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A framework for understanding the path to achieve high resilience of maritime supply chain

Xiuqian Chen[1], Liangyong Chu[1,2] ✉, Mengyao Wang[1] & Qion Chen[1]

In recent years, a significant rise in international sudden risk events has resulted in impacts and disruptions to maritime supply chains (MSC). The resilience of maritime supply chains has garnered attention from the academic, industrial, and government sectors. The paper proposes a methodological framework based on the structural equation model (SEM), Necessary Condition Analysis (NCA), fuzzy set qualitative comparative analysis (fsQCA), and utilizes questionnaire data from the maritime industry in China to evaluate the resilience in MSC. The computational results indicate that: (1) The high resilience of MSC is the result of the synergistic interaction among multiple factors, and these factors boost MSC resilience through diverse paths; (2) There are four pathways for high MSC resilience: the 'collaboration + carbon reduction + digitization' path, the 'early warning + collaboration' path, the 'agility + early warning' path, and the 'carbon reduction' path; (3) Digitization level can play a catalytic role in increasing the resilience of MSC by helping other factors. This paper reveals the multiple routes to enhance the resilience of MSC, which can instruct MSC members to choose the correct resilience management strategies based on their existing resources and situations and can help both practitioners and researchers to understand in more detail of the various dimensions and nuances of resilience in the context of MSC.

Currently, over 80% of global goods are transported by ships. However, in the past few years, the frequent occurrence of major international emergencies has brought great challenges to the security of the MSC[1]. In February 2020, the outbreak of COVID-19 led to 8.5% of global container congestion in ports, triggering a surge in shipping prices[2]. In March 2021, the Suez Canal was blocked for 6 days, and more than 1000 cargo ships were routed around the Cape of Good Hope in Africa[3]. In February 2022, the Russia-Ukraine conflict resulted in the sudden closure of Ukrainian ports, affecting the global security of energy and food supply chains. In December 2023, the Red Sea crisis caused about 82% of container ships on the Suez Canal route to be diverted, greatly increasing the cost of shipping from Asia to Europe. Given the increasing complexity of the global trade landscape, the resilience of the MSC, as a key factor in global supply chain security, is becoming increasingly prominent[4].

To enhance the resilience of MSC, we need to address the following issue: "How can maritime-related enterprises use their resources to build a resilient MSC?" .When discussing the resilience of MSC, most existing scholars rely on statistical techniques that are based on the assumption of independent variables, unidirectional linear relationships and symmetrical causality[5]. These techniques analyze the marginal "net effect" of independent variables on dependent variables while controlling for other factors, and thus fail to explain the complex causal relationships, such as the interdependencies among independent variables[6,7]. In reality, the resilience of maritime supply chains is not influenced by a single factor alone, it is likely subject to the influence of multiple factors, with different elements interdependent and interconnected[8]. Additionally, it is important to recognize that different combinations of these elements can lead to the same outcomes, hence the pathways to achieve high resilience in maritime supply chains are not singular[9].

The configurational perspective and qualitative comparative analysis (QCA) adopt a holistic analytical approach, treating the research object as a configuration of different combinations of conditional variables[10]. This approach integrates the strengths of case study and variable research methods, and through set analysis, it uncovers the relationship between element configurations and outcomes[11]. It is instrumental in addressing complex causal issues such as multiple concurrent causal relationships, causal asymmetry, and the equivalence of

[1]College of Navigation, Jimei University, Xiamen 361021, Fujian, China. [2]Fujian Shipping Research Institute, Xiamen 361021, China. ✉email: chuliangyong@163.com

various solutions[12]. This perspective represents a new path in management research. Currently, configurational perspective and QCA have been widely applied across various fields of management, including strategic management, business model innovation, corporate governance, human resources, international business, and digital transformation[10–14]. However, its application in the resilience of MSChas not yet been explored.

To address the limitations of existing research, this paper proposes an analytical framework for enhancing the resilience of MSC based on the configurational perspective and QCA. The framework integrates SEM, Necessary NCA, and fsQCA to systematically investigate the pathways to improving MSC resilience. The reasons for employing this analytical framework are as follows: Firstly, SEM is based on a structured model that incorporates a large number of items and constructs, which can be used to examine the impact of individual factors on MSC resilience[15,16]. However, this analytical approach is limited to examining the average influence of exogenous constructs on endogenous constructs[17]. Sencdly, fsQCA is a type of QCA method, which has the advantage of being able to handle fuzzy data[18]. This method is particularly useful for analyzing how different configurations of conditions generate specific outcomes for different groups of cases[19,20]. However, the fsQCA method can only qualitatively determine whether the antecedent conditions are necessary for the outcome[21]. Thirdly, NCA is a method that helps researchers identify the necessity of individual conditions, assess their effect size and statistical significance, and determine to what extent a predictor variable acts as a bottleneck to the outcome variable[22,23]. NCA can complement and expand methods such as SEM and fsQCA[22,23].In this way, our study proposes a new analytical framework to verify the 'causal complexity' of MSC resilience and enriches the application of quantitative research in this area. Specifically, this paper reveals the multiple paths to achieve high resilience of MSC, which can help MSC members to choose the appropriate resilience management strategy based on their existing resources and situations.

The remaining part of this paper is organized as follows: Sect. 2 is literature reviews. Section 3 provides theoretical background and hypothesis development. Section 4 outlines the methodological framework of the expanded analytical process. Section 5 conducts empirical analysis. Section 6 presents the conclusion.

Literature reviews
Maritime supply chains
MSC is a network structure composed of upstream and downstream enterprises or departments providing maritime services to the ultimate users[5]. Fernando et al.[6]defined the maritime supply chain as a linked structure that integrates essential logistics functions such as transportation, storage, and information processing, in accordance with the physical flow of goods from their place of origin to destination. This process is collaboratively completed by related enterprises in the maritime, port, and terrestrial sectors, with shipping companies at its core[7]. MSC includes maritime equipment suppliers (shipbuilding companies and fuel suppliers etc.), maritime service suppliers (shipping companies or agents), maritime demand parties (shippers or their agents), as well as ports and customs[8]. The network structure of MSC is shown in Fig. 1.

Maritime supply chains resilience
The concept of supply chain resilience means the ability of a supply chain to respond to unforeseen disruptions and return to normal operation[24,25]. Ribeiro et al.[26]believed that a resilient supply chain should be capable of preparing for, responding to, and recovering from disruptions, while maintaining positive steady-state operations within acceptable costs and time frames. Rodrigue[27]pointed out that the resilience of a transport system is its capability to resume operations at a level similar to that before a disruption occurred. As the MSC has been
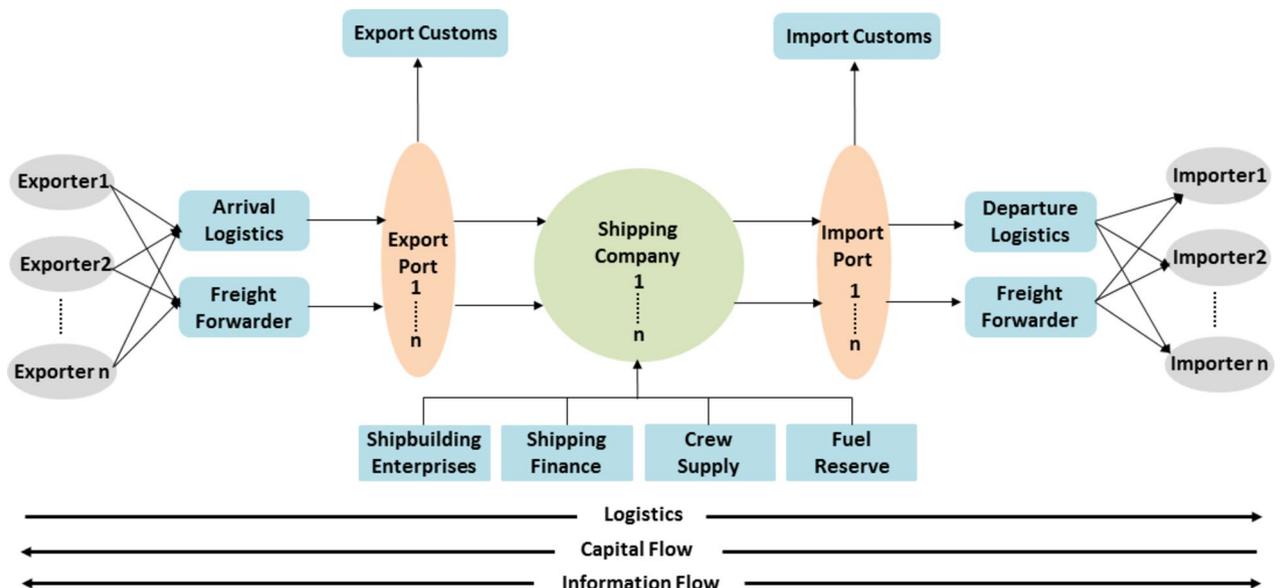

Fig. 1. Maritime supply chain network structure.

exposed to risks and disasters due to its complexity, vulnerability, and uncertainty, the resilience-building is a critical approach to mitigating risks and keeping the competitiveness[28]. The definition of MSC resilience can be defined as the capacity of the MSC to promptly respond to the risks of international maritime disruptions, and to maintain or restore stable operations to its initial state[4,5,9].

Paths to enhancing the resilience of MSC

Scholars have made preliminary explorations on how to improve the resilience of MSC. Lam and Bai[5] developed an original quality function deployment approach to enhance MSC resilience. They found that contingency plans, monitoring and maintenance, and supply chain relationship management are the top three measures that enhance resilience. Gu et al.[29] proposed an integrated method that combines the Best-Worst Method and fuzzy TODIM (Interactive and Multi-criteria Decision-Making, the acronym in Portuguese) approach to prioritize strategies for MSC resilience. Their findings demonstrated that the accelerated container turnover, human resource backup, and long-term shipping contracts emerge as paramount strategies for effectively improving resilience. Zavitsas et al.[30] established a link between environmental and network resilience performance for MSC and provides a methodological framework to analyze the impact of various abatement options, regulatory and pricing strategies. Liu et al.[9] concluded that robustness and adaptability are the two most important resilience goals, and the resilience strategy of collaboration and flexibility should be paid more attention in the post COVID-19 era. Liu et al.[28] pointed out that "Government support", "Resource sharing", "Emerging technology", "Maritime infrastructure", and "Redundancy plan" are significant enablers in enhancing MSC resilience during pandemic, in which the most influential enabler is the redundancy plan.

The configurational perspective and qualitative comparative analysis

The configurational perspective and the QCA method, as an emerging research paradigm, are well-suited for analyzing the causal complexity of concurrent multi-factor issues and have been widely applied in management research[10–14]. Zheng et al.[10] employed fsQCA to identify alternative configurations leading to high innovation performance from the perspective of knowledge management and innovation ecosystems. Alnoor et al.[11] utilized a three-stage SEM-fsQCA-MCDM to identify the optimal configuration of marketing influencers on impulsive buying behavior. Linyu et al.[12] employed the the panel data-based qualitative comparison method to analyze the driving factors that affect the green development of energy systems in various countries and the configuration effect on the vertical axis of time and its synergistic promotion path.

Hypothesis development

Current research on pathways to enhancing the resilience of supply chains most frequently adopts the Dynamic Capabilities Theory (DC)[31–36] and the Organizational Information Processing Theory (OIPT)[37–40]. The DC emphasizes the dynamic attributes of resource capabilities[31,32]. 'Dynamic' refers to the ability to continuously adjust and innovate in response to changes in the external environment, while 'capabilities' include the ability to build, integrate, and restructure for reuse[33,34]. Supply chain resilience precisely addresses the issue of supply chain disruption caused by external shocks in a dynamic and unpredictable environment[35,36]. According to the DC, combined with the increasingly complex international trade situation and decarbonization requirements faced by the maritime supply chain, this paper believes that agility, cooperation and carbon emission control are the key factors to improve the resiliences of the MSC.

The OIPT is a theoretical framework about how organizations process and use information[37]. The OIPT theory emphasizes that in the information age, organizations need to process and use information efficiently to adapt to the rapidly changing environment[38]. The core of OIPT theory is to understand how an organization optimizes its decisions and actions through information processing[39]. Digitalization can improve the transparency and circulation speed of upstream and downstream information in the MSC, help maritime related enterprises better cope with challenges in a complex and uncertain environment, and thus improve the resilience of the MSC[40]. Thus, according to OIPT, this paper believes that early warning ability and digitalization level are the key factors to improve the MSC resiliences .

Therefore, based on the theory of DC and OIPT, this paper posits hypotheses regarding the impact on MSC resiliences from five perspectives: early warning capability, agility, collaboration, digitalization level, and carbon emission control.

Early warning capability and MSC

Early warning capability refers to the ability to predict unexpected events and prepare in advance[41]. Alliger et al.[42] believed that early warning capability can help organizations develop plans before the risk event. Mittal et al.[43] viewed early warning capability as a market sensing ability, which reflects a company's ability to perceive market opportunities and threats. Kanamoto et al.[44] pointed out that early warning capability can be reflected in two aspects: risk awareness and visibility. Risk awareness helps enterprises quickly identify maritime-related risks and take appropriate measures, thus minimizing the risk of interruption[45]. The visibility of the MSC will enhance its warning capability[46]. Therefore, the following hypothesis is proposed:

H1. Early warning capability positively affects MSC resilience.

Agility and MSC

MSC face risk shocks because they cannot respond timely to market demand changes or supply interruptions[47]. Agility enables enterprises to act more quickly, select appropriate plans and strategies to reduce the impact of interruptions, and thus achieve faster recovery[48]. Moreover, agility can compress response time, reduce interruption costs, and maintain the shipping industry's competitive advantage, thereby improving the resilience

of MSC[38]. The complexity of the MSC and the dynamic adjustment capabilities of the core enterprises affect the agility of the MSC[43]. Therefore, we propose the following hypothesis:

H2. Agility positively affects MSC resilience.

Collaboration and MSC

Collaboration refers to the ability to effectively collaborate with partners in the supply chain to quickly respond to disruptions[49]. Simatupang et al.[50] believed that collaboration is "the glue that holds supply chain partners together in a crisis". Wu et al.[51] indicated that strengthening collaboration among supply chain members can enhance the response ability to supply chain disruptions, and thus improve supply chain resilience. Lai et al.[52] proved that information sharing will improve the collaboration of the MSC, thus mitigating the "bullwhip effect" of MSC. The information sharing, collaboration mechanisms, profit, and risk-sharing mechanisms impact the Collaboration of the MSC[53]. Based on these, we propose the following hypothesis:

H3. Collaboration positively affects MSC resilience.

Digitalization level and MSC

Bahrami and Shokouhyar[39] proved that supply chain resilience requires more support from data science than ever before. Firstly, digitalization can improve the organization's capability to prepare for supply chain-related emergencies by gathering internal and external information[54]. Secondly, when a disruptive event occurs, digitalization can enable companies to collect a wealth of information from various sources throughout the supply chain to support quick decision-making and timely risk response[55]. Thirdly, prior experience, information, and knowledge of dealing with disruptive events contribute to the improvement of supply chain resilience[56]. Therefore, the following hypothesis is proposed:

H4. Digitalization level positively affects the resilience of MSC.

Carbon reduction and MSC

In 2023, the carbon emissions of the shipping industry exceeded 1 billion tons, accounting for 2–3% of the global total, and the shipping industry is undergoing a green and low-carbon transformation[42]. In 2018, the International Maritime Organization (IMO) established carbon emission reduction targets for the shipping industry: Compared to 2008, the total greenhouse gas emissions from international shipping should be reduced by at least 50% by 2050[62]. On November 1, 2022, the International Convention for the Prevention of Pollution from Ships entered into force, compelling all ships to calculate their existing ship energy efficiency index[58]. On April 25, 2023, the European Council adopted five legislative proposals to address climate change, with shipping emissions being included in the European Emissions Trading System for the first time[59]. Therefore, the level of carbon emission control will become a key factor for the future MSC resilience[60]. Hence, we propose that:

H5. Carbon reduction positively affects MSC resilience.

The combination effect of these factors on MSC

As the MSC is an open complex system with numerous enterprises[8], and the resilience of MSC is not necessarily affected by a single factor, having only a single capability is difficult to achieve high MSC resilience[9]. Based on configurational perspective[10–14], this paper proposes hypothesis 6.

H6. MSC resilience is the result of the combination effect of multiple factors.

Integrating the above assumptions, this article proposes a conceptual model of factors influencing the resilience of MSC, as shown in Fig. 2:

Methodology

Figure 3 presents the methodological framework of the study[22]. In stage 2, the SEM method is utilized to examine the impact of individual factors on MSC resilience. In stage 3, the NCA and fsQCA methods are employed to investigate the synergistic effects of multiple conditions on MSC resilience. All methods employed in this study were carried out in accordance with relevant guidelines and regulations. All experimental protocols in this sduty were approved by College of Navigation, Jimei University, and informed consent has been obtained from all participants in the questionnaire survey or their legal guardians.

Structural equation model

The SEM includes four parts: the measurement model, the structural model and the model assumptions. In the measurement model, we can measure the internal structure of latent variables through manifest variables[16]. In this study, a total of six potential variables are considered, including early warning capability, agility, Collaboration, digitalization level, carbon reduction, and the resilience of MSC. The first five variables serve as exogenous variables, while the resilience of MSC is the endogenous variable. Because all six variable data in this study are obtained through a questionnaire survey, both the exogenous and endogenous variables are latent. The model is shown as follows[17]:

The measurement model:

$$y = \Lambda_y \eta + \varepsilon \tag{1}$$

$$x = \Lambda_x \xi + \delta \tag{2}$$

The structural model:

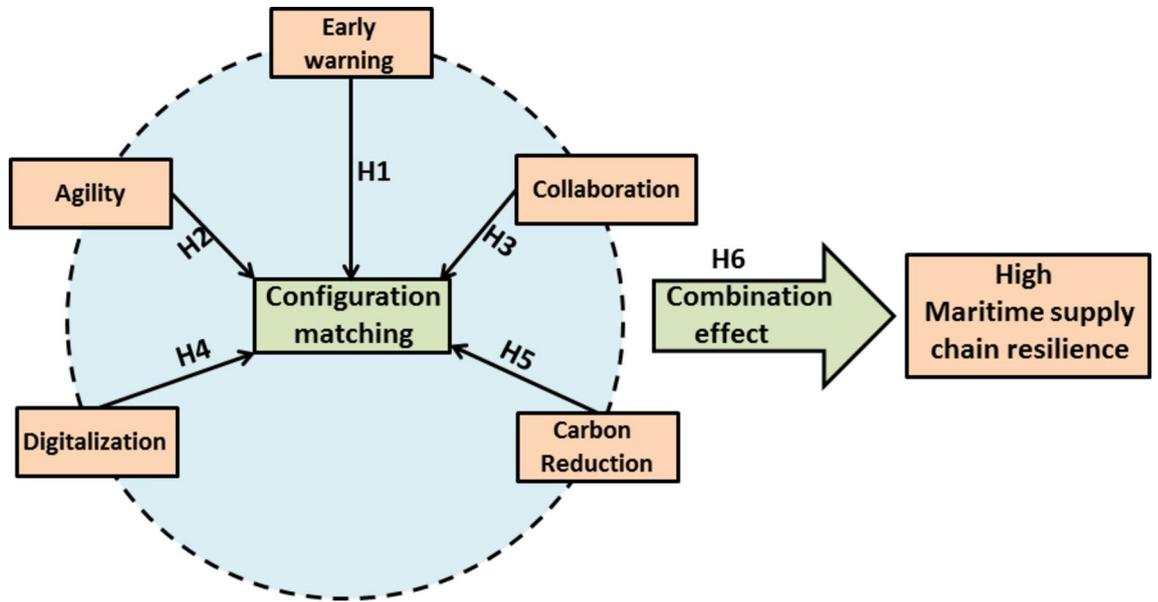$$\eta = B\eta + \Gamma \xi + \zeta \tag{3}$$

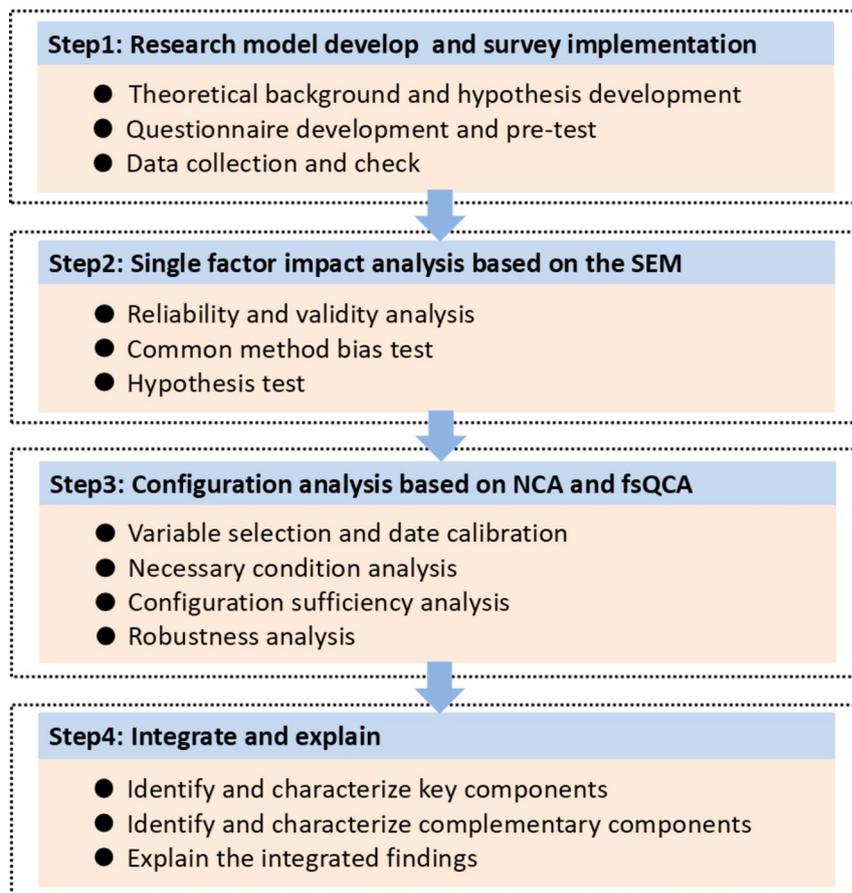**Fig. 2**. Conceptual model of factors impacting the resilience of maritime supply chains.

Fig. 3. Methodological framework.

Equation (1) is the measurement equation of the endogenous variable, y is a $p \times 1$ vector composed of p endogenous indicators, η is a $m \times 1$ vector composed of m endogenous latent variables (factors), Λ_y is the $p \times m$ factor loading matrix of y on η, and ε is a $p \times 1$ vector composed of p measurement errors. Equation (2) is the measurement equation of the exogenous variable, x is a $q \times 1$ vector composed of q exogenous indicators, ξ is a $n \times 1$ vector composed of n exogenous latent variables (factors), Λ_x is the $q \times n$ factor loading matrix of x on ξ, and δ is a $q \times 1$ vector composed of q measurement errors. In the structural Eq. (3), B is an $m \times m$ coefficient matrix that describes the influence between endogenous latent variables η; Γ is an $m \times n$ coefficient matrix that describes the influence of exogenous latent variables ξ on endogenous latent variables η; and ζ is a $m \times 1$ residual vector.

Based on the measurement model and the structural model, the covariance matrixes are shown as follows.

$$\sum{}_{xx}(\theta) = \Lambda_x \Phi \Lambda_x' + \Theta_\delta \tag{4}$$

$$\sum{}_{yy}(\theta) = \Lambda_y \breve{B} \left(\Gamma \Phi \Gamma' + \Psi \right) \breve{B}' \Lambda_y' + \Theta_\varepsilon \tag{5}$$

$$\sum{}_{yx}(\theta) = \Lambda_y \tilde{B} \Gamma \Phi \Lambda_x' \tag{6}$$

Equation (4) is the covariance matrix of x, Φ is the covariance matrix of the latent variable ξ, Θ_δ is the covariance matrix of δ; Eq. (5) is the covariance matrix of y, Ψ is the covariance matrix of the residual term ζ, Θ_ε is the covariance matrix of ε; Eq. (6) is the covariance matrix of y and x; Eq. (7) is the covariance matrix of the $(p+q) \times 1$ vector composed of all indicators (y', x').

$$\sum (\theta) = \begin{pmatrix} \Lambda_y \breve{B} (\Gamma \Phi \Gamma' + \Psi) \breve{B}' \Lambda_y' + \Theta_\epsilon & \Lambda_y \tilde{B} \Gamma \Phi \Lambda_x' \\ \Lambda_x \tilde{B} \Gamma \Phi \Lambda_y' & \Lambda_x \Phi \Lambda_x' + \Theta_\delta \end{pmatrix} \tag{7}$$

The model assumptions:
  (1) The mean of the error terms ε and δ in the measurement equation is zero;
  (2) The mean of the residual term ζ in the structural equation is zero;
  (3) The error terms ε and δ are uncorrelated with the factors η and ξ, and ε and δ are uncorrelated;
  (4) The residual term ζ is uncorrelated with ξ, ε, and δ.

Fuzzy set qualitative comparative analysis and necessary condition analysis

Sociologist Ragin (1987) introduced the Qualitative Comparative Analysis (QCA) method in 1987. This method employs set theory and Boolean algebra operations to identify necessary and sufficient conditions that affect outcomes, thereby determining which factors are crucial for the occurrence of results and further understanding the interactions among factors[18]. fsQCA is a type of QCA method, which can effectively analyze the interaction of more than 3 variables and is suitable for addressing configuration issues[19,20]. However, the fsQCA method can only qualitatively determine whether the antecedent conditions are necessary for the outcome[22]. The NCA method can measure the antecedent conditions that are necessary for the result at "a specific level"[23]. The integration of fsQCA with NCA exhibits a higher degree of scientific rigor[22].

Empirical analysis
Questionnaire survey
Questionnaire design
This paper uses survey data as samples to examine the influence factors and their combination mechanisms on the resilience of the MSC. The questionnaire items use the Likert five-level scale measurement, where "1→5" respectively represents "completely disagree, a bit disagree, unclear, agree, completely agree"[21]. The specific measurement indicators and sources of each variable are shown in Table 1.

Data collection
Beginning in May 2023 and ending in November 2023, with the help of the China Shipowners' Association, this study distributed questionnaires to over a hundred MSC-related companies in China. The individuals who completed the questionnaire were experienced maritime industry staff and managers. We applied multiple questionnaire survey methods such as face-to-face interviews (distributing 20 copies), questionnaires online (distributing 150 copies), and email (distributing 75 copies), and ultimately 151 valid questionnaires were obtained, with a valid questionnaire recovery rate of 61.6%.

Sample descriptive analysis
We can find in Table 2 that the survey respondents cover various types of maritime-related companies in China, and the questionnaire compilers include senior, middle, and grassroots staff, which ensures the reliability of the questionnaire data.

Single-factor impact analysis based on the SEM
Reliability and validity analysis
The reliability of the scale data is generally assessed by two indicators: the internal consistency coefficient (Cronbach's α) and the composite reliability. The SPSS 26.0 software (Statistical Package for the Social Sciences

Variable	Question Items	Reference source
Early warning (EA)	EA1: Our company can accurately predict the fluctuations in the shipping market.	Alliger et al.[39] and Kanamoto et al.[41]
	EA2: Our company can dynamically monitor and assess key risks in maritime transportation.	
	EA3: Our company has established a comprehensive maritime risk warning mechanism.	
	EA4: Our company can establish smooth risk information transmission channels with upstream and downstream enterprises in the MSC.	
Agility (AG)	AG1: Our company can quickly adjust resources such as routes, capacity, personnel, and equipment in the face of maritime emergencies.	Belhadi et al.[44] and Omer et al.[47]
	AG2: Our company can quickly adjust its business processes in the face of maritime emergencies.	
	AG3: Our company can quickly carry out organizational restructuring in the face of maritime emergencies.	
	AG4: Our company has emergency plans and regular drills for various maritime emergencies.	
Collaboration (CO)	CO1: Our company has established long-term and stable cooperative relationships with customers.	Wu et al.[50] and Lai et al.[51]
	CO2: Our company has established long-term and stable cooperative relationships with upstream and downstream partners in the MSC.	
	CO3: We have clear collaboration goals, organizations, processes, and mechanisms for sharing benefits and risks between our company and enterprises in the MSC.	
	CO4: Our company has a high level of information sharing with upstream and downstream enterprises in the MSC.	
Digitalization (DL)	DL1: Our company has improved the operational efficiency and decision-making level of maritime-related businesses through digitization.	Ambulkar et al.[55] and Bahrami and Shokouhyar[34]
	DL2: Our enterprise can provide customers with a full process visualization and one-stop supply chain logistics solution through digitization.	
	DL3: Our maritime supply chain has established a big data platform to integrate, share and collaborate with trade, maritime, logistics and customs data.	
	DL4: The MSC in which our company operates utilizes digital technologies such as blockchain to achieve paperless documentation.	
Carbon Reduction (CR)	CR1: Our company has established a clear carbon emission control plan.	Zhang et al.[60] and Wang et al.[59]
	CR2: Our company strictly implemented carbon emission control as planned.	
	CR3: Our company actively uses green shipping related decarbonization technology.	
Maritime supply chain resilience (MSCR)	MSCR1: Our company has the ability to adapt to MSC shocks.	Lam and Bai[5] and Shi et al.[4]
	MSCR2: Our company is able to respond quickly to MSC shocks.	
	MSCR3: Our company can reduce its losses in the face of MSC shocks.	

Table 1. Measurement items of influence factors on maritime supply chain resilience.

26.0, https://spss.mairuan.com/xiazai.html) is used for reliability analysis, and the results are shown in Table 3. The Cronbach's α and composite reliability value of each variable all exceed 0.8, indicating that the scale used in this study has good reliability[54].

The validity analysis of the scale includes content validity, structural validity, convergent validity, and discriminant validity. The scales used in this study refer to internationally published and validated mature scales in international journals, which to a certain extent ensure the content validity of this study[17]. The results of the confirmatory factor analysis show that $\chi 2/df = 2.476 < 3$, RMSEA = 0.089 < 0.1, RMR = 0.042 < 0.05; GFI = 0.936, NFI = 0.949, CFI = 0.923, IFI = 0.924, all greater than 0.9, indicating the scale has good structural validity[16]. The factor loadings of all items are greater than 0.5, the average ex-traction variance (AVE) of each factor is greater than 0.5, and the composite reliability is greater than 0.8 for each factor, demonstrating that the scale has good convergent validity[17]. The square root of the AVE for each variable is greater than the correlation coefficient between that variable and other variables, testifying that the scale has good discriminant validity.

Common method bias test
In this study, the Harman single factor method is employed to test for common method bias in the questionnaire survey conducted[17]. From Table 4, it can be observed that there are five factors with eigenvalues greater than one, exceeding the single factor. Moreover, the variance explained by the largest factor is 38.351%, which is below 40%. Therefore, we can conclude that there is no severe common method bias present in the current study.

Hypothesis test
Based on the good model fitting, this study conducted a SEM test using the SPSS 26.0 software. The hypothesis testing results are presented in Table 5, and the single factor impact analysis diagram is shown in Fig. 4.

From Fig. 4; Table 5, it can be seen that the early warning capability ($\beta = 0.43$, $p < 0.05$), agility ($\beta = 0.337$, $p < 0.1$), collaboration ($\beta = 0.46$, $p < 0.01$), digital level ($\beta = 0.372$, $p < 0.01$), carbon reduction ($\beta = 0.464$, $p < 0.01$), all have a significant positive impact on the resilience of the maritime supply chain. Hypotheses H1-H5 are supported by the SEM.

Configuration analysis based on NCA and fsQCA
Variable selection and date calibration
Based on the previous theoretical analysis and empirical research results, this study selects early warning capability, agility, collaboration, digital level, and carbon emission control as conditional variables, and MSC resilience as the result variable. The fsQCA3.0 software (Fuzzy-Set Qualitative Comparative Analysis 3.0, https://sites.socsci.uci.edu/~cragin/fsQCA/software.shtml) is used to calibrate each variable data into fuzzy set membership degrees between 0 and 1. Firstly, the mean value of each variable corresponding to the item is

Item	Description	Accounted for
Enterprise nature	Foreign-funded enterprises	15%
	State-owned enterprises	48%
	Private enterprises	30%
	Hong Kong, Macao and Taiwan enterprises	4%
	Joint venture	3%
Enterprise scale (size of the staff)	<100	32%
	101–300	17%
	301–500	8%
	501–1000	12%
	1001–2000	9%
	>2001	22%
Which department in the maritime supply chain does the enterprise belong to	Shipping companies	33%
	Port groups	14%
	Freight forwarding companies	22%
	shipping agent companies	5%
	Shipbuilding companies	3%
	Crew service companies	1%
	Marine fuel oil supply company	3%
	Shipping finance companies (insurance, finance leasing, etc.)	2%
	Import and export companies	9%
	Shipping-related government departments (customs, maritime bureau, commodity inspection, etc.)	3%
	Port collection and distribution companies (road, railway, inland river, etc.)	2%
	Others	3%
Position of respondent	Enterprise senior management	26%
	Enterprise middle management	46%
	Enterprise grass-roots staff	28%

Table 2. Descriptive analysis of samples.

Item	EA	AG	CO	DL	CR	MSCR
EA	0.643					
AG	0.734***	0.664				
CO	0.618***	0.603***	0.648			
DL	0.618***	0.648***	0.691***	0.680		
CR	0.625***	0.656***	0.601***	0.639***	0.783	
MSCR	0.656***	0.663***	0.675***	0.644***	0.705***	0.764
Cronbach's α	0.861	0.863	0.835	0.855	0.877	0.905
Composite reliability	0.842	0.854	0.847	0.864	0.879	0.906
AVE square root	0.802	0.815	0.805	0.825	0.885	0.874

Table 3. Reliability and validity analysis of scale. Note: diagonal values representing the average variance extracted (AVE) for each variable; the values between different variables represent the Pearson correlation coefficients; *** indicates $p < 0.01$.

calculated as the reflective value of the variable. Then, we set three calibration points for the 5-point Likert scale used in the questionnaire, where "5" is the fully belonged calibration point, "3" is the intersection point, and "1" is the fully not belong calibration point. Since the data system with a membership of 0.500 will not be included in the truth table analysis, a calculation of + 0.001 is performed[18].

Necessary condition analysis
We conduct necessary condition analysis through the upper bound regression (UR) and upper bound envelope analysis (UE) methods, and the following conditions need to be met to determine the antecedent conditions as necessary conditions: the effect size (d) ≥ 0.1, and the Monte Carlo simulation permutation test (P Value) < 0.01[62]. Table 6 NCA necessary condition analysis and Fig. 5 NCA scatter plot were calculated using R4.3.1 software (R Project for Statistical Computing 4.3.1, https://www.r-project.org/). We can observe that: the effect size of collaboration (SY), calculated using both the UR and UE methods, is greater than 0.1, and the P value is significant. This suggests that SY is a necessary condition for MSC resilience. The effect size of the digitalization

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	14.505	38.351	38.351	14.505	38.351	38.351
2	1.870	6.232	44.583	1.870	6.232	44.583
3	1.566	5.220	49.803	1.566	5.220	49.803
4	1.277	4.256	54.059	1.277	4.256	54.059
5	1.012	3.373	57.432	1.012	3.373	57.432
6	0.958	3.195	60.627			
7	0.834	2.779	63.406			

Table 4. Harman's single factor test.

Hypothetical path	Hypothetical	Standard road Diameter coefficient	Standard error (S.E.)	T-value (C.R.)	Significance (P)	Hypothesis testing
EA→MSCR	H1	0.430	0.222	2.401	0.016**	Verified
AG→MSCR	H2	0.337	0.161	1.932	0.053*	Verified
CO→MSCR	H3	0.460	0.189	3.414	0.001***	Verified
DL→MSCR	H4	0.372	0.148	2.835	0.005***	Verified
CR→MSCR	H5	0.464	0.113	3.361	0.001***	Verified

Table 5. Results of hypothesis testing. Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$, and * indicates $p < 0.1$.
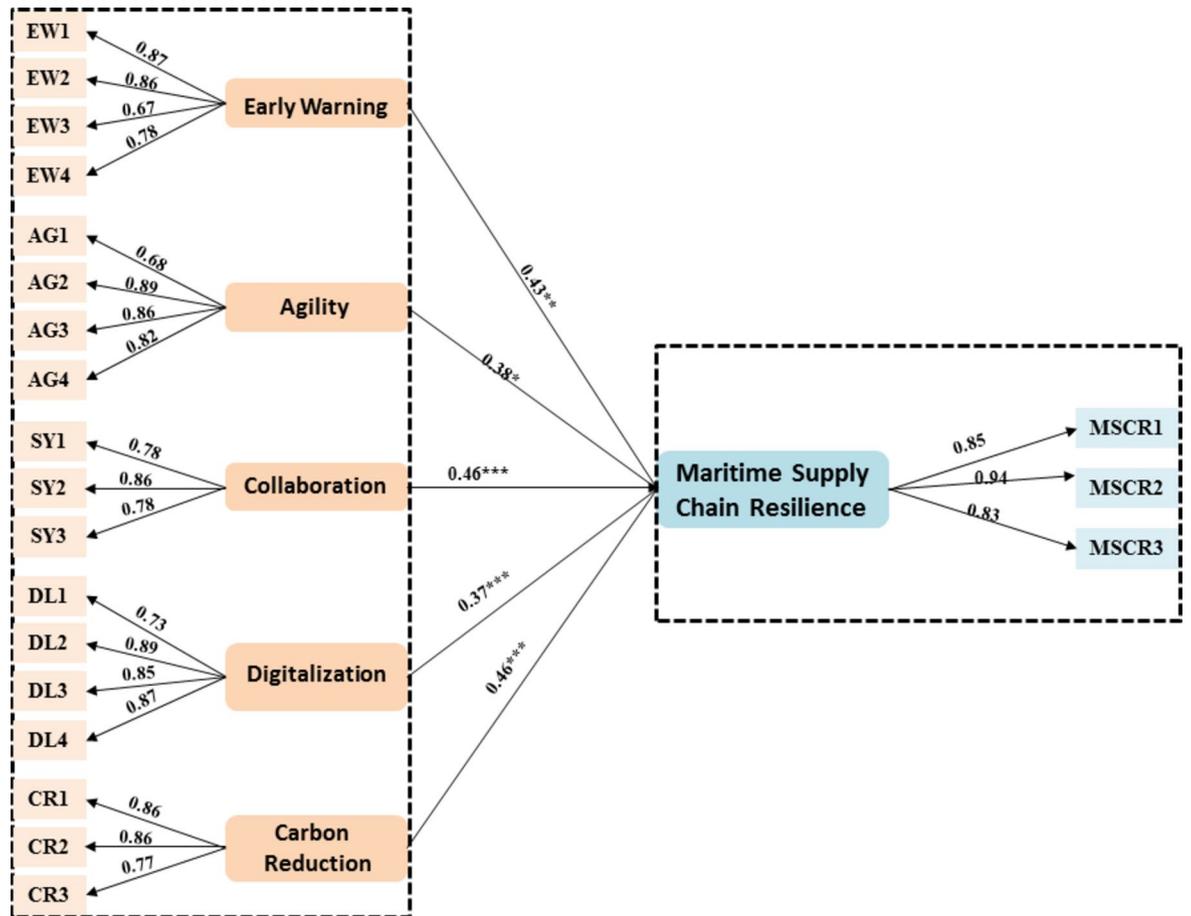

Fig. 4. The single factor impact analysis diagram based on SEM.

Preconditions	Method	Accuracy	Upper Boundary	Effect Size (d)	*P*-Value
EW	UR	100.0%	0.016	0.019***	0.008
	UE	100.0%	0.031	0.039***	0.006
AG	UR	96.0%	0.048	0.060**	0.021
	UE	100.0%	0.036	0.045**	0.035
CO	UR	97.4%	0.221	0.273***	0.006
	UE	100.0%	0.147	0.181***	0.001
DL	UR	96.0%	0.091	0.112***	0.007
	UE	100.0%	0.071	0.087**	0.012
CR	UR	98.7%	0.060	0.074**	0.062
	UE	100.0%	0.084	0.098**	0.082

Table 6. Necessary condition analysis. Note: the effect size d ranges from 0 to 0.1, indicating a 'low level'; d ranges from 0.1 to 0.3, indicating a 'medium level'; and d is above 0.3, indicating a 'high level'. The P-value represents the permutation test in NCA, with a P-value closer to 0 indicating a more significant impact.

level (DL) calculated by the UR method, is greater than 0.1 and has a significant P value, indicating that DL is a necessary condition for the resilience of MSC to some degree. The same method was applied to calculate other variables, but they do not qualify as necessary conditions.

The NCA can not only determine whether a variable is a necessary condition but also analyze the effectiveness of the necessary conditions[22]. The effectiveness is also known as the bottleneck level, which refers to the minimum level value (%) that each antecedent condition needs to meet within its observed range. The results of the bottleneck level analysis are shown in Table 7. Based on the results, to achieve a 100% resilient MSC, the level of early warning capability, agility, collaboration, digitalization level, and carbon emissions control, need to reach 50%, 42.2%, 73%, 48.7%, and 46.9% respectively. In the fsQCA approach, antecedent conditions with a consistency level exceeding 0.9 are considered necessary conditions[19]. The fsQCA 3.0 software is used for the necessary condition testing. Table 8 reveals that, except for the consistency of collaboration and digitalization level surpassing 0.9, all other causal conditions do not qualify as necessary conditions for the resilience of MSC. The analysis results are consistent with the NCA method. In NCA, the necessary condition refers to the lower level of the antecedent condition. That is to say, the lower level of digitalization and collaboration needs to be paid attention in the process of improving the resilience of MSC. In fsQCA, the necessary condition refers to the achievement of a certain level of membership. In this article, we analyze the necessary conditions for achieving high resilience in MSC. Therefore, this study believes that the five conditions do not exist independently to produce high MSC resilience, and we need to conduct a multi-factor configuration analysis.

Configuration sufficiency analysis
The fsQCA software outputs three types of solutions: complex solutions, simple solutions, and intermediate solutions. Intermediate solutions are used for configuration analysis, supplemented by simple solutions to distinguish core and auxiliary conditions[18]. Core conditions are those that appear simultaneously in the intermediate and simple solutions. Auxiliary conditions are those that appear only in the intermediate solutions[23]. In conducting configuration analysis, this study sets the consistency threshold value at 0.8, the PRI value at 0.7, and the frequency threshold value at 10, retaining more than 80% of the cases[23]. We obtain four types of causal configurations that trigger high MSC resilience (In Table 9). Therefore, hypothesis H6 "The resilience of MSC is the result of a combination effect of multiple factors." is verified.

(1) The M1 path 'collaboration + carbon reduction + digitization'. In this path, the core conditions are collaboration and carbon emissions control, with digital proficiency as an auxiliary condition. The consistency of this configuration is 0.9531, which can explain 83.1% of the sample enterprises. Configuration M1 indicates that digitalization can improve the collaboration efficiency among different members in the MSC, alleviate the information asymmetry between cross-border departments, reduce communication and human resource costs, and simultaneously enhance the risk perception ability in the international market, ultimately improve the resilience of the MSC. Besides, "carbon emissions" and "carbon capture" based on digitalization will directly reduce the absolute carbon emissions intensity of shipping industries, which is conducive to the green development of the MSC.

(2) The M2 path 'early warning + collaboration'. This path includes two configuration conditions, M2a and M2b. Configuration M2a is a path with early warning capability and collaboration as core driving factors, and digitalization level as auxiliary factors. The consistency of M2a reaches 0.9588, which can explain 79.3% of the sample enterprises. Configuration M2b is a path with early warning capability, collaboration, and carbon emissions control as core conditions. The consistency of M2b is 0.9694, which can explain 77.3% of the sample cases. Configuration M2 demonstrates that it is necessary to establish an early warning mechanism alliance with the main chain enterprises (shipping companies or ports) taking the lead and supporting enterprises (import and export companies or freight forwarding agencies) playing a secondary role. Meanwhile, it is essential to build a dynamic database for MSC, which can comprehensively, dynamically, and timely reflect the development status and trends of international maritime transport. Lastly, this mechanism should promote the smooth transmission of risk information in MSC and enhance the monitoring capacity for key risks in maritime transportation.
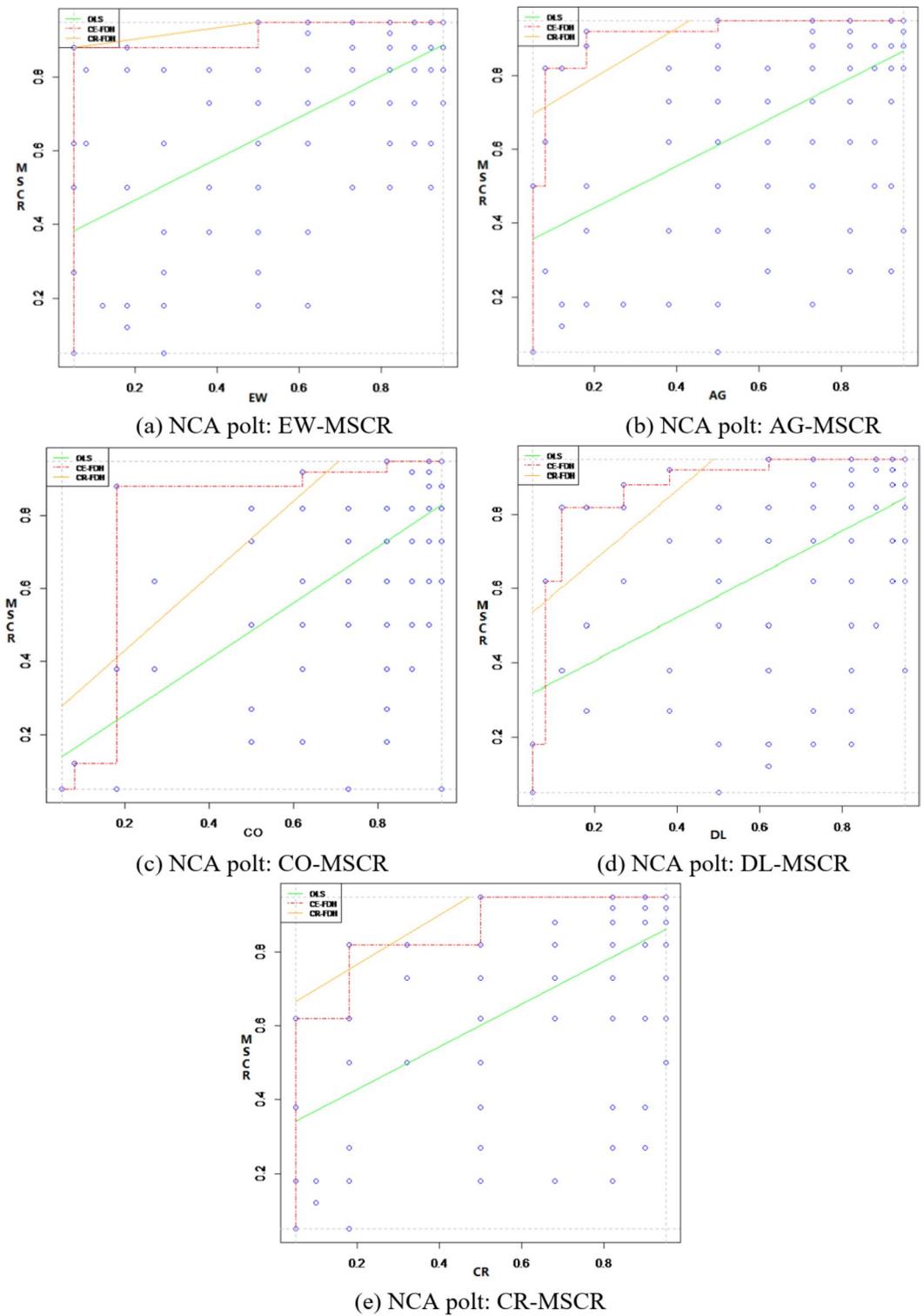
Fig. 5. Scatter plot from NCA analysis. (a) NCA polt: EW-MSCR (b) NCA polt: AG-MSCR. (c) NCA polt: CO-MSCR (d) NCA polt: DL-MSCR. (e) NCA polt: CR-MSCR.

(3) The M3 path 'Agility + Early Warning'. This path focuses on agility and early warning capability as the core condition, with non-carbon emissions control as an auxiliary condition. The consistency of M3 is 0.9623, which can explain 25.3% of the sample cases. Configuration M3 emphasizes the importance of agility in the rssilience of MSC. The agility of MSC includes three aspects: digital agility, physical agility, and process agility. Digital agility refers to the ability of enterprises in MSC to use information flow to improve and accelerate decision-making. Physical agility refers to the ability to quickly adjust physical assets to minimize risks, such as maritime transportation capacity, routes, personnel, and equipment. Process agility refers to the ability of companies in

Maritime supply chain resilience	Early warning capability	Agility	Collaboration	Digitalization level	Carbon reduction
0	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN
30	NN	NN	4.7	NN	NN
40	NN	NN	14.5	NN	NN
50	NN	NN	24.2	NN	NN
60	NN	NN	34.0	6.3	NN
70	NN	NN	43.7	16.9	2.2
80	NN	12.4	53.5	27.5	17.1
90	NN	27.3	63.2	38.1	32.0
100	50.0	42.2	73.0	48.7	46.9

Table 7. Bottleneck level analysis (%) based on NCA .Note: using CR analysis, NN represents non-essential.

Preconditions	High resilience of maritime supply chain		
	Consistency		Coverage
Early Warning	0.836500	0.932335	
∼Early Warning	0.381407	0.759225	
Agility	0.875429	0.916990	
∼Agility	0.334507	0.751875	
Collaboration	0.967282	0.864623	
∼Collaboration	0.219946	0.783168	
Digitalization level	0.908055	0.889989	
∼Digitalization level	0.295672	0.779570	
Carbon Reduction	0.885346	0.908244	
∼Carbon Reduction	0.309482	0.728562	

Table 8. Necessary condition analysis based on fSQCA.

Conditional configuration	High maritime supply chain resilience				
	Configuration M1	Configuration M2a	Configuration M2b	Configuration M3	Configuration M4
EW		●	●	●	⊗
AG				●	⊗
CO	●	●	●		
DL	●	●			
CR	●		●	⊗	●
Consistency	0.9531	0.958781	0.96944	0.962324	0.944702
Original coverage	0.830661	0.793401	0.773288	0.253314	0.245435
Unique coverage	0.063213	0.022245	0.015479	0.004912	0.009083
Consistency of solution	0.93403				
Coverage of the solution	0.90685				

Table 9. The results of configuration sufficiency analysis. Note: ● represent the presence of core conditions, ⊗ represent the absence of core conditions, ● represent the presence of auxiliary conditions ⊗ represent the absence of auxiliary conditions, and spaces represent conditions that can be present or absent.

MSC to quickly adjust and restructure business processes to adapt to changes in the international maritime market.

(4) The M4 path 'Carbon Reduction'. This path takes carbon emission control as the core condition, and non-early warning capability and non-agility as auxiliary conditions. The consistency of this configuration reaches 0.9447, which can explain 24.5% of the sample companies. Configuration M4 manifests efforts should be made to develop new environmentally friendly vessels such as electric ships, fuel cell ships, and LNG ships, as well as low-carbon fuels such as methanol, ammonia, and hydrogen. On the other hand, energy-saving retrofits and carbon capture systems should be conducted on existing vessels to improve energy efficiency and reduce
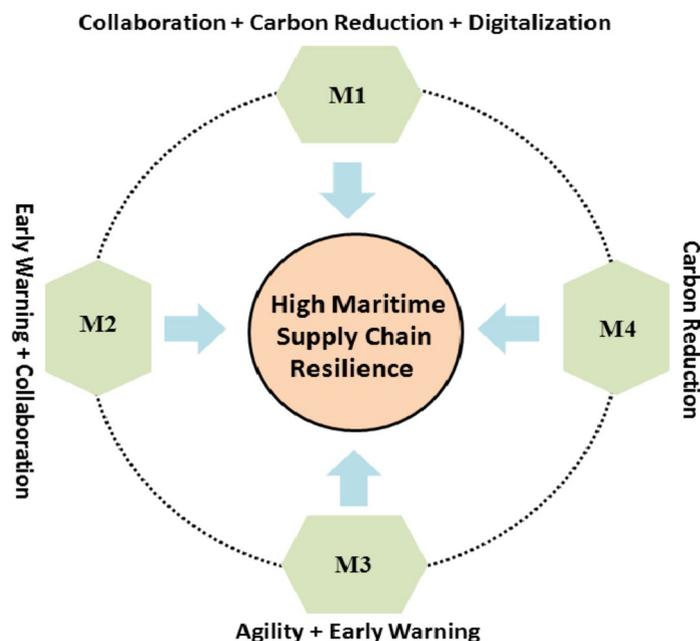
Fig. 6. Conditional configurations affecting the high resilience of the maritime supply chain.

emissions. Furthermore, smart ship technologies should be introduced to reduce travel time and enhance shipping efficiency, thereby reducing carbon emissions.

In summary, Fig. 6 shows the conditional configurations affecting the high resilience of the MSC.

Robustness analysis

This article increases the frequency threshold and original consistency threshold to conduct robustness analysis[54,58]. First, the frequency threshold is increased from 10 to 14. The resulting configurations M1 and M2b, are subsets of the original configuration. Second, the original consistency threshold is increased from 0.80 to 0.85. The results show that the consistency of the overall solution has improved, while the coverage of the overall solution has decreased, and all indicators have experienced only minor changes. Hence, the research conclusions of this paper are robust.

Conclusions

In the past few years, the increasing uncertainty and complexity of the international environment have led to an increased risk of disruption in global supply chains. This paper's review has shown that there is no unified or absolute definition of resilience in MSC, and different approaches to understanding it are taken depending upon the focus and framework of reference adopted. This study designs and applies a new methodological framework based on the SEM-NCA-fsQCA model and uses the questionnaire survey data of the MSC enterprises in China to empirically analyze the key factors and different paths to achieve high resilience in MSC.

Theoretical implications

The findings reported in this paper demonstrate that the developed SEM-NAC-fsQCA methodology framework can be successfully and systematically applied to identify and compute the driving factors to achieve high resilience in MSC. Contrary to previous research, our study put forwards a new analytical framework to validate the 'causal complexity' of MSC resilience and enriches the application of configurational perspective and QCA in this area.

Firstly, few existing literatures consider carbon emission control as an influencing factor of MSC resilience. Our empirical research result of the SEM shows that the carbon emissions control has the largest and most significant impact on the resilience of the MSC, which is more aligned with the evolving demands of international shipping carbon emissions.

Secondly, through the dual necessity verification of the NCA method and fsQCA method, it was found that the five conditions do not exist independently to produce high resilience in MSC. Configuration M1 (collaboration + carbon reduction + digitization) has the highest original and unique coverage, which can be considered the core configuration. Carbon emissions control, early warning ability, and Collaboration are all core conditions in three of the paths, indicating that these three elements are key factors in improving the resilience of MSC.

Thirdly, the level of digitization appears the most times in the auxiliary conditions, which indicates that digitization can play a catalytic role in enhancing the resilience of the maritime supply chain by helping other preconditions. The role of the same element in different paths may be opposite, indicating that antecedent elements will produce different effects depending on the changes in companies or environments.

Managerial implications

The presence of synergistic effects among multiple conditions reflects the complexity of managing the resilience of the maritime supply chain. With these findings, we should be able to better comprehend the resilience enhancement mechanism of MSC, which will be useful not only for academic and practitioner communities but also for the policymakers in describing and evaluating the impacts of such policies in a more systematic fashion. Different types of maritime-related companies and departments can take targeted measures to improve the resilience of the maritime supply chain based on their existing factor endowment.

Firstly, the M1 path 'collaboration + carbon reduction + digitization' emphasizes that to improve the resilience of the MSC, we need to apply digital technology to achieve interconnection and shared interests among all parties in the MSC, and jointly respond to problems in any link or process, including solving the problem of maritime decarbonization.

Secondly, The M2 path 'early warning + collaboration' encourage organizations in MSC to use digital technologies such as big data, knowledge graphs, artificial intelligence, 5G, and blockchain to build a dynamic early warning mechanism alliance. The M3 path 'Agility + Early Warning' emphasizes that the ability to take rapid action after discovering significant risk events through the early warning system is crucial.

Thirdly, the M4 path 'Carbon Reduction' indicates that with the IMO's '2023 Ship Greenhouse Gas Emission Reduction Strategy' released and the implementation of the EU carbon tax policy, the international shipping industry is facing increasing pressure to decarbonize. In the future, enterprises in the MSC need to continuously invest and cooperate in Carbon emission reduction to ensure resilience.

Limitations and propose directions for future research

This study still has several limitations which provide avenues for future research. First, this study collects data through questionnaire surveys, which may be subject to some degree of subjectivity. In the future, further exploration can be conducted on how to use actual operational data of enterprises related to maritime transportation for empirical research. Second, this study doesn't analyze the differences in resilience management strategies among enterprises of the maritime supply chain. Further research is needed to explore the heterogeneity of resilience management among different enterprises. Third, this study only analyzes data from a specific period of the maritime supply chain, without including cross-temporal case data. Future research can select longer periods and use methods such as linear growth QCA and multi-temporal multi-linear growth QCA to track complex dynamic changes.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

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Author contributions

Conceptualization, X.C., L.C.; methodology, L.C., X.C.; software, X.C., M.W.; validation M.W. and X.C.; formal analysis M.W., Q.C. and X.C.; investigation, L.C., X.C.; resources, Q.C. and X.C.; data curation, M.W., X.C.; writing—original draft preparation, L.C., X.C.; writing—review and editing, L.C., X.C.; visualization, M.W., X.C.; supervision, L.C., Q.C.; project administration, L.C.; funding acquisition, L.C.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to L.C.

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