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A Comprehensive Resilience Assessment Model for Smart Ports: A System Dynamics Simulation of Ningbo-Zhoushan Port in the Context of Digital Transformation

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Abstract

As a key node in the global supply chain, the resilience of ports is crucial for coping with multiple risks such as increasingly frequent climate change, operational accidents, and geopolitics, and ensuring the smooth flow of trade and sustainable development. This paper takes Ningbo-Zhoushan Port, which leads the world in throughput, as the research object, aiming to construct a comprehensive port resilience assessment model. Through the system dynamics method, the smart port system is deconstructed into three interrelated subsystems: meteorology, production, and economic-politics, and a simulation model including a causal relationship diagram and a system flow diagram is established accordingly. The model is verified to be effective and robust through historical data testing and sensitivity analysis. By setting different scenarios, this paper quantitatively analyzes the impact of single and compound risk shocks such as extreme weather, production accidents, and tariff policies on port throughput, and classifies port resilience into three levels: strong, medium, and weak. The research results show that Ningbo-Zhoushan Port shows strong resilience to the above-mentioned single risks. Even when the risk parameters are increased by 100%, the change rate of port throughput is less than the historical average annual change rate by 5.06%. However, in the extreme scenario of multiple risk couplings, the decline in port throughput is more significant, highlighting the importance of coping with compound risks. Further strategy simulation reveals that accelerating the economic development of the hinterland, increasing investment in port infrastructure, increasing the frequency of equipment maintenance, expanding the proportion of high-quality employees, and strengthening public facility management for accurate risk prediction are all effective ways to enhance port resilience. This research provides a scientific decision-making support tool for port managers, and the proposed resilience enhancement strategies have important theoretical and practical significance for ensuring the long-term stable operation of ports and the sustainable development of the regional economy.

Keywords: port resilience assessment; Ningbo-Zhoushan Port; system dynamics; smart port

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1. Introduction

As a key node and logistics hub in the global supply chain system, ports handle over 80% of global trade volume. The "node failure" of ports can cause cascading disruptions in the supply chain, easily triggering extensive chain reactions and posing a serious threat to the stability of the entire supply chain [1]. However, in recent years, the operating environment of global ports has become increasingly complex, and the multiple uncertainties they face have significantly increased. On the one hand, extreme weather events (such as super typhoons and severe storm surges) caused by climate change occur more frequently and with greater intensity, posing a continuous threat to port infrastructure and the safety of continuous operations [2,3]. On the other hand, "black swan" and "Grey rhino" events, such as geopolitical conflicts, trade protectionism, international sanctions, and fluctuations in tariff policies, emerge in an endless stream. In recent years, events such as the China-US trade friction, the blockage of the Suez Canal, and the global pandemic of COVID-19 have all had a severe impact on the normal operations of global ports, exposing the vulnerability of traditional port systems in the face of sudden disturbances and systematic risks, and further highlighting the importance and urgency of enhancing the resilience of port systems [4,5]. Therefore, in this context, how to scientifically quantify and evaluate the resilience performance of ports in the face of multiple and complex disturbances and systematically explore effective paths to enhance resilience based on this has become a core issue related to the security of the global supply chain and the sustainable development of the regional economy.

Since the concept of resilience was proposed in the field of ecology, it has continuously evolved and integrated, and intersected and integrated with multiple disciplines such as engineering, sociology, and management, and its connotation has been continuously enriched and deepened [6]. Current research generally believes that the resilience of modern ports is a comprehensive capability system covering multiple levels and dimensions. It requires ports to have the ability to cope with internal and external disturbances and pressures at multiple levels, including physical facilities, operational processes, organizational management, and the embedded supply chain network: not only being able to effectively absorb and mitigate shocks, maintain the basic operation of key functions, but also being able to quickly recover to the original state, or achieve system transformation through adjustment and adaptation, so as to reach a better new state [7,8]. Early research on port resilience mainly focused on coping with natural disasters, such as the damage to port facilities caused by typhoons, tsunamis, earthquakes, etc., and their recovery processes [9]. With the increasing complexity of the global supply chain, researchers have gradually realized that port resilience not only depends on the disaster resistance of infrastructure but also involves multiple factors such as management ability, policy response, economic adaptability, and social coordination [10].

In recent years, when scholars construct the conceptual framework and evaluation system of a port, they generally recognize that resilience is a multi-dimensional and dynamic composite concept and attempt to quantitatively evaluate the resilience level by constructing a multi-dimensional indicator system that includes reliability, redundancy, recovery speed, etc. [11]. From qualitative or semi-quantitative comprehensive evaluations based on expert interviews and the construction of indicator systems, to using network models to analyze the structural vulnerability of port systems and proposing optimization plans, and then to using simulation technology to simulate dynamic processes [12–14]. Some studies use the indicator system method to comprehensively evaluate port resilience by constructing evaluation indicators covering multiple dimensions such as infrastructure, operational management, and emergency response [15]. Other studies introduce methods such as system dynamics, Bayesian networks, and complex networks to explore

the dynamic relationships and feedback mechanisms between internal variables in port systems [16,17]. For example, some scholars construct a port resilience model based on system dynamics to simulate the response path and recovery process of ports under natural disasters or policy shocks [18,19]. At the same time, an empirical evaluation framework based on the perception of stakeholders has gradually emerged. Researchers construct a multi-level port resilience measurement framework based on surveys of stakeholders such as ports, hinterlands, enterprises, and governments, providing an important tool for the structural evaluation of port resilience. The evaluation methods of port resilience are developing in the direction of multi-dimensional, dynamism, modeling, and empiricism. However, existing research still has certain limitations: some simulation models are too simplified and fail to fully integrate the coupling effects among multiple subsystems, such as nature, operations, and the economy, while some comprehensive evaluation frameworks are comprehensive but lack the ability to predict the dynamic evolution process of resilience. Therefore, constructing an integrated analysis model that can reflect multi-dimensional influencing factors and simulate their dynamic interactions and long-term evolution processes is crucial for in-depth understanding and enhancing port resilience [20,21]. This is also the starting point for this study to attempt to construct a system dynamics model of the "environment—production—economic and political" multi-subsystems of the Ningbo-Zhoushan Port.

Research generally believes that port resilience is affected by a combination of various internal and external factors [22,23]. Natural environmental factors such as extreme weather (typhoons, floods, etc.), geographical location, and long-term trends of climate change are fundamental external factors that affect the safety and continuity of port operations; infrastructure and technological factors such as the redundancy of port facilities, the degree of digitization and intelligence directly determine the physical basis for ports to withstand shocks and recover quickly; operational and management factors; economic and market factors; as well as institutional and policy factors, etc. [24].

The factors affecting port resilience have been widely discussed in the academic community. Research generally believes that it is the result of the intertwined effects of multiple internal and external factors. In terms of natural environmental factors, extreme weather events such as typhoons, heavy rains, floods, and sea-level rise not only directly damage port infrastructure but may also cause channel siltation, ship delays, and interruptions in loading and unloading, and are fundamental external variables that threaten the safety and continuity of port operations [25]. In terms of infrastructure and technological factors, the redundancy of port facilities, earthquake and wind resistance capabilities, and the level of automation and intelligence directly determine the buffer capacity, function maintenance degree, and recovery speed of ports under shocks. Operational and management factors focus on the internal efficiency of the system and are the key to controlling endogenous risks and improving response efficiency [26,27]. Economic and market factors involve the external vitality and adaptability of the system. The scale and resilience of the hinterland economy, the diversity of goods, and the elasticity of market demand jointly determine the port's ability to withstand emergencies. Institutional and policy factors provide macro-level guarantees and guidance, including government planning, investment policies, trade agreements, and cross-departmental coordination mechanisms. The above factors are coupled with each other and jointly form the basis of the complex port resilience system [28].

As the world's largest trading country, the stable operation of China's ports is crucial for global trade. The Ningbo-Zhoushan Port, as an important hub port on the eastern coast of China, is one of the ports with the largest cargo throughput in the world [29,30]. However, this port is often affected by typhoons in summer every year, and the risk of natural disasters is prominent; its huge cargo throughput places extremely high requirements on wharf

operation efficiency and production safety; at the same time, as one of the main windows for China's foreign trade, it is extremely sensitive to fluctuations in international market demand and changes in trade policies [30]. Systematically evaluating and enhancing the resilience of the Ningbo-Zhoushan Port is not only related to its own safety and sustainable development but also of great significance for enhancing the reliability of the global supply chain [31].

The purpose of this study is to make up for the above deficiencies. Taking the Ningbo-Zhoushan smart port as a case, a system dynamics model covering meteorological, production, and economic and political subsystems is constructed to simulate the operating states of the port under different risk scenarios and resilience measures enhancement. Evaluate the resilience level of the Ningbo-Zhoushan Port under different single risk factors and combined risks, explore the influence mechanisms of key factors (such as public facility investment, equipment maintenance, employee quality, port investment, etc.) on port resilience, and put forward targeted policy suggestions and management strategies for enhancing the resilience of the Ningbo-Zhoushan Port and similar large ports.

2. Methods

This study aims to elaborate on the construction process of a system dynamics model for evaluating the port resilience of Ningbo-Zhoushan Port. First, the system boundaries and core assumptions of the model are defined to clarify the research scope and simplification conditions. Second, by drawing causal loop diagrams and system flow diagrams, the interaction mechanisms among various elements in the resilience system are revealed. Then, the basis for establishing the key equations in the model and the sources of the data used are explained in detail. Finally, through structural and historical tests, the validity and reliability of the model are verified, laying the foundation for subsequent scenario simulation analysis.

2.1. System Boundaries and Assumptions

To construct a model that focuses on key issues and is operable, this study reasonably defines and simplifies the real-world complex system.

This study regards the resilience of Ningbo-Zhoushan Port as a composite system composed of three interrelated and mutually influential subsystems: environment (meteorology), production (safety), and economic-political. The core functions of each subsystem are defined as follows:

Environmental subsystem: It mainly reflects the port's resistance and recovery capabilities when facing extreme weather events such as typhoons and heavy fog.

Production subsystem: It mainly reflects the port's buffering and rapid recovery capabilities when internal production accidents, such as mechanical failures and operational errors, occur.

Economic-political subsystem: It mainly represents the port's adaptability when dealing with geopolitical and economic fluctuations, such as international trade frictions and changes in tariff policies.

For quantitative analysis, the model sets clear boundaries in space and time:

Spatial boundary: Considering the close economic hinterland relationship between Ningbo-Zhoushan Port and Zhejiang Province, this study determines Zhejiang Province as the direct economic hinterland of Ningbo-Zhoushan Port. In the model, "hinterland GDP" refers to the GDP of Zhejiang Province.

Temporal boundary: The time span of the model simulation is from 2014 to 2028. Among them, 2014 is the base period of the simulation, 2014–2023 is the historical data

fitting period, 2024–2028 is the prediction and simulation period, and the simulation step is one year.

To simplify the complexity of the model and focus on the main contradictions, the following core assumptions are proposed:

(1) In the model, the investment amount of the port is only affected by the fixed—asset investment in the water transportation industry in its direct hinterland (Zhejiang Province), and direct investments at the national level or from other provinces are not considered for the time being. As a rational simplification for system dynamics modeling, this assumption is supported by the official regulations on port investment subjects in the Ningbo-Zhoushan Port Master Plan (2014–2030) and the actual port investment structure data released in the information disclosure reports of the Ningbo Municipal Finance Bureau.

(2) In the model, geopolitical and economic factors such as global economic fluctuations only affect the port through influencing the cargo throughput of international routes, and it is assumed that they have no direct impact on the throughput of domestic routes [32,33]. This setting is based on the operational characteristic that international maritime trade is more sensitive to global economic and political shocks, which has been verified in existing port resilience research.

2.2. Causal Loop Diagram and System Flow Diagram

Based on the analysis of the resilience-influencing mechanism, this study draws the causal loop diagrams of each subsystem, respectively, and finally integrates them into the overall system flow diagram.

The causal loop diagrams in this study were developed through a systematic two-stage process to ensure theoretical soundness and practical relevance, which is also aligned with the operational characteristics of Ningbo-Zhoushan Port:

(1) Literature synthesis: Initial variable selection and linkage design were based on established frameworks from port resilience and system dynamics research [31,32].

(2) Iterative refinement: The diagrams were refined through multiple internal reviews and team discussions to ensure clarity, completeness, and dynamic consistency [18].

This hybrid approach combines theoretical grounding with empirical validation, enhancing the robustness of the model structure.

2.2.1. Meteorological Factor Sub-System

Meteorological disasters are one of the main factors affecting port production. The variables included in the meteorological factor sub-system are: hinterland GDP, fixed investment assets, investment in the water transportation industry, port investment, the number of port facilities and equipment, port throughput capacity, public facilities management industry, the number of extreme weather events, the quantity of goods affected by extreme weather, natural handling tons of the port, and port revenue.

As can be seen from the causal relationship diagram of the meteorological factor sub-system in Figure 1, an increase in the hinterland GDP leads to an increase in fixed investment assets, which directly affects the number of port facilities and equipment, and increases the natural handling tons of the port. The increase in the number of facilities and equipment also reduces the impact of extreme weather. The increase in fixed investment assets also improves the public facilities management industry, enhances the prediction of extreme weather, and reduces the quantity of goods affected by extreme weather.

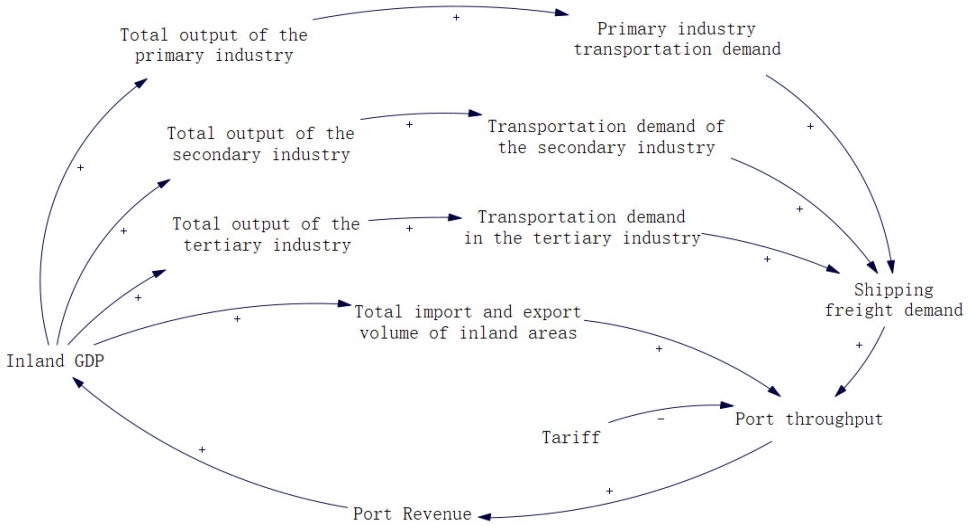


Figure 1. Causal relationship diagram of the meteorological factor sub-system.

2.2.2. Production Factor Sub-System

Production accidents are one of the factors affecting port production efficiency. The variables in the production factor sub-system include: hinterland GDP, fixed investment assets, investment in the water transportation industry, port investment, the number of port facilities and equipment, education expenditure, the number of high-quality workers in the port, the rate of production accidents, the number of production accidents, the volume of cargo handling affected by accidents, natural handling tons of the port, port revenue, and port throughput capacity.

As can be seen from the causal relationship diagram of the production factor sub-system in Figure 2, an increase in the hinterland GDP leads to an increase in fixed investment assets, which directly affects the number of port facilities and equipment, and increases the natural handling tons of the port. The increase in the number of facilities and equipment also reduces the impact of production accidents. The increase in the hinterland GDP also increases education expenditure, raising the number of college students per 10,000 people. As the education level of workers improves, the probability of production accidents also decreases, reducing the number of production accidents, increasing the natural handling tons of the port, and increasing port revenue.

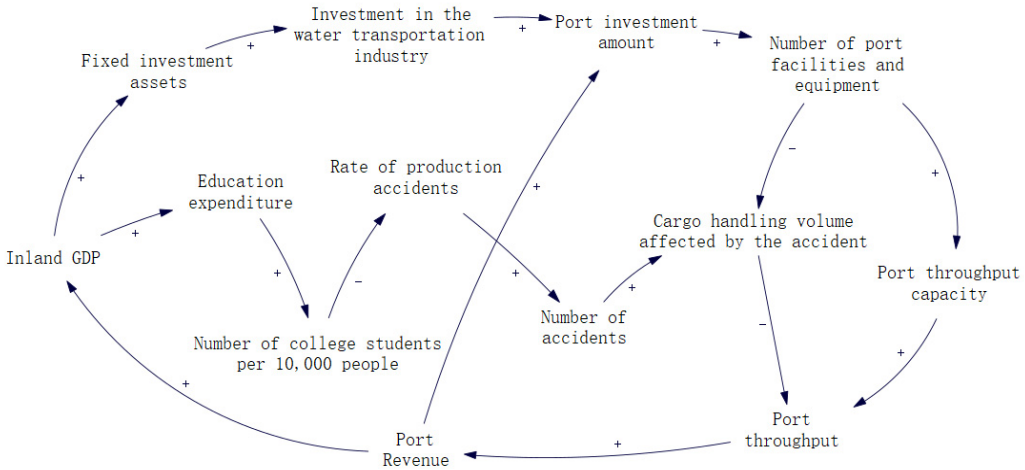


Figure 2. Causal relationship diagram of the production factor sub-system.

2.2.3. Economic and Political Factor Sub-System

As a node in the shipping industry, the port's handling volume is constantly affected by the development dynamics of the shipping industry. Economic and political factors, as one of the important factors affecting the shipping industry, also affect the port's handling volume. The economic and political influencing factors are too complex, and many factors are difficult to analyze quantitatively. Therefore, this paper mainly analyzes the changes in tariffs. The economic and political factors mainly include: hinterland GDP, the total output value of the primary, secondary, and tertiary industries, the transportation demand of the primary, secondary, and tertiary industries, the shipping freight demand, the total import and export volume of the hinterland, tariffs, natural handling tons of the port, and port revenue.

As can be seen from the causal relationship diagram of the economic and political factor sub-system in Figure 3, an increase in the hinterland GDP leads to an increase in the total output value of the primary, secondary, and tertiary industries, promotes an increase in the industrial transportation demand, and also affects the shipping freight demand, increasing the natural handling tons of the port. The increase in the hinterland GDP also promotes an increase in the total import and export volume of the hinterland, affecting the natural handling tons of the port. However, an increase in tariffs will lead to a decrease in the total import and export volume, reducing the natural handling tons of the port.

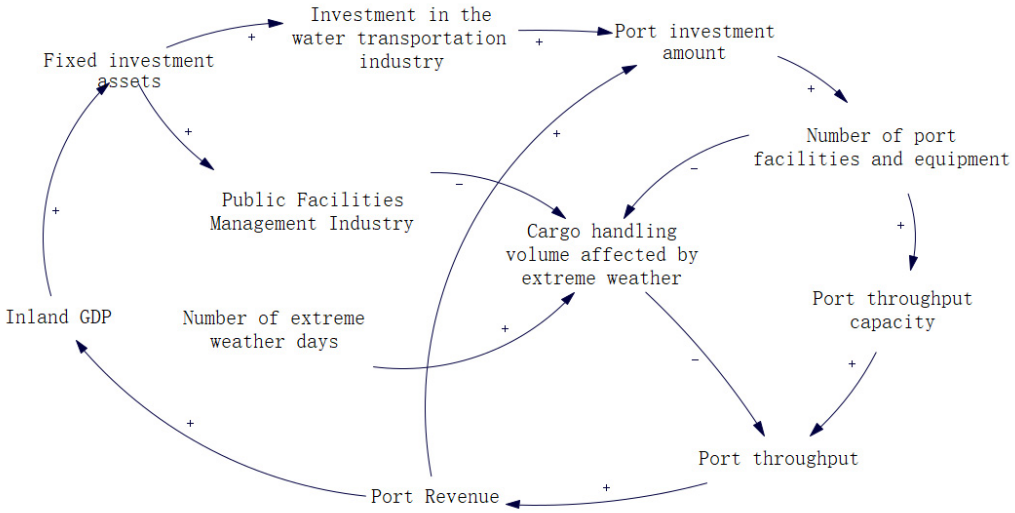


Figure 3. Causal relationship diagram of the economic and political factor sub-system.

2.2.4. Overall Causal Loop and Flow Diagram of the System

By integrating the three sub-systems, the overall causal loop diagram of the port resilience system of Ningbo-Zhoushan Port was drawn, and multiple key feedback loops were identified, such as the growth loop of "hinterland GDP → port investment → facilities and equipment → throughput → port revenue → hinterland GDP". On this basis, a system flow diagram including state variables, rate variables, auxiliary variables, and other elements was further drawn, and the types and units of all variables were clarified, providing a clear framework for subsequent equation writing and simulation.

2.3. Model Equations and Data Sources

2.3.1. Data Sources

The data required for the model mainly comes from official and authoritative sources such as China Port Yearbook, Zhejiang Statistical Yearbook, the database of the National Bureau of Statistics, and the Zhejiang Government Service Network, ensuring the reliability of the data.

2.3.2. Key Equations and Parameter Setting

The core relationships in the model are quantified through equations in various forms, such as table functions, linear functions, and constants. Parameter values are mainly determined based on regression analysis of historical data, industry reports, and expert experience. Taking the hinterland GDP (Zhejiang Province's GDP), a key state variable, as an example, its historical data from 2014 to 2023 are used for model calibration, and the predicted values from 2024 to 2028 are used as simulation inputs.

2.3.3. Prediction Method: Gray Prediction Model

For the data that need to be predicted (such as the future hinterland GDP), this study uses the gray prediction model GM (1,1), which is suitable for small-sample and trend prediction. First, a ratio test is conducted on the original sequence of Zhejiang Province's GDP from 2014 to 2023. All the ratio values σ(k) fall within the allowable coverage interval (see Table 1), which proves that the data are suitable for establishing a gray model. After modeling and calculation, the average relative error of the model fitting is less than 5% (see Table 2), indicating a good fitting effect. Thus, the predicted values of the hinterland GDP from 2024 to 2028 are obtained (see Table 3) and substituted into the system dynamics model.

As can be seen from Table 2, the relative error of the model obtained through fitting is <5%, which means that the model has a good fitting effect.

Table 1. Results table of ratio test.

Year	Original Value	Level Ratio
2014	40,023.5	-
2015	43,507.7	0.92
2016	47,254	0.921
2017	52,403.1	0.902
2018	58,002.8	0.903
2019	62,462	0.929
2020	64,689.1	0.966
2021	74,040.8	0.874
2022	78,060.6	0.949
2023	82,553.2	0.946

Table 2. Table of model fitting results.

Year	Original Value (100 Million Yuan)	Predicted Value (100 Million Yuan)	The Residual Error (100 Million Yuan)	The Relative Error (%)
2014	40,023.5	40,023.5	0	0
2015	43,507.7	44,601.354	−1093.654	2.514
2016	47,254	48,283.346	−1029.346	2.178
2017	52,403.1	52,269.298	133.802	0.255
2018	58,002.8	56,584.304	1418.496	2.446
2019	62,462	61,255.529	1206.471	1.932
2020	64,689.1	66,312.379	−1623.279	2.509
2021	74,040.8	71,786.689	2254.111	3.044
2022	78,060.6	77,712.922	347.678	0.445
2023	82,553.2	84,128.385	−1575.185	1.908

Table 3. Table of model prediction results.

Predicted Year	Predicted Value (100 Million Yuan)
2024	91,073.466
2025	98,591.887
2026	106,730.979
2027	115,541.980
2028	125,080.359

2.4. Model Validation

To ensure the scientific nature of the constructed model and the credibility of the simulation results, strict model verification was carried out.

2.4.1. Structural Validation

Model operation verification: After completing the input of the system flow chart and equations in the Vensim PLE software, www.vensim.com, use the "Check Model" function of the software to conduct dimensional consistency checks and syntax checks to ensure that the model has no structural errors and can run normally.

Sensitivity analysis: To test the robustness of the model to parameter changes, select the "impact coefficient of GDP on imports and exports" as the sensitive parameter for perturbation analysis. Use the formula $S(t) = [\Delta Y(t)/Y(t)]/[\Delta X(t)/X(t)]$ to calculate the sensitivity of key output variables (such as port throughput and hinterland GDP). The results in Figure 4 show that within the reasonable variation range of the parameters, the sensitivities of the output variables are all lower than 0.5, indicating that the model structure is relatively robust and not sensitive to parameter changes.

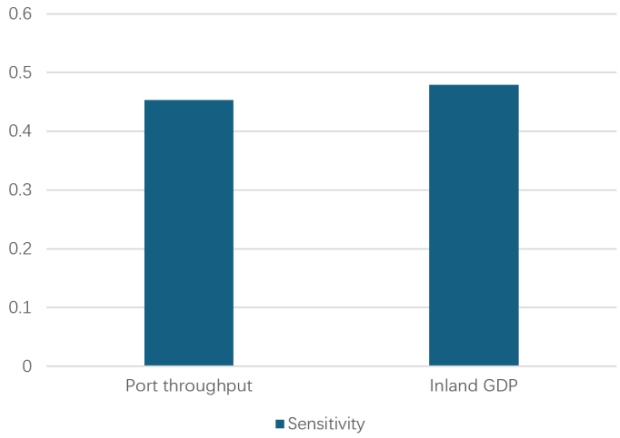


Figure 4. Model sensitivity analysis results.

2.4.2. Historical Validation

As shown in Tables 2 and 4, the effectiveness of the model is verified by comparing the degree of agreement between the simulated values of the model and the historical real values from 2014 to 2023. Two core indicators, hinterland GDP and port throughput, were selected for comparison. From the test results (corresponding to Tables 3 and 5 in the original text), it can be seen that the relative errors between the simulated values and the real values in most years are within ±5%, and only in individual years (such as the epidemic in 2020) due to external shocks, the errors are slightly larger. Generally speaking, the model can reproduce the historical system behavior well, has passed the historical test, and can be used for the simulation of future scenarios and policy analysis.

Table 4. Historical test results of the port resilience system dynamics model.

Year	Hinterland GDP (100 Million Yuan)			Port Throughput (100 Million Ton)		
	True Data	Simulation Data	Relative Error	True Data	Simulation Data	Relative Error
2014	40,023.5	40,023.5	0.00%	8.73	8.79	0.69%
2015	43,228.1	43,221.1	−0.64%	8.89	9.12	2.59%
2016	47,001.7	46,986.8	−0.53%	9.22	9.99	8.35%
2017	51,078	51,054.5	−2.53%	10.1	10.37	2.67%
2018	57,700.6	57,667.6	−0.52%	10.84	10.85	0.09%
2019	65,060.2	65,017.5	4.16%	11.19	11.37	1.61%
2020	70,098.1	70,046.7	8.36%	11.72	11.87	1.28%
2021	74,553.3	74,493.3	0.69%	12.24	12.38	1.14%
2022	78,776.5	78,708.3	0.92%	12.61	12.91	2.38%
2023	83,006.1	82,930	0.55%	13.24	13.47	1.74%

Table 5. Port resilience rating table for Ningbo-Zhoushan Port.

Port Resilience Level	Grade Range
High resilience	The change rate of port throughput < 5.06%
Medium resilience	5.06% ≤ The change rate of port throughput < 10.12%
Low resilience	The change rate of port throughput ≥ 10.12%

2.5. Analysis of Model Results

Relevant data and parametric equations from 2014 to 2023 are inputted to conduct a simulation analysis of the port throughput of Ningbo-Zhoushan Port. The port resilience of Ningbo-Zhoushan Port is reflected through the changes in the port throughput of Ningbo-Zhoushan Port under different scenarios in the following text. The simulation results after the model runs are shown in Figure 5.

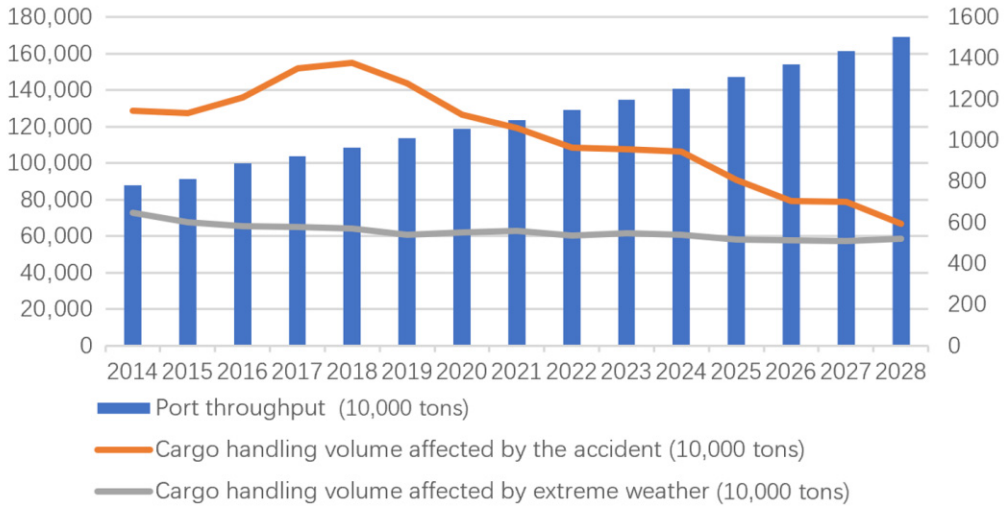


Figure 5. The comparison of model simulation results.

3. Results

Based on the constructed and verified system dynamics model of the port resilience of Ningbo-Zhoushan Port, a multi-scenario simulation is carried out in this chapter. First, different change scenarios of influencing factors are designed, and a quantitative standard for the resilience level centered on the change rate of port throughput is established. Then, the responses of the port under single-factor disturbances of meteorology, production,

economy and politics and multi-factor combined risks are simulated respectively to evaluate its inherent resilience level. Furthermore, the potential effects of a series of active resilience improvement measures are simulated. Finally, based on the simulation results, systematic suggestions for improving the resilience of Ningbo-Zhoushan Port are put forward.

3.1. Scenario Design

To scientifically evaluate the port resilience, it is necessary to set up simulation scenarios with comparability and establish a quantifiable resilience evaluation standard.

Port resilience is reflected by its ability to maintain core functions (here, cargo throughput) under external disturbances. This study focuses on three types of disturbance factors:

Meteorological factors: Taking the number of days of extreme weather as the core variable to simulate the impact of natural disasters.

Production factors: Taking the basic probability of production accidents as the core variable to simulate the internal operational risks.

Economic and political factors: Taking the import and export tariff rate as the core variable to simulate the impact of changes in the external trade environment.

To quantitatively evaluate the resilience level, the concept of "port resilience level" is introduced in this study. As shown in Table 5, based on the historical data of the throughput of Ningbo-Zhoushan Port from 2014 to 2023, the average annual growth rate is calculated to be 5.06%. Taking this as the benchmark, when a certain influencing factor deteriorates by 100%, the following is defined:

This standard means that a port with "high resilience" should have a throughput loss caused by a single major shock less than its natural annual growth under normal development conditions, which reflects the system's shock resistance and stability.

3.2. Resilience Simulation Analysis Under Different Sub-Systems

3.2.1. Simulation of Meteorological Factor Disturbances

This study adjusted the number of extreme weather days in the model to analyze the changes in port throughput at Ningbo-Zhoushan Port under increasingly severe meteorological disasters, aiming to study the port's resilience in the face of extreme weather. The simulation scenarios are shown in Table 6.

Table 6. Port meteorological resilience simulation scenarios.

Scenario	Scenario Design
Scenario 1	Base scenario: Number of extreme weather events remains unchanged at five days
Scenario 2	The number of extreme weather events increased by 100% in the baseline scenario, totaling ten days
Scenario 3	The number of extreme weather events increased by 200% in the baseline scenario, totaling fifteen days

As shown in Figure 6, the simulation results show that an increase in extreme weather days reduces port throughput. When the number of extreme weather days increases by 100% to 10 days, the annual throughput of Ningbo-Zhoushan Port decreases by 0.07%; when it increases by 200% to 15 days, the annual throughput decreases by 0.15%, both of which are significantly lower than the 5.06% high resilience threshold (the historical average annual growth rate of the port's throughput). It can be concluded that while the port throughput of Ningbo-Zhoushan Port is affected by the number of extreme weather days, the impact is minimal, demonstrating the port's strong resilience in the face of extreme weather.

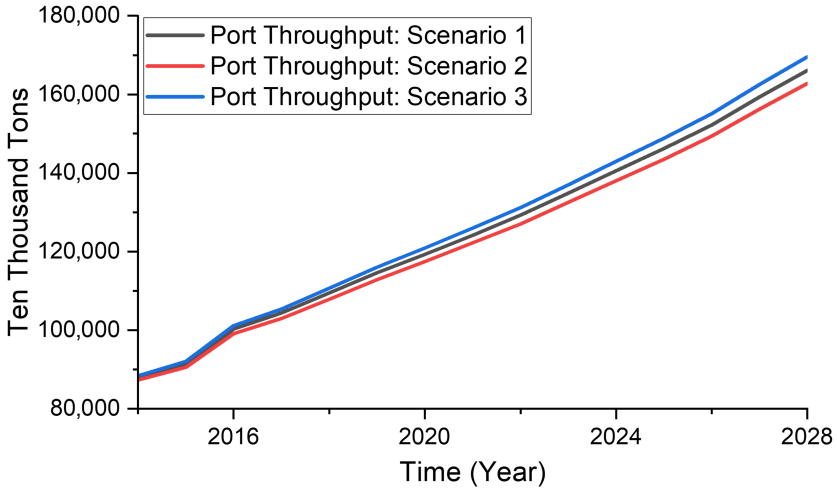


Figure 6. Simulation diagram of port meteorological resilience.

3.2.2. Simulation of Production Factor Disturbances

This chapter investigates the port resilience of Ningbo-Zhoushan Port in the face of production accidents by varying the base probability of such accidents. The simulation scenarios are shown in Table 7.

Table 7. Simulation design of port production resilience.

Scenario	Scenario Design
Scenario 1	Base scenario: The base probability of production accidents remains unchanged at 5%
Scenario 2	The base probability of production accidents increases by 100% in the baseline scenario, reaching 10%
Scenario 3	The base probability of production accidents is increased by 200% in the base scenario, reaching 15%

As illustrated in Figure 7, the simulation shows that when the probability increases to 10%, the average annual throughput decreases by 2.22%; when it increases to 15%, the average annual throughput decreases by 4.11%. When the risk of production accidents increases by 100%, the throughput loss rate (2.22%) is still lower than 5.06%, indicating that the port has high resilience to production accidents. This reflects the effectiveness of the port's investment in safety management, emergency plans, and redundant equipment. However, it is worth noting that the loss rate (4.11%) is close to the "high-resilience" boundary, indicating that production safety is a sensitive link in the resilience system. If the accident rate continues to rise, it will pose a significant threat to the system's stability.

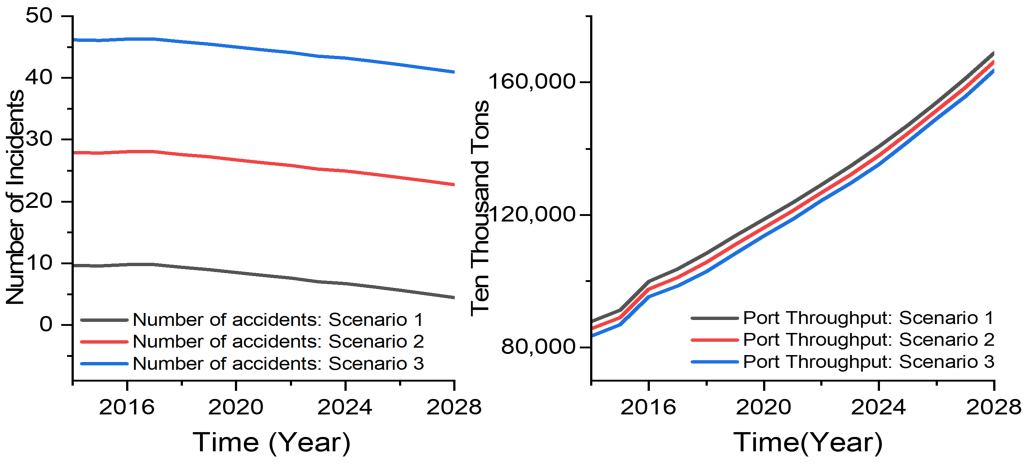


Figure 7. Simulation result diagram of port production resilience.

3.2.3. Simulation of Economic and Political Factor Disturbances

As a node in the shipping industry, the port is subject to various economic and political influences. This study selects import and export tariffs as the negative factor affecting port throughput. The specific simulation scenarios are shown in Table 8.

Table 8. Simulation design of port economic and political resilience.

Scenario	Scenario Design
Scenario 1	Base Scenario: Import and export tariffs remain unchanged at 5%
Scenario 2	Import and export tariffs increase by 100% from the base scenario, reaching 10%
Scenario 3	Import and export tariffs increase by 200% from the base scenario, reaching 15%.

The simulation results in Figure 8 show that when the tariff rate increases to 10%, the throughput of Ningbo-Zhoushan Port decreases by 2.03%; when the tariff rate increases to 15%, the throughput decreases by 4.07%. Although the port's throughput declines as tariffs rise, the magnitude of the decrease is significantly smaller than the rate of tariff increase. Moreover, when the tariff rate is increased by 100% from the baseline scenario, the port throughput change rate remains below 5.06%. It can be concluded that Ningbo-Zhoushan Port is minimally affected by tariff fluctuations and exhibits strong resilience to changes in the foreign trade environment.

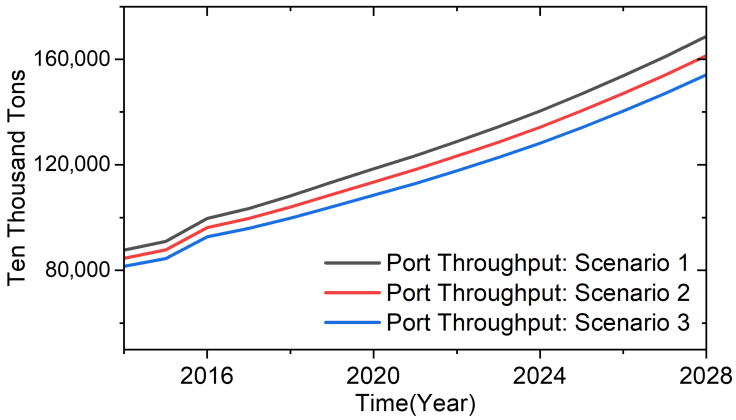


Figure 8. Simulation result diagram of port economic and political resilience.

3.2.4. Simulation of Combined Risks

This chapter examines the changes in port throughput when Ningbo-Zhoushan Port is simultaneously exposed to three risks: increased frequency of extreme weather, a higher base probability of production accidents, and elevated tariff rates. It analyzes the port's resilience under extreme conditions. The specific simulation scenarios are shown in Table 9.

Table 9. Combined risk simulation design.

Scenario	Scenario Design
Scenario 1	Base Scenario: Original parameters unchanged
Scenario 2	Extreme weather days increased by 5 days, the production accident base probability rose by 5%, and tariffs increased by 5%

The simulation results in Figure 9 show that when all three risks occur simultaneously, the throughput of Ningbo-Zhoushan Port decreases by an average of 51.5805 million tons, which can be attributed to the interactions among various factors within the system dynamics model. However, even under such severe simulated conditions, the port's throughput is reduced by only 4.17%, which is lower than its average annual throughput

change rate of 5.06%. This demonstrates that Ningbo-Zhoushan Port possesses strong resilience in the face of various risks, enabling it to maintain relatively stable operations and minimize losses during disruptive events.

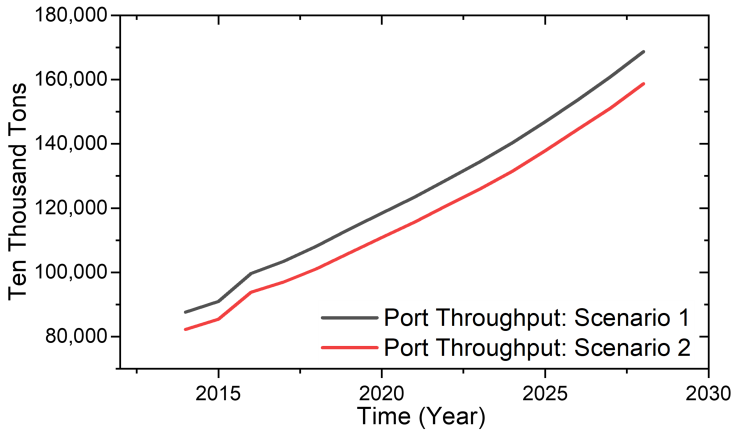


Figure 9. Simulation result diagram of combined risk.

3.3. Simulation Analysis of Resilience Improvement Measures

3.3.1. Measures to Improve the Meteorological Sub-System

Increasing investment in the public facilities management industry, improving the accuracy of meteorological forecasts, and enhancing the timeliness of predictions can effectively mitigate the impact of extreme weather on port loading and unloading operations, thereby increasing port throughput. The simulation scenarios are shown in Table 10.

Table 10. Investment simulation design for the public facilities management industry.

Scenario	Scenario Design
Scenario 1	Base Scenario: Investment share in public facilities management remains unchanged
Scenario 2	Investment share in public facilities management decreases by 5% annually
Scenario 3	Investment share in public facilities management increases by 5% annually

According to the simulation results in Figure 10, increasing investment in the public facilities management industry can reduce the volume of cargo handling affected by extreme weather at Ningbo-Zhoushan Port, thereby increasing the port's throughput and enhancing its resilience. A 5% increase in the investment share of the public facilities management industry reduces the cargo handling volume affected by extreme weather by 5.12%, leading to a 1.79% increase in port throughput compared to the baseline scenario.

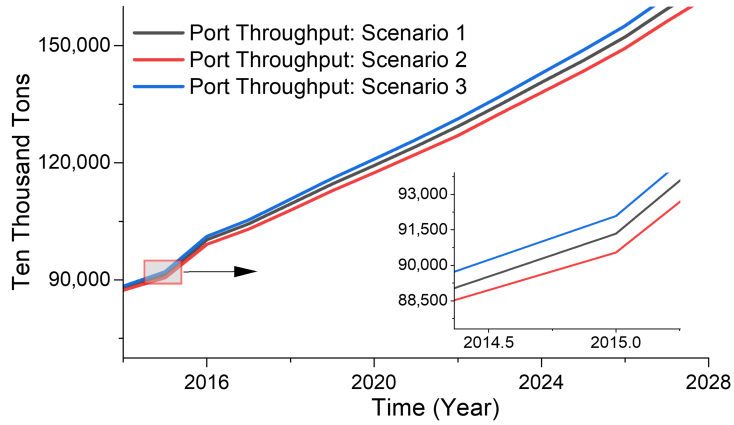


Figure 10. Simulation result diagram of investment in the public facilities management industry.

3.3.2. Measures to Improve the Production Sub-System

Increasing the maintenance frequency of port machinery can reduce the probability of equipment failures, decrease the number of production accidents at the port, and enhance port resilience. These parameter assumptions are based on the recommended routine inspection frequencies specified in the Code for Maintenance of Port Infrastructure. The specific simulation scenarios are shown in Table 11. Increasing the proportion of highly qualified employees at the port can effectively improve its resilience. The number of employees with a bachelor's degree or above is used as a proxy for the number of highly qualified employees at Ningbo-Zhoushan Port. The specific simulation scenarios are shown in Table 12.

Table 11. Mechanical maintenance frequency simulation design.

Scenario	Scenario Design
Scenario 1	Base scenario: Maintenance frequency remains unchanged at 10 times per year
Scenario 2	Maintenance frequency increases to 15 times per year
Scenario 3	Maintenance frequency decreases to 5 times per year

Table 12. Simulation design for proportion of high-quality employees.

Scenario	Scenario Design
Scenario 1	Base Scenario: Proportion of high-quality employees remains unchanged
Scenario 2	Proportion of high-quality employees increases by 5% annually
Scenario 3	Proportion of high-quality employees increases by 10% annually

The simulation results in Figure 11 show that when the maintenance frequency increases to 15 times per year, the number of production accidents occurring annually decreases by 1.825 incidents, and the volume of cargo handling affected by accidents decreases by 2.4759 million tons per year. When the maintenance frequency decreases to 5 times per year, the number of production accidents occurring annually increases by 1.825 incidents, and the volume of cargo handling affected by accidents increases by 2.4759 million tons per year. Increasing the maintenance frequency by five times per year reduces the volume of cargo handling affected by accidents by 25.76%, which significantly enhances the port's resilience in the face of production accidents and reduces the losses caused by such accidents.

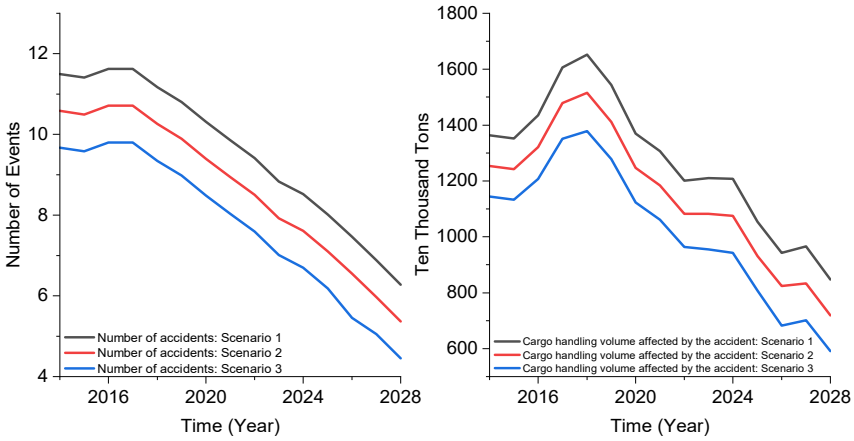


Figure 11. Simulation result diagram of mechanical maintenance frequency.

As depicted in the Figure 12, when the proportion of highly qualified employees increases by 5% annually, the number of production accidents decreases by 0.913 incidents per year, and the volume of cargo handling affected by accidents decreases by

1.238 million tons per year. When the proportion of highly qualified employees increases by 10% annually, the number of production accidents decreases by 1.825 incidents per year, and the volume of cargo handling affected by accidents decreases by 2.4917 million tons per year. Increasing the proportion of highly qualified employees by 5% annually reduces the volume of cargo handling affected by production accidents by 10.12%. The higher the number of employees with a bachelor's degree or above at the port, the lower the losses incurred during production accidents and the greater the port's resilience.

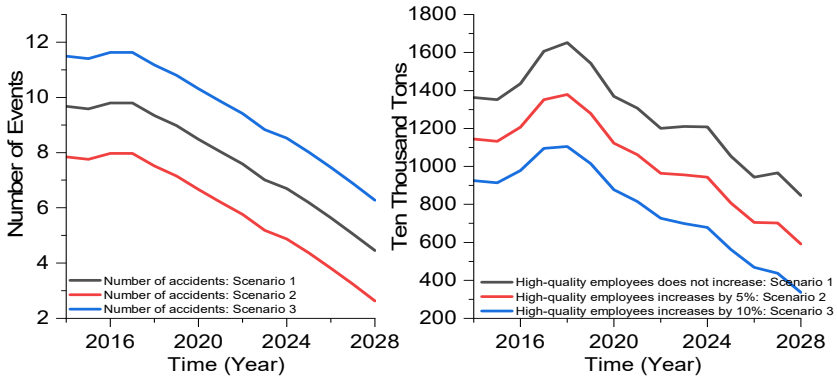


Figure 12. Simulation result diagram of high-quality employees.

3.3.3. Measures to Improve the Economic and Political Sub-System

Hinterland economic growth provides strong support for port throughput. As the hinterland economy expands, industrial transportation demand increases, leading to more goods being traded via shipping, which in turn boosts port throughput. The specific simulation scenarios for hinterland GDP growth are presented in Table 13.

Table 13. Backland GDP simulation design.

Scenario	Scenario Design
Scenario 1	Base Scenario: Backland GDP remains unchanged
Scenario 2	Backland GDP grows by 10% annually
Scenario 3	Backland GDP grows by 20% annually

Increasing the proportion of port investment raises the total investment amount, thereby expanding the number of port facilities and equipment. This enhances the port's throughput capacity and market competitiveness, ultimately increasing port throughput. Furthermore, a greater quantity of facilities and equipment strengthens the port's risk resistance capability, thereby improving its resilience. The specific simulation scenarios are shown in Table 14.

Table 14. Port investment amount simulation design.

Scenario	Scenario Design
Scenario 1	Base Scenario: Port investment share remains unchanged
Scenario 2	Port investment share increases by 1%
Scenario 3	Port investment share increases by 2%

As shown in Figure 13, when GDP increases, shipping demand grows rapidly, thereby driving an increase in port throughput. Hinterland GDP growth directly reflects the expansion of regional production, consumption, and trade scale, generating substantial demand for cargo transportation and providing the port with a stable source of cargo. It serves as the most powerful support for the port when facing reductions in cargo imports

and exports due to geopolitical and other factors, effectively enhancing the port's resilience against economic and political risks.

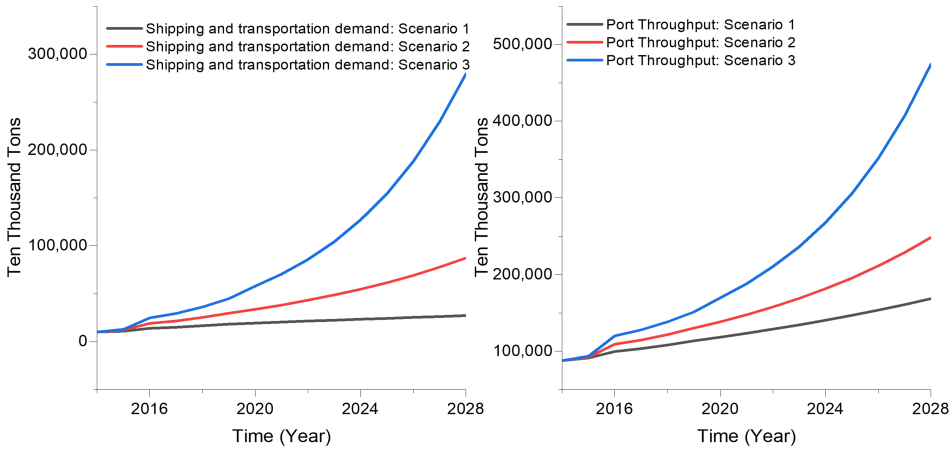


Figure 13. Simulation result chart of hinterland GDP.

As shown in Figure 14, for every 1% increase in port investment, both port throughput capacity and actual throughput experience significant improvement. Specifically, a 1% increase in port investment leads to an average increase of 5.37% in port throughput capacity and an average increase of 4.31% in port throughput. Increasing port investment expands the number of facilities and equipment, enhances port throughput capacity, effectively boosts port throughput, and improves port resilience.

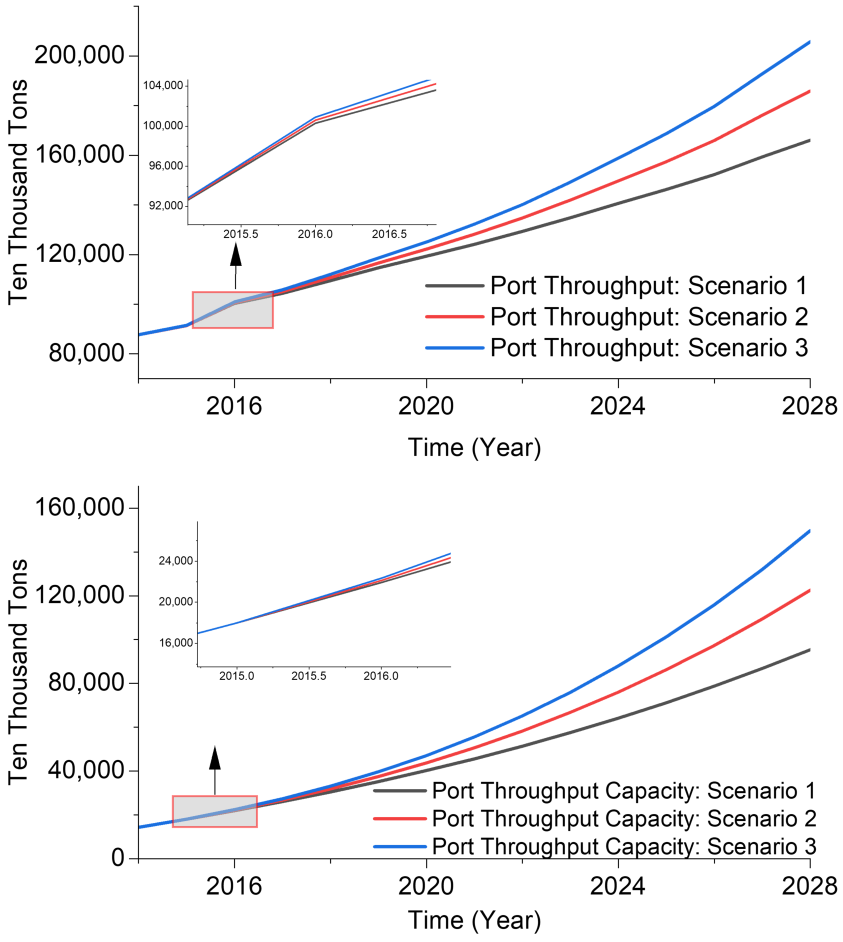


Figure 14. Simulation results of port investment.

4. Discussion

Building upon the simulation results presented in Section 3, this section delves into a discussion of the key findings to interpret the resilience characteristics of Ningbo-Zhoushan Port and derive managerial implications.

4.1. Analysis of Port Resilience Under Single and Compound Risks

Ningbo-Zhoushan Port exhibits a high level of inherent resilience in the face of single meteorological, production, and economic-political risks. Even when the core risk variables are increased by 200%, the port's throughput loss rate remains far below the 5.06% high resilience threshold defined by the historical average annual growth rate of throughput. This robust resilience is not accidental but stems from the port's multiple endogenous advantages and external support conditions, and targeted improvement measures can further amplify such resilience with cost-effective effects.

For meteorological risks, the negligible throughput loss (0.07% and 0.15% under 100% and 200% disturbance) is attributed to the high-standard construction of port infrastructure, such as breakwaters with strong disaster resistance and wind-resistant design of core loading and unloading equipment, which forms a solid physical barrier against extreme weather. In addition, the relatively perfect meteorological early warning and emergency response system enables the port to adjust operational plans in advance, minimizing the impact of short-term extreme weather on cargo handling. The large-scale throughput of the port also provides a natural buffering capacity for temporary operational interruptions, making the impact of extreme weather on the overall throughput almost negligible. Investing in more accurate meteorological prediction, early-warning systems, and disaster-prevention infrastructure can effectively transform the port's "passive response" into "active prevention", which is a cost-effective strategy for improving meteorological resilience. The simulation data quantifies the economic benefits of "technological disaster prevention" and provides a concrete basis for the port's relevant investment decisions on public facilities management.

In terms of production risks, the throughput loss rate of 2.22% and 4.11% under disturbance reflects the port's effective safety management system. The port's continuous investment in equipment redundancy construction, standardized safety operation procedures, and regular emergency drills has significantly reduced the probability and impact of production accidents. However, it is worth noting that the 4.11% loss rate under 200% disturbance is close to the 5.06% high resilience threshold, indicating that production safety is a sensitive link in the port's resilience system. If the production accident rate continues to rise, it will pose a potential threat to the stable operation of the port, which needs to be highly valued by port managers. Two targeted measures of increasing equipment maintenance frequency and improving the proportion of high-quality employees reveal the key paths for improving production resilience, starting from the perspectives of "things" and "people" respectively. Increasing the maintenance frequency is a periodic investment that can directly reduce the equipment failure rate, while improving the quality of employees is a long-term and fundamental investment that can reduce human error rates and improve emergency response capabilities. The combination of the two can build a safe production resilience system of "human-machine collaboration" for the port, realizing dual improvement of production resilience in the short and long terms.

For economic and political risks, similar to the production factors, the throughput loss (2.03%) caused by a 100% increase in tariffs is lower than the resilience threshold, indicating that Ningbo-Zhoushan Port also has high resilience to trade policy fluctuations. This resilience stems from two core aspects: first, the strong hinterland economy of Zhejiang Province, where the internal and external trade structures are complementary to a certain extent, hedging the negative impact of single trade policy changes; second, the port's

status as a global shipping hub, where some rigid international shipping demands are less affected by price elasticity. The port's perfect shipping network and diversified cargo sources further enhance this anti-disturbance ability. However, the simulation results also suggest that continuous trade barriers combined with other risk factors will still have a substantial negative impact on the port's operational performance, which cannot be ignored in long-term risk management.

Under the compound risk scenario where extreme weather, production accidents, and tariff rates all increase by 5 percentage points, the port's throughput loss rate is 4.17%, which is still within the high resilience range, fully demonstrating the overall robustness of the port's resilience system. Even under the rare combined risk shock, the throughput loss rate (4.17%) is still lower than the average annual growth benchmark of 5.06%, which strongly proves the overall robustness of the port resilience system of Ningbo-Zhoushan Port. However, compared with single-factor disturbances, the losses under combined shocks show a non-linear accumulation characteristic (slightly greater than the simple addition of single-factor losses), revealing the potential vulnerability coupling between subsystems. Extreme weather may affect the normal operation of port equipment and increase the probability of production accidents; trade policy fluctuations may reduce the port's infrastructure investment motivation and further weaken its disaster resistance capacity, leading to the formation of a "risk chain reaction" within the system. This highlights the need to be vigilant against the "risk chain reaction" in risk management and the necessity of adopting a systematic defense strategy for the port, rather than coping with various risks in isolation.

4.2. Analysis of the Effects of Resilience Improvement Measures

The simulation results of resilience improvement measures show that all targeted measures for the three subsystems can effectively improve the port's resilience level, and different measures exhibit obvious heterogeneous response characteristics, reflecting the diversity and hierarchy of the port's resilience improvement paths.

For the meteorological subsystem, increasing the investment proportion of the public facilities management industry by an average of 5% annually can reduce the cargo handling volume affected by extreme weather by 5.12% and increase the port's throughput by 1.79%. This measure realizes the transformation of the port from "passive disaster response" to "active disaster prevention" by improving the accuracy of meteorological prediction and the completeness of disaster prevention facilities. It is a short-term and cost-effective resilience improvement strategy, and the investment effect is direct and measurable, which can quickly improve the port's ability to resist meteorological risks.

In the production subsystem, two measures of increasing equipment maintenance frequency and improving the proportion of high-quality employees show different effect characteristics. Increasing the equipment maintenance frequency from 10 times to 15 times a year can reduce accident-related cargo damage by 25.76%, with a more significant short-term effect. This is because increasing maintenance frequency directly reduces the probability of equipment failure, the main cause of production accidents, and the investment in maintenance can quickly translate into the improvement of the production safety level. Increasing the proportion of high-quality employees by an average of 5% annually can reduce accident-related cargo damage by 10.12%, which is a long-term and fundamental improvement measure. High-quality employees have stronger operational standards awareness and emergency response capabilities, which can reduce human errors in the production process and improve the overall operational efficiency of the port. The combination of these two measures forms a "human-machine collaboration" production

safety resilience system, which can realize the dual improvement of the port's production resilience in the short and long term.

For the economic and political subsystem, the growth of hinterland GDP and the increase in port investment are the two core drivers of enhancing the port's long-term strategic resilience. The additional 10% annual growth of hinterland GDP strongly drives the growth of industrial transportation demand and shipping freight demand, providing a stable and continuous cargo source for the port, which is the fundamental "ballast stone" for the port to resist external economic and political risks. Every 1% increase in port investment can drive an average 4.31% growth in port throughput by expanding the number of port facilities and equipment and improving the port's throughput capacity and market competitiveness. Port investment not only directly improves the port's operational capacity but also enhances its risk resistance capacity by optimizing infrastructure layout and increasing equipment redundancy, forming a positive feedback loop of "investment-capacity improvement-resilience enhancement-throughput growth". The two measures complement each other, with the hinterland economy providing external demand support and port investment improving internal operational capacity, jointly building the long-term resilience foundation of the port's economic and political subsystem.

4.3. Practical Implications

4.3.1. Implications for Port Managers

First, establish a compound risk early warning and integrated management mechanism. In view of the non-linear accumulation effect of compound risks, the port should set up a cross-departmental resilience management committee, integrate the data and resources of meteorological, production, operation, and trade departments, build a multi-risk integrated early warning platform, and regularly carry out stress tests and emergency drills under different compound risk scenarios. Formulate integrated business continuity plans to avoid the "risk chain reaction" between subsystems and improve the port's ability to respond to extremely complex situations.

Second, adopt a "short-term + long-term" combined resilience improvement strategy. In the short term, prioritize increasing the investment in the public facilities management industry and the maintenance frequency of port machinery to quickly improve the port's ability to resist meteorological and production risks, and achieve rapid results in resilience improvement. In the long term, focus on cultivating high-quality employees and optimizing the talent training and introduction system, improve the overall quality of the port's operational team, and at the same time strengthen the in-depth cooperation with the hinterland economy to realize the coordinated development of port and hinterland industries, laying a solid foundation for the sustainable improvement of the port's resilience.

Third, optimize the port's investment structure and implement refined investment management. Allocate port investment funds to intelligent early warning systems, automated terminals, green disaster prevention infrastructure, and equipment redundancy construction in a focused manner, and avoid blind investment in low-efficiency projects. Evaluate the investment effect of various resilience improvement measures in a quantitative way and adjust the investment direction and proportion according to the simulation results and actual operation data to realize the maximization of the investment efficiency of resilience improvement.

4.3.2. Implications for Local and National Policy Makers

First, strengthen the integrated development of the port-hinterland economy and consolidate the economic foundation of port resilience. The local government should take Ningbo-Zhoushan Port as the core, promote the industrial structure upgrading and

high-quality development of Zhejiang Province and the Yangtze River Delta region, deepen the integration of port, industry and city, and build a port-hinterland industrial chain and supply chain with close links and complementary advantages. Expand the port's economic hinterland, strengthen the economic and trade cooperation between the port and the central and western regions, and further enhance the buffering capacity of the hinterland economy for the port's external risks.

Second, introduce targeted support policies for port resilience construction and provide policy and financial guarantees. The government should give tax incentives and financial subsidies to the port's investment in intelligent transformation, disaster prevention and mitigation infrastructure, and talent training, and encourage the combination of government and social capital to participate in the construction of port public facilities. Establish a special fund for port resilience construction to support the port's research and development and application of new technologies and new equipment in disaster prevention, safety production and intelligent operation, and reduce the cost of the port's resilience improvement.

Third, build a regional port group resilience coordination system and realize the sharing of disaster prevention and risk response resources. Taking Ningbo-Zhoushan Port as the core, integrating the resources of other ports in the Yangtze River Delta port group, build a regional port resilience network, realize the sharing of meteorological early warning information, emergency rescue equipment and professional technical personnel, and form a joint force to resist risks. Formulate unified regional port resilience evaluation standards and management norms, coordinate the resilience construction of each port, avoid vicious competition among ports, and improve the overall resilience level of the regional port system. At the national level, incorporate port resilience construction into the national transportation development strategy, and provide overall planning and guidance for the resilience improvement of major coastal hub ports, so as to enhance the overall stability of China's port system and the global supply chain.

5. Research Implications and Limitations

5.1. Research Implications

Building on the systematic simulation analysis and in-depth discussion of port resilience in Sections 3 and 4, this section summarizes the theoretical and methodological contributions of this study to the research on smart port resilience from four key dimensions.

(1) Methodologically, system dynamics effectively captures the coupling relationships and dynamic feedback mechanisms among the meteorological, production, and economic-political subsystems. It simulates throughput evolution under various risk scenarios and quantifies the effects of resilience-enhancing measures, addressing the limitations of static evaluation methods in analyzing complex dynamic systems.

(2) Empirically, the results reveal that port resilience exhibits strong disturbance resistance under single risks but demonstrates nonlinear accumulation under compound risks. For Ningbo-Zhoushan Port, throughput losses from single risks remain below the high-resilience threshold, while losses from compound shocks exceed the sum of individual losses—highlighting a vulnerability coupling effect among subsystems. This finding confirms that compound risk chain reactions are critical to both resilience research and management.

(3) Strategically, resilience enhancement follows a path of hierarchical heterogeneity across subsystems: technological disaster prevention in the meteorological subsystem, human–machine collaboration in the production subsystem, and port-hinterland economic integration coupled with infrastructure investment in the economic-political

subsystem. These differentiated pathways provide a theoretical foundation for building multidimensional port resilience systems.

(4) Methodologically, for assessment, this study proposes a resilience classification threshold (5.06%) based on the historical average annual throughput growth rate, categorizing port resilience into three levels (high, medium, low). This quantitative framework offers a reference standard for assessing the resilience of similar global hub ports.

5.2. Limitations and Research Implications

This study has several limitations. First, the model simplifies the complex geopolitical and economic dynamics by using tariff rates as the sole proxy, potentially overlooking nuanced influencing factors such as non-tariff trade barriers and global supply chain reconfiguration. Second, the simulation parameters are primarily derived from historical data (2014–2023) and expert empirical assumptions, which limit the model's ability to capture the impacts of unprecedented future disruptions such as extreme climate events and unforeseen black swan incidents. Third, as a single-case study of Ningbo-Zhoushan Port—a large-scale global shipping hub—the generalizability of the findings to other ports with different scales, governance structures, or regional economic contexts requires further empirical validation.

Future research could address these limitations in a targeted manner: first, incorporate more granular geopolitical and economic risk indicators (e.g., the Geopolitical Risk Index) to refine the depiction of the external trade environment; second, integrate real-time IoT and digital twin data to develop an adaptive system dynamics model for port resilience, enhancing the model's dynamic response to emergent risks; third, conduct comparative case studies across diverse port types (e.g., coastal hub ports, inland river ports, regional feeder ports) to identify both context-specific and generalizable resilience mechanisms for smart ports.

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