2020). This study shows the potential of risk assessment models to integrate ESG considerations, especially when dealing with complex and uncertain supply chain environments.

System dynamics model

System dynamics models excel in analyzing the dynamic behavior of complex systems. Alameru and Brishaud (2020) discussed the application of a systemadynamic approach to supply chain ESG integration, by building models to simulate the impact of different strategies on corporate ESG performance. Their research shows that system-dynamic models can help firms understand the long-term consequences of their decisions on social and environmental impacts (Alamerew & Brissaud, 2020). This provides a new perspective on the decision-making process in crisis management, emphasizing the need for continuous monitoring and evaluation in an ever-changing environment.

Statistical and machine learning models

Statistical and machine learning models are also becoming important tools in supply chain management. Aljohani (2023) used machine learning algorithms to develop a predictive model designed to predict the occurrence of a supply chain crisis (Aljohani, 2023). Their research shows that through data analysis, companies are able to identify potential crises in advance and thus take proactive measures. This model not only improves the accuracy of forecasting, but also emphasizes the importance of data-driven decision-making in supply chain management.

Research Methodology

This study adopts a systematic methodology and focuses on analyzing the feasibility of different mathematical models in environmental, social and corporate governance (ESG) integration and supply chain crisis management. The research method mainly includes the following steps:

1. Literature review

First, a comprehensive literature review was conducted to identify the main challenges and research status of ESG integration and supply chain crisis management. The literature review focuses on relevant research in the last three years, especially in the application of mathematical models and machine learning methods, to understand the advantages, disadvantages and applicability of different methods.

2. Construction of theoretical framework

Based on the results of the literature review, a theoretical framework is constructed that aims to integrate ESG indicators in supply chain management, especially in crisis situations. This framework covers a variety of mathematical models, including:

- Optimization model: Explore ways to find the best resource allocation under different constraints, taking into account environmental and social impacts.
- Simulation model: By simulating different scenarios, analyze the responsiveness and potential risks of the supply chain, and provide decision support.
- Machine Learning Models: Evaluate their feasibility in demand forecasting, supply chain disruption and risk identification, and analyze their impact on supply chain flexibility.

3. Analysis of mathematical models

Conduct a detailed analysis of the advantages and disadvantages of the constructed mathematical model. Discuss the applicability of each model in ESG integration and crisis management and its potential limitations. This process includes:

- Model comparison: Compare the ability of different mathematical models to respond to supply chain crises and their environmental and social impacts.
- Feasibility assessment: Analyze the feasibility of each model in practical applications, especially the constraints of enterprise resources, data availability, and technical level.

4. Discussion of methodology

On the basis of the analysis of various mathematical models, the theoretical basis of these models and their methodological significance in practical application are further discussed. This study will consider the following aspects:

- Method selection basis: Analyze how to choose the appropriate mathematical model according to different supply chain characteristics and crisis scenarios. For example, in industries with a high environmental impact, an optimization model may be more effective, while a machine learning model may provide

better prediction accuracy in a scenario where demand fluctuates.

- Model Integration: Explores how to combine multiple mathematical models to form an integrated decision support system to more comprehensively evaluate ESG integration and crisis management strategies.

5. Methods of statistical analysis

Although this study does not involve the collection of empirical data, the statistical analysis methods that may be used by various mathematical models will be discussed to support future research and applications. These include:

- Descriptive statistics: used to summarize and describe the basic characteristics of various ESG indicators in the supply chain, such as mean, standard deviation, distribution, etc.
- Regression analysis: It can be used to examine the impact of ESG factors on supply chain performance, helping to identify key variables and their relationships.
- Factor analysis: Used to explore and confirm the underlying structures that influence supply chain decisions, especially in multivariate situations.
- Scenario Simulation Analysis: By simulating different environmental and market conditions, evaluate the behavior and response of the supply chain in crisis situations, and then adjust strategies.

6. Conclusions and Recommendations

Finally, based on the analysis results of various mathematical models, the research findings are summarized, and the direction and practical suggestions for future research are put forward to help enterprises effectively integrate ESG indicators in supply chain management and improve their ability to cope with crises.

Results and Discussion

Overview: A systems dynamics perspective on the impact of ESG in crisis management

ESG implications of crisis management

When faced with crises such as environmental disasters, social issues, or governance scandals, companies can use ESG frameworks to respond effectively. The main arguments here include:

- ESG as a risk mitigation strategy: ESG frameworks can help companies prevent and respond to potential crisis events. By integrating environmental, social and governance factors, companies can better identify risks and develop response plans.
- Post-crisis resilience: Companies that adopt ESG policies typically show greater resilience after experiencing a crisis. Good ESG practices can promote the resilience of companies and help them recover quickly from challenges.

A. Application of mathematical models for the environmental dimension

Exploring how companies can reduce their environmental impact through ESG frameworks, especially

when addressing environmental challenges such as climate change and resource consumption, the application of mathematical models can provide effective solutions.

B. Application of mathematical models for the social dimension

The social dimension covers employee welfare, community relations and labor rights, etc., and analyzes how to use mathematical models to evaluate the impact of corporate social responsibility, and formulate corresponding policies and measures on this basis.

C. Corporate Governance and Risk Management

Explores the central role of corporate governance in ESG and analyzes how good corporate governance can help prevent and manage corporate risks. By establishing a transparent governance structure, companies can respond more effectively to crises.

D. ESG metrics and data analysis

Analyze how to use data to quantitatively evaluate ESG and use mathematical models to predict its long-term impact on companies. Through systematic analysis of ESG indicators, companies can develop more effective strategies to support sustainable development.

F. Systems thinking for ESG frameworks

The three main dimensions of ESG (environmental, social, and corporate governance) are intertwined to form an overall sustainability framework. This architecture not only considers the impact of a single dimension, but also emphasizes the interaction between them. Key arguments include:

- Systemic risk: Failure at any single level, such as an environmental breach, can have a profound impact on the entire system. This risk underscores the linkages between the various levels of ESG and points to the need for a holistic management strategy.
- Dynamics: Changes in environmental factors, social expectations, and governance standards over time will affect the effectiveness of ESG strategies. Companies need to adapt their strategies to the changing external environment.

Figure1 Schematic diagram of the system dynamics model of ESG

Model 1: System Dynamics Model

A system dynamics model is a systematic model designed to analyze the interactions between multiple variables, which can help researchers model the cascading effects between different levels. This model uses differential equations to describe the feedback mechanisms within the system and shows how the variables affect each other over time, resulting in complex behavioral patterns. In particular, in the context of ESG (Environmental, Social and Governance) framework, system dynamics models can be used to deeply understand the interaction between internal decision-making and the external environment when responding to external challenges, such as environmental change or social unrest.

ESG implications of crisis management

When faced with crises such as environmental disasters, social issues, or governance scandals, companies must effectively use ESG frameworks to respond. An ESG framework can not only help companies identify potential risks, but also provide a set of guiding principles to facilitate the effectiveness of their response strategies.

- ESG as a risk mitigation strategy: By integrating environmental, social and governance factors, companies can develop a more comprehensive risk management strategy. These strategies can help companies prevent and respond to potential crisis events, for example, by reducing the risk of environmental pollution by establishing a sound environmental management system, or by strengthening social responsibility to improve relationships with stakeholders. When faced with a crisis, these preventive measures can effectively reduce losses and improve response efficiency.
- Post-crisis resilience: Research shows that companies that adopt ESG policies typically show greater resilience after experiencing a crisis. These companies are often able to rebuild their brand image more quickly, restore market confidence, and get back to normal operations quickly after a crisis. For example, a company that has established a good social image before a crisis can rely on this trust to quickly restore customer support when faced with difficulties. At this time, ESG policy has become not only a tool for risk management, but also an important cornerstone of the long-term competitiveness of enterprises.

In summary, the application of system dynamics models in the analysis of ESG impact and crisis management can help enterprises understand the challenges they face more comprehensively and design more effective response strategies to cope with the changing market environment and social expectations.

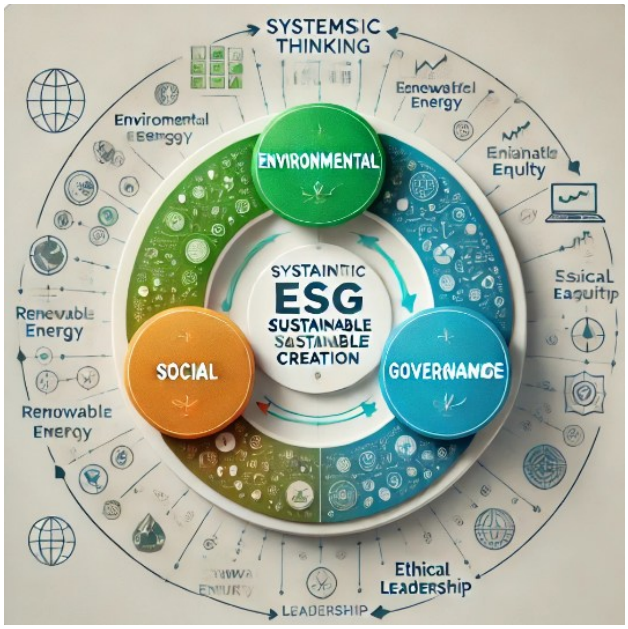

Figure2 the application of system dynamics models in the analysis of ESG

Model 2: Decision Tree Model:

The decision tree model can be used to analyze the decision points and their results of ESG measures under different crisis scenarios

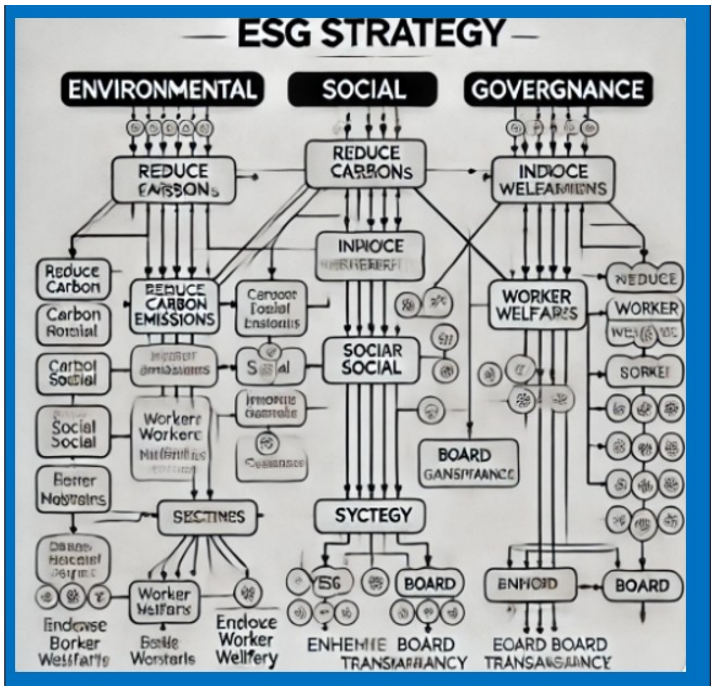

Figure 3 Diagram of the decision tree model applied to the dynamics of ESG systems

The above figure is a decision tree model diagram applied to the dynamics of ESG system, starting from the "ESG strategy" as the root node, and divided into three major areas: environmental, social and corporate governance, each of which has corresponding decision points and possible actions, showing the results or feedback loops of each decision. This graph can help you visualize the dynamic interactions in the ESG decision-making process.

Below is a table that uses decision tree models to solve ESG (Environmental, Social, Governance) system dynamics problems, showing the options and possible outcomes of different decisions:

Table 1 ESG strategy decision-making impact assessment tree

Nodes/decision points	description	choose	Results/Impacts
Root node: ESG strategy decision-making	Develop an overall ESG strategy	Environmental	Take environmental protection measures to reduce pollution and waste of resources
		Social	Improve social welfare, such as employee welfare, labor rights
		Governance	Enhance corporate transparency and shareholder governance
Environment: Reducing carbon emissions	Take steps to reduce your carbon footprint	be	Reduce carbon footprint, enhance corporate image, and comply with policy requirements
		not	Increased environmental risks, which may result in fines or negative publicity
Social: Improving employee welfare	Enhance employee compensation and benefits	be	Enhance employee satisfaction, attract talent, and increase productivity
		not	Employee turnover increases and job morale is low
Governance: Increase transparency	Increase board transparency and openness in corporate decision-making	be	Increase investor trust and improve corporate governance ratings
		not	Investors rebounded, downgrading corporate governance ratings

Table 1 (Cont.)

Nodes/decision points	description	choose	Results/Impacts
Outcome of the decision: Environmental impact assessment	Whether the environmental protection measures taken by the enterprise meet the emission reduction target	be	Reduce long-term operating costs and improve environmental evaluation
		not	Further strategic alignment and policy compliance are needed
Outcome of decision-making: Social impact assessment	The effect of improved employee benefits	be	Improve corporate social responsibility ratings and enhance employee cohesion
		not	Facing social risks such as employee strikes or labor shortages
Outcome of the decision: Governance assessment	Whether the transparency of corporate governance affects the long-term development of the company	be	The company's share price rises, attracting more investment
		not	The company's reputation has been damaged and it is facing scrutiny from regulatory authorities

This table shows how to use a decision tree model to analyze various aspects of ESG and derive the corresponding outcomes or impacts based on different choices.

Model 3: Game Theory Model

Game theory models can be used to study the behavioral interactions between firms and stakeholders, especially in the face of crisis. Game theory models provide a framework for analyzing the behavior and strategy choices of different participants, helping to understand the interaction process of companies, governments, investors, and society in driving ESG systems. Through these models, conflicts of interest and opportunities for collaboration between different actors can be analysed to find the best strategy to improve sustainable development.

The following is a table of game theory models applied to solve the dynamics of ESG (environmental, social, corporate governance) systems, showing how different actors influence each other through strategic choices and achieve or fail to achieve sustainability goals

Table 2 Table of game theory models applied to ESG systems

role	Policy options	Consequences of the act	Types of games	interpretation
enterprise	1. Invest in sustainable technologies	2. Maximize short-term returns	1. Gain long-term profits and reputation	2. Immediate profit increases, but long-term risk increases
government	1. Implement strict environmental protection policies	2. Relax environmental regulations	1. Improved environment, but may reduce corporate investment	2. Short-term and long-term environmental benefits
investor	1. Support ESG-friendly businesses	2. Invest in high-return, high-risk companies	1. Stable long-term returns and reduced risks	2. High-return short-term investment, but exposed to policy risks
Social/Consumer	1. Buy ESG-friendly products	2. Buy products that are less expensive but have a high environmental impact	1. Businesses are gradually transforming into sustainable development	2. Enterprises continue to engage in high-polluting activities, and social costs increase
Non-Governmental Organizations (NGOs)	1. Promote strict ESG standards	2. Take a neutral stance on ESG issues	1. Increase social awareness and promote ESG policies	2. ESG issues are being ignored and companies may continue to behave irresponsibly

Description of the form

1. Roles: Each role involved in the ESG system has different interest drivers, including corporations, governments, investors, consumers, and NGOs. The interaction of these roles is crucial in determining the outcome of an ESG system.

2. Strategy Options: Each character's strategic choices in the game affect their own and other characters' outcomes. Game theory models allow these roles to make choices under the influence of each other.

- Businesses may choose to invest in sustainable technologies or maximize returns in the short

term.

- Governments can choose to implement environmental policies or relax regulations, affecting the entire economic ecosystem.
- Investors are faced with investing in ESG-friendly companies or those that pursue high risk and high returns.
- Consumers' choices directly affect a company's product strategy and have a significant impact on market demand.

3. Behavioral outcomes: Each strategy choice has a corresponding outcome, and different choices will affect the sustainability of the ESG system.

- If a company invests in sustainable technology, it will gain long-term benefits and reputation, but if it chooses short-term benefits, it may face environmental risks and negative reputation.
- The implementation of strict environmental protection policies by the government may reduce short-term investment by enterprises, but it will benefit long-term environmental protection.
- Investors support ESG-friendly companies with reduced long-term risks, while investing in high-risk companies may face policy risks.

4. Game Type: This column describes the type of game that each character interacts with. Different game models can be used to simulate interactions between characters.

- The prisoner's dilemma: the choice between short-term and long-term benefits. Cooperation is good for sustainable development, but individual behavior tends to be maximized in the short term.
- Social contract game: The contractual relationship between the government and society determines the balance between the environment and the economy.
- Public Wealth Game: Consumers' choices affect the use of public resources, and individual decisions affect society as a whole.
- Coordination game: NGOs and other organizations need to coordinate with companies and governments to promote the achievement of ESG goals.

Model 4: Carbon Footprint Calculation Model

The mathematical model of the environmental dimension can be applied to explore how companies can reduce their environmental impact through ESG frameworks when responding to environmental challenges such as climate change and resource consumption. The carbon footprint calculation model is used to assess the carbon emissions of a company during production and operations. It helps companies and organizations quantify their carbon emissions at all ESG levels, so as to formulate corresponding emission reduction measures. The model not only helps companies understand their own carbon emissions and those of their supply chains, but also helps them make greener business decisions and drive overall sustainability. This approach reduces environmental risks and enhances social responsibility, promoting transparency in corporate governance and long-term profitability.

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The following is a table of how the Carbon Footprint Calculation Model is applied to solve the dynamics of ESG (Environmental, Social, Governance) systems, showing how the carbon footprint can be measured and managed at different levels of ESG, and the impact on sustainability:

Table 3 A table in which the carbon footprint calculation model is applied to the ESG system

ESG dimension	Carbon Footprint Measurement Project	Calculation Method/Model	Results & Impact	Application note:
environment	Corporate carbon emissions	GHG Emissions Calculation	Calculate the total carbon emissions of a company from the production of products or services	Help enterprises identify links with high carbon emissions and promote the application of emission reduction technologies
society	Supply chain carbon footprint	Supply Chain Carbon Footprint Model	Calculate carbon emissions at all stages of the supply chain, including transportation, logistics, and material use	Help enterprises choose low-carbon suppliers and improve the environmental benefits of the supply chain
Corporate Governance	The carbon impact of management's decisions	Carbon Footprint Decision Model	Quantify the impact of decisions on carbon emissions and set sustainable development goals	Help enterprises take carbon emissions into account at the strategic decision-making level and promote green governance

Table 3 (Cont.)

ESG dimension	Carbon Footprint Measurement Project	Calculation Method/Model	Results & Impact	Application note:
products	Carbon emissions over the life cycle of a product	Product Carbon Footprint Assessment	Calculate the carbon footprint of a product from production to disposal, including materials, manufacturing, transportation, etc	Help enterprises optimize product design, choose environmentally friendly materials, and reduce carbon emissions throughout the product life cycle
Employee Behavior	Carbon emissions from employee travel and the working environment	Employee Carbon Footprint Model	Calculate the carbon footprint of your employees' commuting, traveling, and office environments	Help enterprises implement remote work, low-carbon commuting, and create a low-carbon working environment
Energy use	Renewable energy use	Energy Carbon Intensity Model	Calculate the carbon intensity of energy use compared to renewables versus conventional energy sources	Encourage companies to use low-carbon energy sources and gradually reduce their dependence on fossil fuels
Waste management	Carbon footprint of waste disposal	Waste Carbon Footprint Model	Calculate carbon emissions in the waste treatment process, including recycling, incineration, landfilling, etc	Helping companies develop more effective waste reduction and recycling programs

Table 3 (Cont.)

ESG dimension	Carbon Footprint Measurement Project	Calculation Method/Model	Results & Impact	Application note:
Green procurement	Purchases of low-carbon products and services	Green Procurement Carbon Model	Calculate the carbon footprint of the procurement process to drive the procurement of low-carbon products and services	Helping companies implement sustainable procurement policies and reduce their overall carbon footprint

Description of the form

1. ESG Dimensions: The table covers different aspects of ESG, including environmental, social, corporate governance, and related specific application areas (e.g., products, employee behavior, energy use, etc.), showing how to calculate carbon footprints at each level.

2. Carbon Footprint Measurement Programs: Each ESG level has a corresponding carbon footprint measurement program, which helps companies and organizations accurately calculate the sources of their carbon emissions and develop emission reduction strategies.

- The environmental dimension focuses on the direct carbon emissions of the company.
- The social dimension focuses on the management of carbon emissions in the supply chain.
- Corporate governance, on the other hand, emphasizes how corporate decisions affect the overall carbon footprint.

3. Calculation Methodology/Model: Different carbon footprint calculation models are used to quantify carbon emissions at each ESG level. These models include:

- GHG Emission Formula: Used to calculate a company's carbon emissions.
- Supply Chain Carbon Footprint Model: Used to track supply chain carbon emissions.
- Product Carbon Footprint Assessment: Analyze the carbon emissions of the whole life cycle of a product.
- Employee Carbon Footprint Model: Calculated for carbon emissions from employee travel and work environments.
- Energy Carbon Intensity Model: Calculates the carbon intensity of renewable and conventional energy sources.

4. Results & Impacts: The results of carbon footprint calculations have a direct impact on your company's

decision-making and strategy implementation.

- Reducing carbon emissions can reduce the negative environmental impact of a company and improve its social responsibility rating.
- Controlling the carbon footprint of the supply chain can help companies achieve greener procurement and supply management, and drive supplier transformation.
- The low-carbon transformation of employee behavior can reduce carbon emissions at work and improve sustainability within the organization.

5. Description of the app:

- At the environmental level, companies can use carbon footprint calculations to identify high emission segments and promote emission reduction technologies, such as energy-saving technologies or the use of renewable energy.
- At the societal level, carbon emission management in the supply chain is becoming more and more important, and companies should choose low-carbon suppliers and improve logistics links.
- At the corporate governance level, the carbon footprint decision evaluation model helps management integrate carbon emission considerations into long-term strategies and achieve more transparent sustainability goals.

Model 5: linear programming

It can be applied to optimize the allocation of resources, such as how to minimize environmental costs while meeting production needs. Below shows a table of how linear programming models can develop their role in ESG integration and crisis management, and provides specific mathematical models and expected effects to help better understand their application in the supply chain.

Table 4 Analysis of mathematical models of supply chain sustainability and resource optimization

Applications	Specific applications	Mathematical models	What to expect
Resource allocation	Optimize resource allocation in the supply chain and balance environmental and economic benefits	Maximize/minimize the objective function, subject to resource constraints	Improve resource efficiency and reduce environmental impact
risk management	Evaluate and adjust supplier selection to reduce risk in crisis scenarios	A risk minimization model that takes into account supplier performance and stability	Enhance the resilience of your supply chain and respond quickly to emergencies

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Table 4 (Cont.)

Applications	Specific applications	Mathematical models	What to expect
Environmental Impact Assessment	Quantify carbon emissions and other environmental metrics from supply chain activities	Carbon Minimization Model	Comply with ESG standards and enhance corporate image
Social Responsibility Management	Evaluate and improve the performance of suppliers in terms of social responsibility	Social Responsibility Maximization Model	Enhance social trust and improve the overall sustainability of the supply chain
Integrate supply chain strategies	Integrate environmental, social and governance factors across the supply chain to optimize operational processes	A model that integrates minimizing costs and maximizing social value	Promote the synergy of all links in the supply chain and improve the overall performance

Model 6: Social Impact Model

Social impact models can simulate the positive or negative impact of a business on a local society. The social aspects include employee welfare, community relations, labor rights, etc., and explore how to use mathematical models to evaluate the impact of corporate social responsibility.

The following table demonstrates the application of social impact models in ESG integration and crisis management, and provides a specific model framework and expected effects to help understand their impact in the supply chain.

Table 5 Analysis of supply chain social impact and responsibility assessment model

Applications	Specific applications	Model framework	What to expect
Community involvement	Assess the impact of supply chains on local communities and promote community engagement and support	Stakeholder analysis model	Enhance community trust and brand image

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Table 5 (Cont.)

Applications	Specific applications	Model framework	What to expect
Employment opportunities	Quantify the impact of supply chain operations on the creation and disappearance of local jobs	Job opportunity growth forecasting model	Promote economic development and enhance social stability
Education & Training	Evaluate the contribution of supply chain companies to education and training in terms of social responsibility	Educational Impact Assessment Model	Improve the quality of the workforce and promote sustainable development
Health & Safety	Analyze the impact of supply chain activities on worker health and safety	Health risk assessment model	Reduce the accident rate and improve the working environment
social welfare	Quantify the supply chain's investment and return on social welfare programs	Analytical model of social welfare benefits	Enhance social well-being and enhance the image of corporate social responsibility
Poverty alleviation	Assess the contribution and impact of supply chains to poverty alleviation	Poverty Impact Assessment Model	Improving living standards and promoting social equity

Model 7: Multi-objective Optimization Model

A multi-objective optimization model can analyze how to balance multiple social factors such as benefits, compensation, training, etc. The following table demonstrates the application of multi-objective optimization models in ESG integration and crisis management, and provides a specific model framework and expected effects to help understand its impact in the supply chain.

Table 6 Analysis of multi-objective optimization model for supply chain operation and ESG integration

Applications	Specific applications	Model framework	What to expect
Environmental and economic balance	Balance environmental sustainability with economic benefits to optimize supply chain operations	Environmental-economic dual-objective model	At the same time, environmental protection and cost control are achieved, and the overall efficiency is improved
Risk & Efficiency Management	Balance risk minimization with maximizing operational efficiency in crisis management	Risk-efficiency multi-objective optimization model	Enhance supply chain resilience and responsiveness
Social Impact Assessment	At the same time, we consider social responsibility and economic benefits to achieve the optimization of social impact in the supply chain	Socio-economic dual-objective model	Enhance corporate image and promote social development
Resource placement	Optimize resource allocation under multiple sustainability goals, such as energy use, material recycling, etc	Multi-objective optimization model for resource allocation	Improve resource efficiency and reduce environmental impact
Long-term vs. short-term goals	Consider both short-term profits and long-term sustainability goals to develop a balancing strategy	Short-term and long-term equilibrium optimization model	Achieve long-term sustainability and competitiveness of your business
Integrate ESG metrics	Balance ESG (Environmental, Social and Governance) indicators and develop an integrated strategy	ESG integration multi-objective optimization model	Ensure balanced development across all ESG dimensions to improve overall performance

Model 8: Risk Analysis Model

Corporate governance must understand the central role of ESG and how to prevent and manage corporate risks through good corporate governance. A risk analysis model uses mathematical methods to calculate risks in corporate governance, such as potential risks in the board structure or internal control system. The following table shows the application of risk analysis models in ESG integration and crisis management, and provides a specific model framework and expected effects to help gain a deeper understanding of their impact in the supply chain.

Table 7 Analysis of supply chain crisis management and ESG risk identification and response model

Applications	Specific applications	Model framework	What to expect
Crisis identification	Assess potential sources of crisis and risk factors in the supply chain, and establish a risk identification system	Risk Identification Model	Improve risk early warning capabilities and reduce the probability of crises
risk assessment	Quantify the likelihood and impact of risk to provide data support for decision-making	Quantitative risk assessment model	Empower managers to make informed decisions based on data
Risk prioritization	Prioritize risks based on their severity and probability of occurrence, and develop priority response strategies	Risk prioritization model	Allocate resources efficiently and focus on high-risk projects
Contingency planning	Develop a crisis response plan based on a risk analysis to ensure rapid response capabilities	Contingency planning model	Enhance the resilience of your supply chain and ensure business continuity
Risk monitoring	Establish a continuous monitoring system to regularly assess the risk profile and adjust response strategies	Risk monitoring and assessment model	Adjust your strategy in a timely manner to respond to the changing risk environment

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Table 7 (Cont.)

Applications	Specific applications	Model framework	What to expect
ESG-related risk analysis	Conduct specific analysis of environmental, social and governance (ESG) risks to ensure compliance with relevant standards	ESG risk analysis model	Improve corporate ESG compliance and reduce potential legal and reputational risks

Model 9: Monte Carlo Simulation

Monte Carlo simulations can be used to simulate the risk of corporate governance decisions under multiple random variables. Table 8 showcases the application of Monte Carlo simulation in ESG integration and crisis management and provides a concrete model framework and expected effects to help better understand its impact in the supply chain.

Table 8 Application analysis of Monte Carlo simulation in the integration of supply chain management and ESG

Applications	Specific applications	Model framework	What to expect
risk assessment	Use Monte Carlo simulations to assess the impact of uncertainties in the supply chain on risk	Uncertainty risk assessment model	Obtain probability distributions of risk ranges to support the decision-making process
Resource placement	Simulate the operational results under different resource allocation scenarios to find the optimal solution	Resource allocation optimization model	Determine the best resource allocation to improve operational efficiency
Environmental impact analysis	Assess the potential environmental impact of supply chain operations and consider uncertainties	Environmental Impact Assessment Model	Predict environmental impacts in different operating scenarios

Table 8 (Cont.)

Applications	Specific applications	Model framework	What to expect
Demand forecasting	Stochastic simulations based on market changes to predict fluctuations in product demand	Demand forecasting models	Improve demand forecasting accuracy and inventory management
Investment decisions	Analyze the return risk of different ESG investment solutions, and provide the distribution of risk and return	Return on investment risk assessment model	Help businesses make more informed investment decisions
Crisis response strategies	Simulate the effects of different crisis response options to find the most effective response strategy	Crisis response simulation model	Enhance resilience to ensure supply chain continuity

Model 10: Regression Analysis

ESG indicators are the best basis for data analysis and can be used to model the relationship between ESG indicators and corporate performance, so researchers must understand how to use data to quantitatively evaluate ESG and predict its long-term impact on enterprises through mathematical models. Table 9 demonstrates the application of regression analysis in ESG integration and crisis management, and provides a specific model framework and expected effects to help better understand its impact in the supply chain.

Table 9 Application of regression analysis model in ESG forecasting and supply chain performance management

Applications	Specific applications	Model framework	What to expect
ESG performance forecasts	Use regression analysis to predict your organization's environmental, social, and governance (ESG) performance	ESG performance forecasting model	Understand the factors influencing ESG performance and inform your improvement strategy

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Table 9 (Cont.)

Applications	Specific applications	Model framework	What to expect
Supply chain performance analysis	The key variables affecting supply chain performance were analyzed, and a regression model of supply chain performance was established	Supply chain performance regression model	Identify key factors to improve supply chain efficiency
Evaluation of the effectiveness of crisis response	Evaluate the impact of crisis management measures on business performance and quantify the effectiveness of response strategies	Regression model of crisis response effect	Improve the effectiveness of responses to support future crisis management decisions
Cost and benefit analysis	Analyze the relationship between the costs and benefits of supply chain operations and optimize resource allocation	Cost-benefit regression analysis model	Achieve cost control and improve resource allocation efficiency
Market demand forecast	Based on the historical data analysis of the influencing factors of market demand, a market demand regression model was established	Market demand forecasting regression model	Improve the accuracy of demand forecasts and optimize inventory management
Social Impact Assessment	Analyze the impact of corporate activities on society and quantify the contribution of social responsibility to corporate performance	Social Impact Assessment Regression Model	Promote socially responsible investment and enhance the social image of enterprises

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Model 11: Structural Equation Modeling (SEM)

Structural equation models can analyze the interrelationships between ESG indicators and their overall impact on corporate performance. Table 10 demonstrates the application of structural equation modeling in ESG integration and crisis management, and provides a specific model framework and expected effects to help understand its impact in the supply chain. These themes and mathematical models can help managers explore the multi-dimensional approach to systems thinking about ESG frameworks and crisis management, and highlight how the interaction between different levels affects the overall performance of the organization.

Table 10 Application analysis of structural equation model (SEM) in ESG integration and supply chain crisis management

Applications	Specific applications	Model framework	What to expect
ESG factor relationship analysis	Use SEM to analyze the interrelationship between ESG factors (environmental, social, governance).	Structural equation model of ESG factors	Identify the key factors influencing ESG performance and their interactions
Evaluation of crisis management strategies	Evaluate the impact of different crisis management strategies on supply chain performance, and analyze the causal relationship between strategies	SEM model of crisis management strategy	Improve the effectiveness of crisis management strategies and optimize resource allocation
Factors influencing supply chain performance	The influencing factors of supply chain performance were analyzed, and a structural equation model was established to evaluate its overall impact	SEM model of supply chain performance	Provide comprehensive performance reviews to help develop improvement strategies
The relationship between social responsibility and performance	Explore the relationship between corporate social responsibility (CSR) and business performance, using SEM for quantitative analysis	SEM model of social responsibility performance	Understand the impact of CSR on business performance and promote socially responsible investment

Table 10 (Cont.)

Applications	Specific applications	Model framework	What to expect
Consolidate metrics	Integrate different ESG metrics into a single model and analyze their impact on supply chain management	ESG metrics are integrated with SEM models	Improve the systematization and integrity of supply chain management
Simulate future scenarios	Use SEM to simulate future scenarios to assess the potential impact of different policies or action options on the supply chain	Scenario simulation SEM model	Help managers anticipate and respond to future risks and challenges

Advantages of using structural equation modelling studies

There are several advantages using the SEM for modeling. The analysis of latent and observed variables offers several significant advantages, including the following advantages over other research methods:

1. Analyze the relationship between multiple variables at the same time

SEM is able to consider multiple latent variables (e.g., ESG factors, crisis management strategies, supply chain performance, etc.) and observed variables (e.g., specific indicator data) at the same time, and can evaluate the causal relationship between them. This comprehensiveness allows researchers to understand the complex interactions between different factors, whereas other methods, such as regression analysis, typically focus on a single causal relationship.

2. Ability to deal with latent variables

SEM can effectively deal with latent variables that cannot be directly observed, which is particularly important in the research of ESG and crisis management. For example, latent variables such as corporate social responsibility or environmental awareness cannot be directly measured, but can be estimated through relevant observed variables (e.g., employee surveys, implementation of environmental policies, etc.). This property makes SEM very useful when exploring and quantifying these abstractions.

3. Provide model fit evaluation

SEM provides a variety of metrics to evaluate the fit of the model (e.g., CFI, TLI, RMSEA, etc.), which enables researchers to intuitively understand the fit of the model and make adjustments accordingly. In contrast, many traditional statistical methods, such as single regression analysis, often fail to provide such a comprehensive fit assessment, and it is easy to overlook the overall applicability of the model.

4. Recognize the impact of measurement errors

SEM can take measurement errors into account, which means it can provide more accurate estimates.

In ESG and crisis management research, SEM can help researchers better control the impact of these errors due to possible bias in data sources and collection methods, thereby improving the reliability of results.

5. Build complex causal models

SEM allows researchers to build and test complex causal models, which is particularly important when exploring the relationship between ESG integration and crisis management. For example, consider how environmental, social, and governance factors work together to impact supply chain resilience and performance. Other research methods may not be able to deal with such multi-level causation at the same time.

6. Adaptable

SEM has a high degree of flexibility, and researchers can adjust the model structure according to the research needs, and conduct multiple tests and optimizations, so as to continuously improve the explanatory power and prediction ability of the model. This adaptability makes SEM particularly well-suited to the rapidly changing supply chain environment and ESG requirements.

The advantages of structural equation modeling in ESG integration and crisis management research, especially in its ability to effectively deal with the complex relationship between latent variables and observed variables, evaluate model fitting, control measurement errors, and construct multi-level causal models, provide researchers with powerful analytical tools and insights, making it a more effective research method in exploring the sustainability and resilience of supply chains.

Model 12: Machine Learning Model

Machine learning models are methods developed by artificial intelligence. The application of machine learning models in ESG integration and supply chain crisis management not only improves efficiency and accuracy, but also enhances the ability of enterprises to respond to uncertainty and risk, thereby promoting sustainable development.

There are several advantages to using machine learning models:

1. Efficient data processing capabilities: Machine learning models can process large volumes and complex data, which is especially important in supply chain management. These models are able to collect data from a variety of sources, including suppliers, consumers, environmental impacts, and more, and quickly analyze that data to derive insights.

2. Prediction accuracy: Through training on historical data, machine learning models are able to identify trends and patterns to provide accurate predictions. For example, these models can predict changes in demand, supply chain disruptions, and their potential impacts, helping companies adjust their strategies in a timely manner.

3. Real-time responsiveness: Machine learning models have the ability to learn and adapt in real time, continuously updating their predictions and recommendations based on the latest data. This is crucial in crisis management, as being able to react quickly reduces losses and risks.

4. Multi-dimensional analysis: Machine learning is able to consider multiple variables and complex interrelationships at the same time to conduct multi-dimensional ESG assessments. This capability enables businesses to gain a more comprehensive understanding of the environmental and social impacts of their operations.

5. Enhanced decision support: By generating actionable insights, machine learning models are able to support management in making data-driven decisions. These insights are not limited to forecasting, but also include recommendations for optimal resource allocation and policy adjustments.

6. Continuous improvement: As the amount of data increases and the model is further trained, the predictive ability and accuracy of the machine learning model will improve, and continuous improvement will be achieved, which will have a positive impact on the long-term development of the enterprise.

The following is a table of the research applications of machine learning models including the model name, application purpose, key features, and references.

Table 11 Overview of the application of machine learning models in supply chain crisis management and ESG integration

The name of the model	Purpose of application	Key features:	What to expect
Supervised learning models	Anticipate supply chain crises	Trained with labeled data, it is able to identify potential crisis patterns and trends	Identify the key factors influencing ESG performance and their interactions
Unsupervised learning models	Perform data clustering and feature extraction	Clustering algorithms are used to identify similar features and identify potential problem areas or patterns	Improve the effectiveness of crisis management strategies and optimize resource allocation
Reinforcement learning models	Optimize decision-making processes and improve ESG performance	Learn the best strategies through trial and error to adapt to changing environments and dynamic needs	Provide comprehensive performance reviews to help develop improvement strategies
Deep learning models	Process large-scale data and perform complex pattern recognition	Multi-layer neural networks are used to automatically extract features and deal with nonlinear relationships	Understand the impact of CSR on business performance and promote socially responsible investment

Table 11 (Cont.)

The name of the model	Purpose of application	Key features:	What to expect
Time series prediction models	Anticipate changes in supply chain demand and adjust supply chain strategies in a timely manner	Analyze time series data to forecast future changes in demand and supply	Improve the systematization and integrity of supply chain management
Simulate future scenarios	Use SEM to simulate future scenarios to assess the potential impact of different policies or action options on the supply chain	Scenario simulation SEM model	Help managers anticipate and respond to future risks and challenges

1. Supervised learning model: Trained on labeled historical data, it can effectively predict the occurrence of supply chain crises and help enterprises formulate response strategies in advance.

2. Unsupervised learning model: Through cluster analysis, potential patterns in data can be found and decision support can be provided, especially in ESG assessment.

3. Reinforcement learning models: Ability to continuously adjust decision-making processes to improve ESG performance and adapt to dynamic supply chain environments.

4. Deep learning models: Suitable for processing large-scale and complex data, it can automatically identify nonlinear relationships and improve the accuracy of predictions.

5. Time series forecasting models: Leverage historical data to forecast future demand for more precise resourcing and risk management.

This table briefly summarizes the application of machine learning models in supply chain ESG integration and crisis management, and provides relevant references.

Conclusions and Recommendations

Conclusion

This paper emphasizes the value of mathematical models in ESG integration and supply chain crisis management and echoes the research goal of exploring the feasibility of different mathematical models and their practicability in crisis management. Through in-depth analysis, we found that mathematical models play a key role in supporting companies in navigating various crisis challenges. These models not only provide a framework for

risk identification and assessment, but also help companies optimize resource allocation to improve the resilience and sustainability of their supply chains. The need for ESG integration has become more prominent, and the application of mathematical models provides a clear path for companies to make informed decisions in the midst of uncertainty.

In the discussion of methodology, we analyze the advantages and disadvantages of various mathematical models, including optimization models, simulation models and machine learning models. Each model exhibits different advantages in specific scenarios, for example, optimization models have good performance in resource allocation and cost control, while machine learning models have shown strong potential in predicting future risks and trends. These analyses not only provide theoretical support for ESG integration in the academic community, but also provide practical reference for the industry when implementing relevant strategies.

Recommendations for future research

Future research should focus on the integration and empirical validation of these mathematical models to further deepen the understanding of ESG integration and its impact on supply chain management. With the increasing attention of ESG factors in global supply chain management, how to effectively use mathematical models to promote sustainable development will become an important research topic. In particular, consideration should be given to combining the strengths of different mathematical models to develop a comprehensive framework to adapt to changing market conditions and needs. In addition, future research can also explore the adaptability and effectiveness of mathematical models in different industrial contexts, so as to provide specific strategic suggestions for enterprises in different industries.

To sum, this study not only provides a rich theoretical basis for academic discussion in related fields but also provides practical guidance for decision-making in enterprise practice, and lays a solid foundation for future supply chain management. Further research and empirical evidence will help enhance the resilience of enterprises in the face of uncertainties and risks and promote a more sustainable development path.

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