Journal of
Marine Science and Engineering

MDPI

Article

Spatial Structure and Vulnerability of Container Shipping Networks: A Case Study in the Beibu Gulf Sea Area

Mengyu Xia [1], Jinhai Chen [1,*], Pengfei Zhang [1], Peng Peng [2] and Christophe Claramunt [2,3]

[1] Navigation College, Jimei University, Xiamen 361021, China; xiamy19929@163.com (M.X.)
[2] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Beijing 100101, China; christophe.claramunt@ecole-navale.fr (C.C.)
[3] Naval Academy Research Institute, 29160 Brest, France
* Correspondence: jhchen@jmu.edu.cn

Abstract: Ports play an important role in maintaining the effectiveness of maritime logistics. When ports encounter congestion, strikes, or natural disasters, the maritime container transportation network might be significantly affected. The Beibu Gulf sea area is a key channel to supporting China's participation in international economic cooperation in the western region. It is highly susceptible to the influence of the political and economic instability. This study introduces a dual-component framework to analyze the inherent structure and potential vulnerabilities of the container transportation network in the Beibu Gulf Sea areas. The findings show that the core layer of the network exhibited circular solidification characteristics. The entire network heavily relies on some core ports, such as Haiphong Port, Ho Chi Minh Port, and Qinzhou Port, and it highlights the potential increases in vulnerability. The finding shows that deliberate attacks have a greater impact than random attacks on the normal operations of maritime networks. If ports with high intermediary centrality are attacked, the connectivity and transportation efficiency of the Beibu Gulf maritime network will be significantly affected. However, under such circumstances, redistributing cargo transportation through route adjustments can deal with the transmission of cascading failures and maintain the network's resilience. Based on the existing knowledge and the data collected in a case study, this research stands out as the first to provide a critical examination of the spatial structure and vulnerability of container shipping networks in the Beibu Gulf sea.

Keywords: container shipping network; network structure; vulnerability; complex network; Beibu Gulf sea area; maritime transport

Citation: Xia, M.; Chen, J.; Zhang, P.; Peng, P.; Claramunt, C. Spatial Structure and Vulnerability of Container Shipping Networks: A Case Study in the Beibu Gulf Sea Area. *J. Mar. Sci. Eng.* **2024**, *12*, 1307. https://doi.org/10.3390/jmse12081307

Academic Editors: Lingxiao Wu and Shuaian Wang

Received: 16 June 2024
Revised: 29 July 2024
Accepted: 31 July 2024
Published: 2 August 2024

1. Introduction

Given the promotion of construction in China's coastal economic belt, the marine transport industry has shown prosperous development trends [1]. At the same time, the cooperation between China and Association of Southeast Asian Nations (ASEAN) countries continues to deepen, with each country helping to build the "China–ASEAN Free Trade Area" [2]. In this context, the Beibu Gulf sea area and its surrounding ports have emerged as a major maritime area [3]. The Beibu Gulf sea represents an important gateway for the west of China [4], as it faces the nearest sea to the ASEAN countries and organically connects the "Belt and Road". Consequently, this area is becoming one of the most dynamic and strategic regions in the global economy, with the construction of new land and sea passages in the west, the construction of surrounding ports as a breakthrough, and the expansion of the ASEAN as an opportunity.

Maritime transportation significantly supports the development of successful trade worldwide. Due to its safety, ease of operation, and flexibility in multimodal transport, container transport accounts for more than 80% of the international trade in goods and 70% of the total value in world maritime trade [5]. Despite the rapid development of global seaborne trade, increasingly complex globalization, and the intensification of global geopolitical tensions and conflicts have triggered a high level of interest in “de-risking” supply chains. Although the direct impact of geopolitical conflicts on shipping markets is relatively limited and localized, a significant increase in regional tensions, such as a sharp escalation of conflict in the Red Sea region and the potential disruption of transport through the Strait of Hormuz, would have significant additional global geopolitical and macroeconomic implications.

Given the current situation, the disruption of port operations and sea lanes both affect the overall transport efficiency of the maritime network and have significant socio-economic implications [6]. Therefore, there is a growing interest in conducting comprehensive assessments of the vulnerability of the maritime network. As an important strategic fulcrum of China’s domestic and international double circulation, the Beibu Gulf sea plays an important role in promoting the common prosperity of the regional economy and the sound development of the region. It is necessary to fully understand the spatial structural characteristics of the Beibu Gulf maritime transportation network and its ability to withstand sudden situations.

As a real transportation network, the topology structure composed of transportation relationships between ports is the carrier of its real freight spatial distribution. In this study, we utilize the navigation data of containers in the Beibu Gulf sea to construct a container transportation network representative of the actual transportation situation. This model is used to study the spatial topology of the Beibu Gulf sea container transportation network and the functional status of ports in the network. Furthermore, we construct a cascading failure model that considers port overload capacity to analyze the inhibitory capabilities of different port failure modes and load redistribution strategies on the cascading failure of the Beibu Gulf sea shipping network. Studying the topology and resilience of maritime networks can help to better understand the spatial–structural characteristics of the network and the risks posed by various emergencies and provide policy recommendations for the construction and development of the Beibu Gulf maritime network.

2. Related Work

2.1. Maritime Transport Networks Analysis

The process of containerization has accelerated since the 1980s thanks to worldwide economic and trade integration. The shipping industry has gradually evolved from break bulk cargo transport to today’s container liner shipping transport, which is characterized by fixed routes and ports. In recent years, the analysis of maritime transport networks has attracted significant attention in academia [7–11]. Complex networks, as structural models that can abstractly reveal objective laws of nature and social systems through networks, have undergone extensive empirical research in multiple fields such as society [12–14], economy [15,16], biology [17,18], and transportation [19–22]. On this basis, complex network theory has become a popular tool for studying maritime transportation systems. The simplest and most common way to model a maritime transportation network is to use complex network theory to treat ports as nodes in the network and routes connecting different ports as edges of the network [23]. Scholars usually establish a maritime network for the studied area based on the data of ships docking at ports recorded in maritime databases or the route information provided by shipping companies. The goal of this network is to describe the relationships between various parts of the system in the form of a network, emphasize the topological properties of the system, and explain the properties and evolutionary mechanisms of existing systems.

The significance of topological structures in transport systems, especially in maritime transport, has led many researchers to examine and describe the characteristics of the underlying structures that make transport networks complex systems [24]. These studies have applied several network attributes both globally and regionally, revealing important hidden information, including macroscopic structures such as scale-free and small-world structures, the vulnerability and resilience of ocean networks, connectivity levels, and community structures [25–27]. Centrality metrics are amongst the most widely used approaches to characterizing transport networks (e.g., structure) and their elements (e.g., importance of nodes), and thus are a common tool for also analyzing container service networks [28]. For example, Jin et al. [29] evaluated the impact of COVID-19 on China's international liner transportation by using structural indicators such as the degree, weighting degree, median centrality, and average path length of China's container shipping network to determine the trends of network changes and corresponding weak links. In the field of ocean transportation, ports are the most critical link in the global transportation system and play an indispensable role in the global cargo flow supply chain. Lee and Ducruet [30] re-examined the hierarchical structures of individual ports, including ports in Northeast Asia and global ports, analyzing changes in the locations of major hub ports in the network. Leveraging the mentioned pioneering results, many scholars have analyzed the container transportation network. Ducruet and Zaidi [31] explored the role of both container hubs and regional ports, with an application of a k-clusters approach to identify relevant sub-networks. Nguyen and Woo [32] analyzed the structures of container shipping networks in Southeast Asia and measured the competitiveness of ports through their direct and indirect external linkages.

Complex networks are constructed based on the interactions or relationships between actual individuals (such as ports) and entities (such as shipping routes) in complex systems, and statistical physics is used to analyze the network structure and its dynamic characteristics. Among these, degree distribution, clustering coefficient, and average path length are the three most fundamental characteristics of complex networks. Complex network indices have been regularly applied to study the structural characteristics of maritime transportation networks, such as degree, weighted degree, betweenness centrality, etc., to explore the dynamic properties of regional port systems, reveal the connection relationships between ports, and determine the respective roles of ports in the network. The aforementioned works have contributed significant references and empirical analyses to enhance our understanding of the Beibu Gulf sea's network topology and vulnerability analysis.

2.2. The Vulnerability of Maritime Transport Networks

The vulnerability of a complex network refers to the ability of a system to maintain normal operations after some of its components (such as nodes or edges) are damaged. For example, the outbreak of COVID-19 resulted in port closures and operational disruptions, leading to severe congestion at other ports in the network and compromising the functionality of the entire maritime transportation network [33–35]. Transportation systems are inevitably affected by various internal and external factors, which may lead to uncertainty in the operation and security of the system. In particular, the maritime transportation system is extremely vulnerable to man-made and natural disasters, which further exacerbates the uncertainty of system operations.

The resilience of complex networks can be categorized into static resilience and dynamic resilience. Scholars often use simulations to attack networks by selectively or randomly removing specified ports from the topological networks and evaluate the network's resilience based on changes in network characteristic indicators. Wu et al. [36] quantitatively studied the vulnerability changes in global container shipping networks before and after the COVID-19 pandemic. The authors identified the critical collapse point of the global container shipping network based on its geographical connectivity and network collapse process and highlighted relevant policy recommendations to ensure the interconnectivity of the global container shipping network. Nevertheless, the susceptibility of the maritime transportation network is not limited to the topological configuration of the shipping network, it is also impacted by the dynamic reassignment of trade flows in response to disruptions at ports. Therefore, Yang et al. [37] proposed a cascading failure model that can comprehensively describe the failures of ports at different levels during the propagation process. The authors redistributed the traffic flow into three levels according to the specific role of the interrupted ports and analyzed the vulnerability of the global container shipping network based on large-scale ship trajectory data. Yao et al. [38] proposed a research framework for the resilience of container port shipping networks, analyzing the resilience of container shipping networks through changes in network performance indicators before and after attacks. Xu et al. [39] proposed a new cascade model to study the propagation process of port congestion in the global liner shipping network (GLSN) and introduced a port dynamic criticality index to measure the impact of each port on the GLSN's survivability. Li et al. [40] developed a three-node reinforcement strategy based on different levels of node capacity redundancy and designed a survivability evaluation index that comprehensively considers the structure and node load. The study found that node capacity redundancy has a strong inhibitory effect on cascading failure. Many previous studies have typically used container throughput as the primary measure of port capacity. However, this method ignores the influence of factors such as fully loaded or unloaded ships because, during COVID-19, many ships were unloaded. In addition, their research often regards shipping networks as undirected networks, without considering the dynamic changes in network load and the dynamic behavior of port failures in network risk transmission. Moreover, existing research on the dynamic resilience of complex networks is mostly based on the assumption that ports will completely fail immediately after being attacked. This perspective simplifies the failure state as a deterministic result, ignoring the adaptability of ports to overload situations in real scenarios. In fact, under the accumulation of pressure, ports do not immediately stop operating; instead, their operational efficiency gradually decreases, thus increasing the possibility of failure under sustained pressure.

Existing research on maritime transportation network models, network topology, and network vulnerability has provided valuable insights and empirical analyses that serve as important references for our study. However, our approach distinguishes itself by integrating two complementary components: (1) network-based and topological modeling of transportation flows between different ports and (2) the dynamic propagation of disruptions following specific incidents in a given port. This dual-component framework offers a more comprehensive understanding of the network's resilience. Furthermore, while the Beibu Gulf sea area is a critical corridor for China's east–west trade, and thus pivotal for the development of its surrounding ports, there has been a notable lack of studies examining the organizational structure of its transportation and its risk resistance from a holistic spatial perspective. Our framework fills this gap by applying a novel integrated modeling approach specifically to the Beibu Gulf sea area. This approach not only highlights the network's topological vulnerabilities but also examines the impact of dynamic trade flow redistributions triggered by port disruptions, thereby providing a nuanced analysis of the network's robustness in the face of potential disturbances.

3. The Geographical Research Area and Methodology

3.1. The Geographical Scope and Data

The geographical scope of the Beibu Gulf sea area refers to the parts of Guangdong, Guangxi, and Hainan provinces along the southern coast of China and the northern coastal area of Vietnam. In 2006, China introduced the concept of the Pan-Beibu Gulf Economic Zone (PBEZ), adding ASEAN countries such as Malaysia, Singapore, Brunei, Indonesia, and the Philippines to the China–Vietnam economic cooperation region. The Pan-Beibu Gulf Economic Zone is a port-rich region. There are more than 100 ports of various types in ASEAN countries, with Chinese ports including southwestern ports in Guangdong, Guangxi, Hainan, and Hong Kong.

To fully study the structural characteristics of the container shipping network in the Beibu Gulf area, we selected the sea area covered by the Pan-Beibu Gulf Economic Zone as the research area and all container ports in the research area as the area of interest. The resulting spatial distribution map is shown in Figure 1, where yellow nodes represent ports in China, purple nodes represent ports in South Korea and Japan, green nodes represent ports in Vietnam, and blue nodes represent ports in Indonesia.

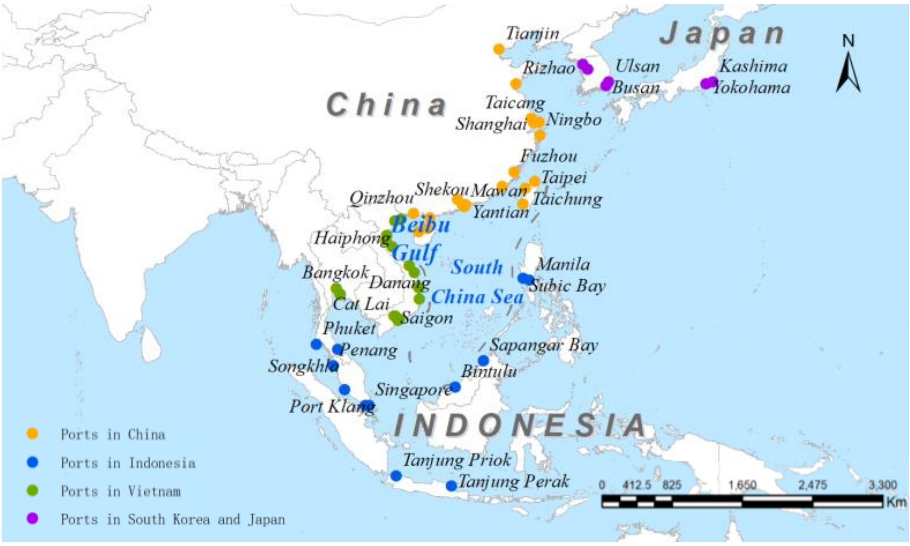


Figure 1. Research area and involved ports.

For this study, we use container AIS data (provided by Elane (Beijing, China) Data Technology Co., Ltd.) from the Beibu Gulf sea area as the base data and select September 2019 and September 2021, when shipping schedules are relatively stable, as the control data set.

3.2. Methodology

This study uses Beibu Gulf sea's AIS container data from 2019 to 2021 to construct a container shipping network model and analyze the entire Beibu Gulf sea shipping network using a series of indicators of complex networks, including degree centrality, mediation centrality, proximity centrality, K-core decomposition, network efficiency, and maximum connectivity subgraphs. Each indicator provides a different perspective on the structure and function of the Beibu Gulf sea area's shipping network, in addition, the vulnerability of the network is evaluated by simulating the ability of the network to maintain normal functions after random or intentional port interruptions, as well as the ability of different load redistribution strategies to resist cascading failures after port interruptions. In summary, the application of complex networks provides a detailed and nuanced perspective on the Beibu Gulf sea container shipping network. This study expands upon traditional analyses by considering the complex interrelationships between nodes in the network. This approach can identify inherent weaknesses in the system and be used to propose effective interventions to improve the system's stability.

3.2.1. Centrality Measures

The quantitative index of centrality can be used to identify important ports in the network, study their locational advantages and functional properties, and analyze the development characteristics of important ports in the Beibu Gulf sea area.

Degree centrality DC_i represents a port's direct accessibility to other ports in the shipping network. This factor reflects the breadth and opportunities of external shipping links that a port provides to its hinterland through the actual number of routes it takes:

$$DC_i = \sum_{i=1}^{N} k_{ij} \quad (1)$$

where k_{ij} is the degree of node i, i.e., the number of edges connected to node i.

Betweenness centrality is measured by the number of weighted shortest paths between pairs of nodes in the network passing through a given node. The index reflects the port's cargo trans-shipment capacity and articulation function; the higher the number of shortest paths passing through the port, the greater the trans-shipment capacity of the port:

$$BC_i = \frac{\sum_{k \neq i \neq j} \frac{N_{kj}(i)}{N_{kj}}}{\sum_{i=1}^{N} \sum_{k \neq i \neq j} \frac{N_{kj}(i)}{N_{kj}}} \quad (2)$$

where N_{kj} denotes the number of all weighted shortest paths between node k and node j, and $N_{kj}(i)$ is the number of shortest paths between node k and j that pass through node i.

The K-core analysis model gradually strips away the peripheral nodes in the network by repeatedly removing nodes and their connected edges with degree values less than k until none of the remaining nodes in the network has a degree value less than k. This method uses k = 1, 2, 3, in turn, to obtain a structure of closely related subgraphs that match the specified core degree value in the network graph. The K-core model is used to simplify the shipping network in the Beibu Gulf area and analyze its hierarchical characteristics, as well as its core ports. Using these results, we can explore the relatively stable, direct, and closely connected core network formed between ports.

3.2.2. Network Efficiency and Maximal Connected Subgraphs

The failure of nodes (edges) in complex networks due to random or deliberate attacks can cause changes in the spatial structure of the network, resulting in a certain impact on the connectivity of the entire network. Jiang et al. [41] defined the interconnectivity between ports as the connectivity of the network, which is used to characterize the proximity between a port and other ports in the network. Here, the connectivity index of a complex network is introduced as an indicator to evaluate the invulnerability of a complex network considering the two aspects of network connectivity and transportation efficiency.

For this analysis, we constructed a directed weighted network for Beibu Gulf shipping and also considered the impact of the frequency, carrying capacity, and direction of routes on network efficiency. In actual maritime transport, network efficiency is positively correlated with the number of voyages and negatively correlated with route distance. The higher the value of E, the stronger the interaction between ports:

$$E = \frac{1}{n(n-1)} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\mathrm{w}_{ij}}{d_{ij}} \quad (3)$$

where n is the number of ports in the Beibu Gulf sea shipping network; d_{ij} is the shortest path length between port i and port j, and w_{ij} represents the edge weight between port i and port j, which is expressed by the carrying capacity between ports.

In complex network theory, the connectivity of a network is measured by the size of the largest connected subgraph in the network—the number of nodes in the largest component. The maximum connectivity subgraph is a fundamental indicator for evaluating network topology connectivity [42]. The larger the maximum connected subgraph, the better the connectivity of the network. The relative size of the maximum connected subgraph is expressed as the ratio of the number of nodes in the maximum connected subgraph in the network to the total number of nodes in the network:

$$G = \frac{N'}{N} \quad (4)$$

where N and N', respectively, represent the maximum connected subgraph size of the complex network before and after cascade failure. The subnetwork with the largest number of nodes that can be connected in the network is called the maximum connected subgraph.

4. Case Study

4.1. Overview of the Beibu Gulf Sea Shipping Network

This study takes the ports around the Beibu Gulf sea area as nodes, abstracts the container shipping routes between ports into edges, and constructs a container OD transportation matrix representing the Beibu Gulf sea. The carrying capacity of each route is used as the weight of the edges to draw a container shipping network diagram for the Beibu Gulf, as shown in Figure 2.

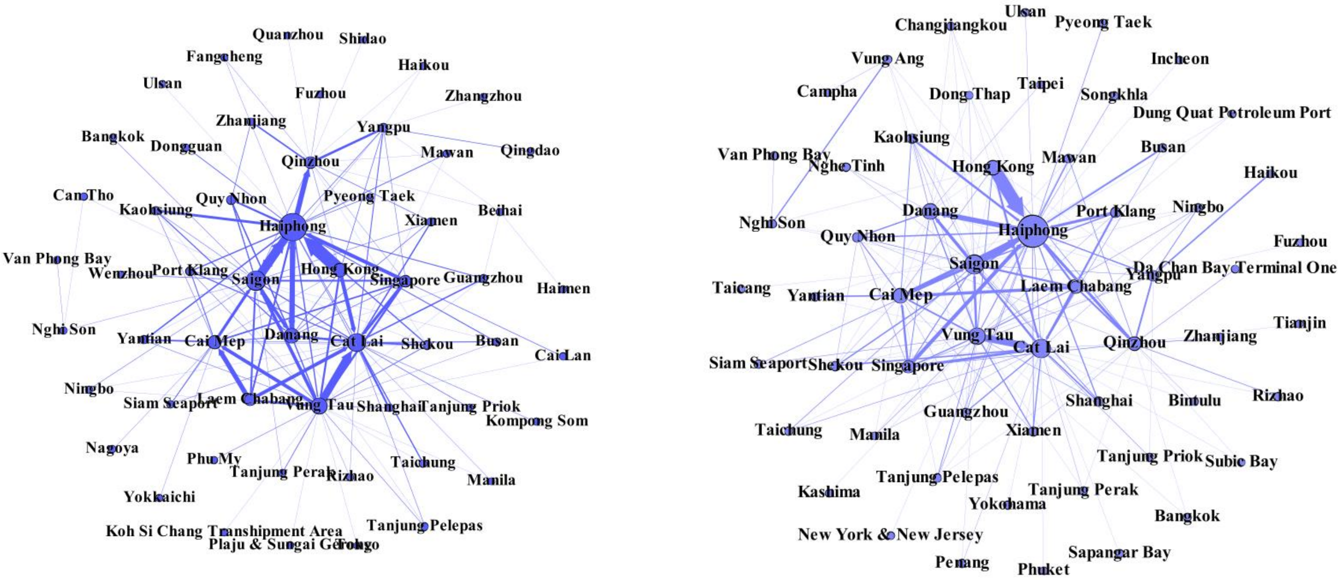


Figure 2. Directed weighted topological structure of the Beibu Gulf sea container shipping network.

According to network theory [43], in a small-world network, most nodes are not direct neighbors, but the neighbors of any given node tend to be neighbors of each other. In addition, any two randomly selected nodes can be linked using a small number of steps. Mathematically, a small-world network exhibits the characteristics of a high clustering coefficient and low average path length. The average path length and clustering coefficient results for the Beibu Gulf sea container shipping network are shown in Table 1. Here, the actual calculated result of the network clustering coefficient in 2021 is approximately 0.413, which indicates that about 41.3% of the ports in the Beibu Gulf sea area may have trade links with each other.

Table 1. "Small World" characteristic indicators of the Beibu Gulf sea container shipping network.

Indicators	2019		2021	
	Average Path Length	Clustering Factor	Average Path Length	Clustering Factor
Container shipping network in the Beibu Gulf sea area	2.429	0.372	2.324	0.413
Random networks of the same size	2.199	0.055	2.205	0.036
Difference	0.230	0.317	0.119	0.377

The average path length of the Beibu Gulf sea shipping network is approximately 2.324. Similar to the six degrees of separation in social networks, nearly three steps are required for goods that need to be transported from one economy to another. The Beibu Gulf sea shipping network has obvious small-world characteristics. For example, the average path length of this network decreased from 2019 to 2021, and its aggregation coefficient was significantly higher than that of the random network. The ports in the region, moreover, show strong cohesion. In addition, the ports around the Beibu Gulf sea area are closely connected and have good network connectivity.

The Beibu Gulf sea container shipping network is scale-free and features high network instability. Based on the degree distribution curve of the Beibu Gulf sea shipping network illustrated in Figure 3, as the degree value increases, the degree probability distribution presents a downward trend. Moreover, the tail declines relatively slowly, with a long tail feature. The power-law fit of the distribution pattern of the node degree of the container shipping network in the Beibu Gulf sea area in 2019 yields $P(k_{i1}) = 0.1241{k_i}^{-0.378}$, R^2 = 0.8555, which represents a good fit. The power-law fit of the nodal degree distribution pattern of the container shipping network in the Beibu Gulf sea area in 2021 yields $P(k_{i2}) = 0.1034{k_i}^{-0.38}$ and R^2 = 0.8948, which indicates an increasingly good fit. Thus, the two curves have a good fitting degree. The degree distribution of the Beibu Gulf sea shipping network basically conforms to the power function distribution law, and the network has scale-free characteristics.

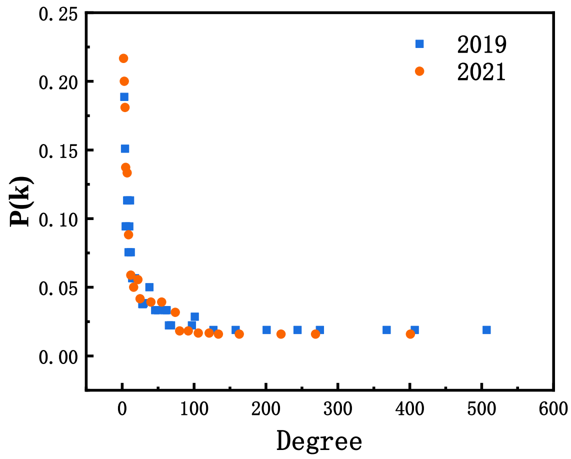
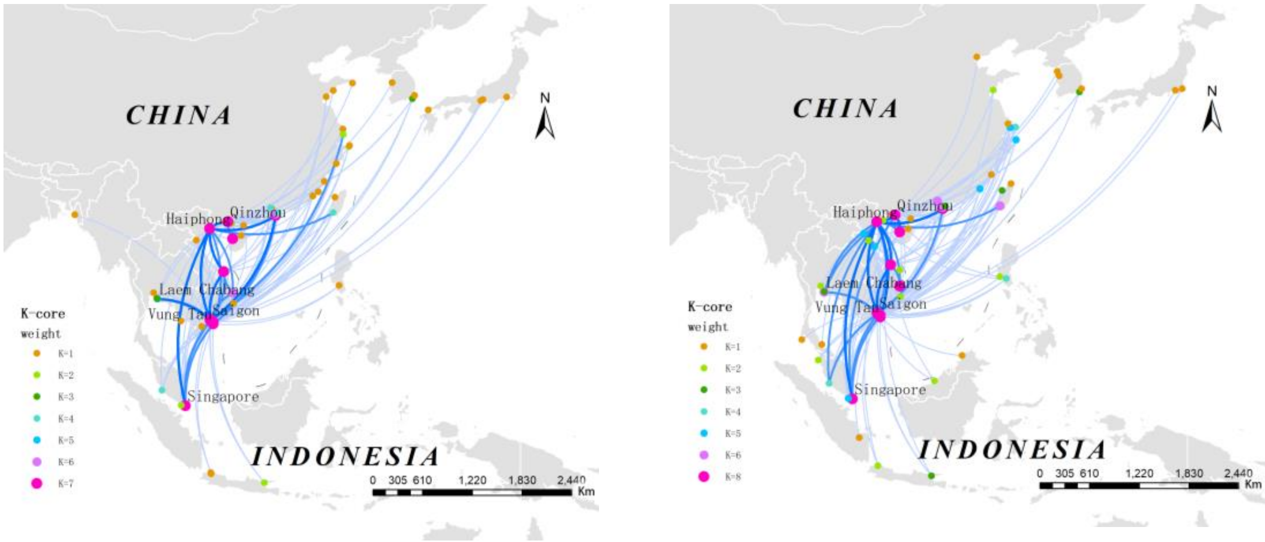


Figure 3. Probability distribution of the port node degrees in the Beibu Gulf sea container shipping network in 2019 and 2021.

According to actual statistics, ports with smaller degrees are more common, and most ports have degrees of less than 130. In addition, the connection status (degree) between ports has seriously uneven distribution characteristics. Ports with higher degrees include Haiphong Port, Ho Chi Minh Port, Vung Tau Port, Da Nang in Vietnam, and Hong Kong in China. High-degree ports are very active in the Beibu Gulf sea shipping network, containing many cargo flows and routes. When new ports are added to the network, ports with higher degrees are more likely to be given priority. The uneven distribution of the network degree reflects the strong instability of the Beibu Gulf maritime transport network. Most ports have a small range of connections, although a few ports with a wider range of connections control the overall network structure. The interconnection and interoperability of the entire maritime transport network will be affected if these ports are disturbed by factors such as natural disasters, wars, pirate attacks, or outbreaks of infectious diseases.

4.2. Analysis of the Network "Core–Edge" Structure

The core layer of the Beibu Gulf sea shipping network has obvious "circle solidification" characteristics. The present study found that the maximum k value of the core network in the Beibu Gulf sea area in 2019 was 7, with a total of 10 ports, as shown in Figure 4a. Ports in the Southeast Asian shipping area occupy a core position, including Haiphong Port, Ho Chi Minh Port, Singapore Port, Vung Tau Port, Da Nang Port, Cai Mep Port, and Qui Nhon Port. Chinese ports include only the Hong Kong Port, Yangpu Port, and Qinzhou Port. In 2021, the maximum k value of the core network in the Beibu Gulf sea area increased to 8; the ports participating in the core network remained unchanged. Moreover, the degree value of ports in the entire network increased, with core layer ports in the network featuring greater participation. Route connections with more ports were established, and the breadth of node connections was increased. However, the geographical coverage range of the core layer network was reduced, as shown in Figure 4b.



(**a**) (**b**)

Figure 4. K-core decomposition of the Beibu Gulf sea container shipping network. (**a**) Beibu Gulf Sea Container Shipping Core Network in 2019. (**b**) Beibu Gulf Sea Container Shipping Core Network in 2021.

The entire network formed a core hub structure primarily composed of Qinzhou Port, Hong Kong Port, Haiphong Port, Singapore Port, Ho Chi Minh Port, Vung Tau Port, and Laem Chabang Port. In addition, the container shipping routes in the Beibu Gulf sea area are densely intertwined. Trade between China and ASEAN countries was more frequent in 2021 than in 2019. Here, container transportation is mainly concentrated between China, Vietnam, and Malaysia. Moreover, Qinzhou Port, Hong Kong Port, and Yangpu Port in southwest China established closer direct connections with Southeast Asian ports. The ports in the core layer play a crucial role in the maritime network of the Beibu Gulf, belonging to regional hub ports. As the distribution centers of various regions, these are important ports in their respective countries and regions, with strong radiation capabilities and a relatively long radiation range. These ports also have strong support capabilities for the development of maritime transportation in the Beibu Gulf sea and, to a certain extent, control and dominate the external transportation of goods in the area.

The core position of Laem Chabang Port in the network gradually increased in prominence, while Laem Chabang Port and Qinzhou Port established closer route connections than those in 2019 because China and Thailand frequently engage in the maritime trade of agricultural products. At the same time, the route density between Qinzhou Port and Singapore Port also increased. As the main operator for the construction of the Western Land–Sea Corridor, Qinzhou Port opened a public liner from Qinzhou to Singapore. In this way, ocean transportation operations in western China successfully achieved a connection between Qinzhou Port and the mother ship of the ocean route.

4.3. Analysis of Port Centrality

Figure 5 shows the degree centrality distribution of all ports in the Beibu Gulf sea shipping network. The top five ports in the network in 2019 and 2021 based on the established Beibu Gulf sea container shipping network are shown in Tables 2 and 3. In the Beibu Gulf sea area, the network structure takes China's Hong Kong Port, Qinzhou Port, and Yangpu Port as the core framework and establishes route connections with many ports in Southeast Asia, such as Haiphong Port and Ho Chi Minh Port.

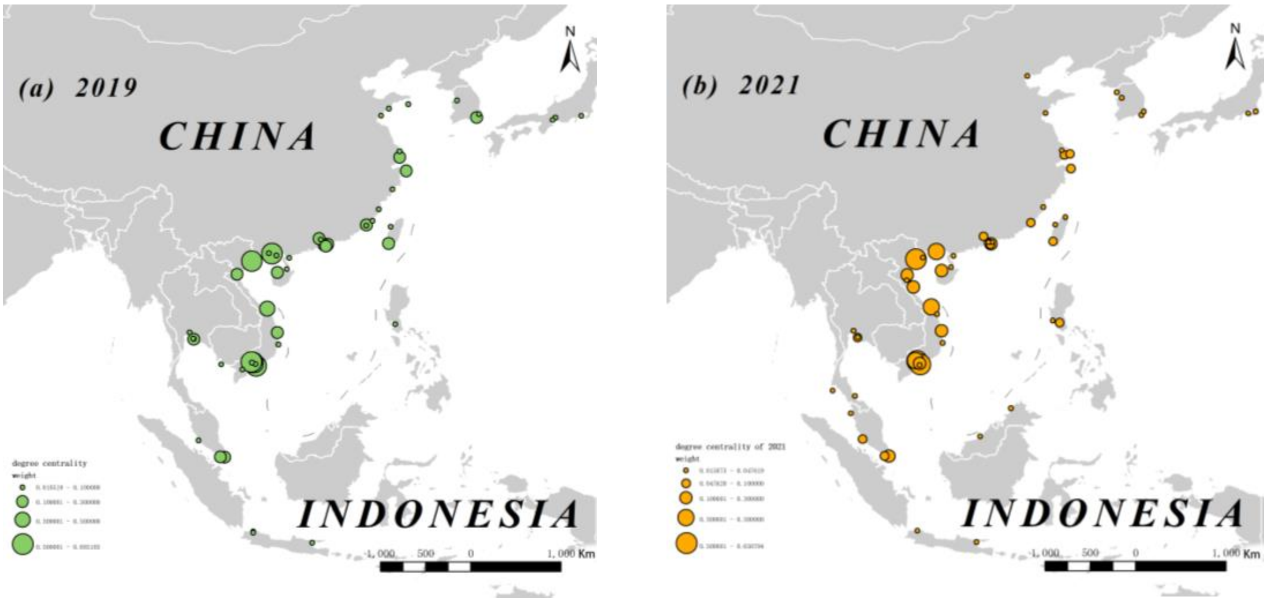


Figure 5. Spatial distribution of port degree centrality in the Beibu Gulf sea shipping network. (**a**) Spatial distribution of port degree centrality in the Beibu Gulf sea shipping network in 2019. (**b**) Spatial distribution of port degree centrality in the Beibu Gulf sea shipping network in 2021.

Table 2. Ranking of Degree Centrality in the Beibu Gulf sea Shipping Network.

Ranking	2019		2021	
	Port	Degree Centrality	Port	Degree Centrality
1	Haiphong	187.0	Haiphong	166.0
2	Hong Kong	139.0	Hong Kong	106.0
3	Ho Chi Minh	111.0	Qinzhou	92.0
4	Qinzhou	106.0	Ho Chi Minh	76.0
5	Yangpu	63.0	Yangpu	51.0

Table 3. Ranking of Betweenness Centrality in the Beibu Gulf sea Shipping Network.

Ranking	2019		2021	
	Port	Betweenness Centrality	Port	Betweenness Centrality
1	Qinzhou	63.5	Qinzhou	71.7
2	Haiphong	35.5	Yangpu	45.7
3	Yangpu	30.0	Ho Chi Minh	19.8
4	Ho Chi Minh	28.5	Haiphong	9.8
5	Beihai	10.5	Danang	8.0

Degree centrality refers to the ability of ports in the network to establish shipping routes with other ports. This factor can intuitively reflect the breadth and opportunity size of the port's provision of external shipping links to its hinterland. The centrality degree of ports in the Beibu Gulf sea shipping network was different in 2021 compared to that in 2019. However, the overall distribution characteristics remained unchanged. Here, hub ports with a higher degree of centrality such as Haiphong Port, Ho Chi Minh Port, Vung Tau Port, Qinzhou Port, and Yangpu Port are mainly distributed around the Beibu Gulf sea area and along the coast of Vietnam and play a key role in the network. Ports with lower centrality degree values are widely distributed in space. In addition to Vietnam and China, some ports are located in Southeast Asian countries such as Japan, South Korea, Malaysia, Singapore, Indonesia, the Philippines, and Thailand. These ports have relatively weak connectivity in the network and mainly rely on core hub ports to maintain the connectivity of the shipping network. China's low centrality ports are clustered and include the Yangtze River Delta and Pearl River Delta.

Highly central ports reflect the "rich man's club" phenomenon. Haiphong Port, Vung Tau Port, Ho Chi Minh Port, Qinzhou Port, Yangpu Port, and Da Nang have always featured a high moderate centrality in the network. From the perspective of port operations, these ports have relatively superior geographical locations, rich resources, many ocean routes, and good docking conditions for large ships. These ports also tend to be more closely connected than other ports, and small ports in the network tend to establish shipping exchanges with these ports first.

In the shipping network, betweenness centrality can measure the hub capacity and control of ports. However, there is still a clear imbalance in the distribution of port betweenness centrality in the Beibu Gulf sea shipping network. Only a few hub ports play a global intermediary role in the network, with many ports possessing poor betweenness in the network.

Betweenness centrality can reflect the cargo trans-shipment capacity and connection functions of the port. The shorter the paths that pass through the port, the stronger the port's ability to act as a trans-shipment "intermediary". Vietnam's Haiphong Port and Ho Chi Minh Port and China's Qinzhou Port control most of the connections between shipping ports in the Beibu Gulf sea. As shown in Figure 6, more ports had a betweenness centrality value of 0 in 2021. As the overall scale of the network decreases, the centrality of some hub ports also shows a downward trend. With its narrow and long terrain and rich seaport resources, Vietnam has become an important trade hub between the East and West.

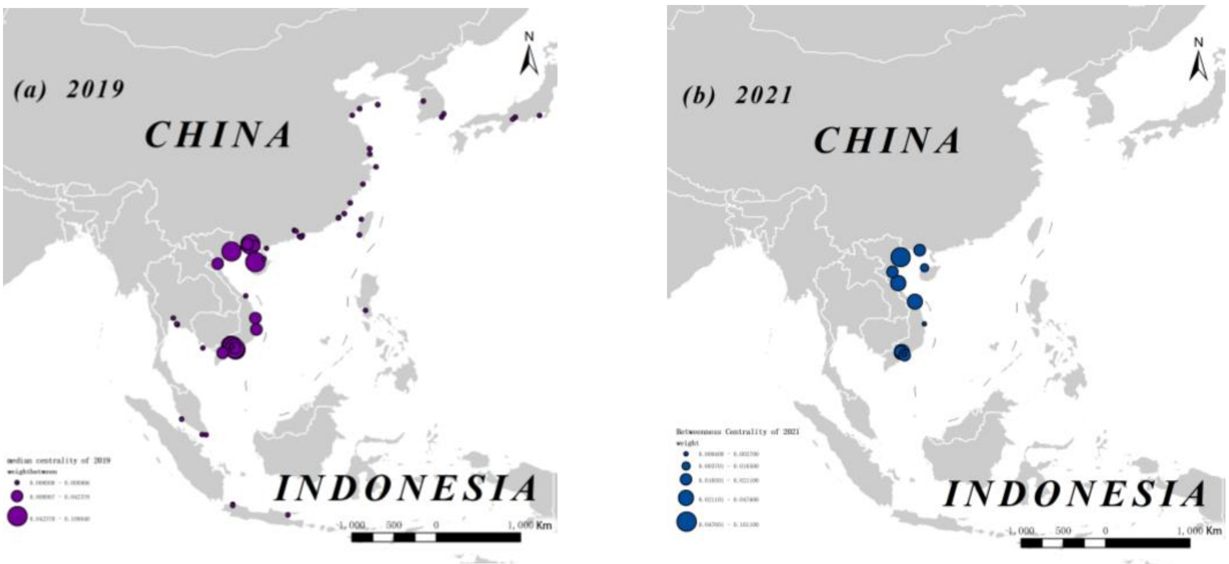


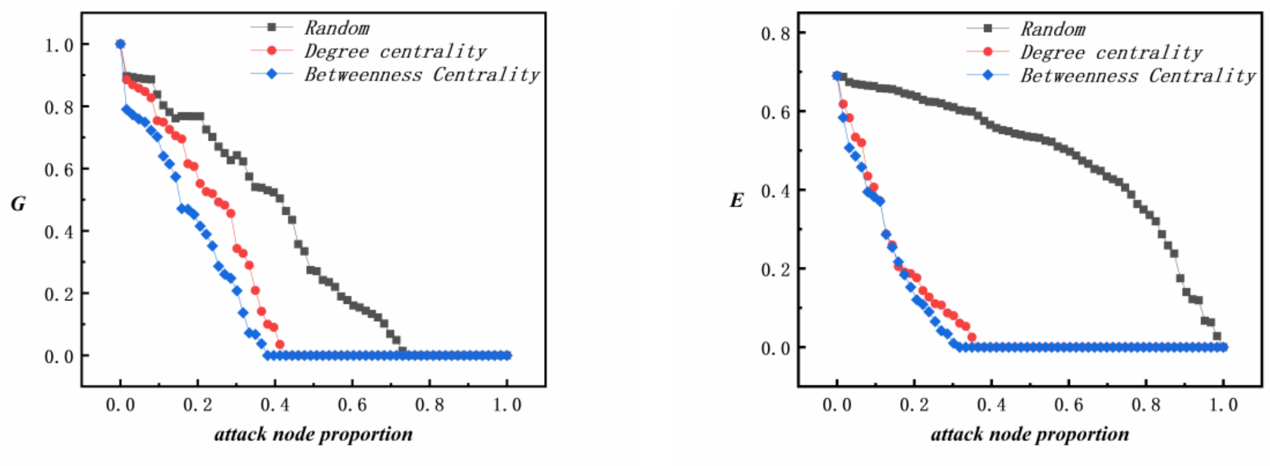
Figure 6. Spatial distribution of port betweenness centrality in the Beibu Gulf sea shipping network. (**a**) Spatial distribution of port betweenness centrality in the Beibu Gulf sea shipping network in 2019. (**b**) Spatial distribution of port betweenness centrality in the Beibu Gulf sea shipping network in 2021.

In September 2019, there were 332 container shipping routes between China and Vietnam. However, in September 2021, 431 container trade routes existed between China and Vietnam, indicating a year-on-year increase of 30%. China's goods are mainly shipped from the Yangtze River Delta port group, Hong Kong Port, and Qinzhou Port to Haiphong Port and Ho Chi Minh Port in Vietnam. Among them, Haiphong Port, as a transit station for the import and export of goods in northern Vietnam, transports goods to Da Nang in central Vietnam and Ho Chi Minh Port in the south. Vung Tau Port and Cai Mep Port in southern Vietnam are the main transit ports for trade with other Southeast Asian countries.

4.4. Analysis of Network Vulnerability

To provide timely and highly relevant analytical results, we selected the ship AIS data in September 2021 as the foundation for the destruction resistance analysis of the Beibu Gulf sea shipping network based on the availability and integrity of the data. Additionally, we found that the data in 2021 could better reflect the actual composition of the current network and its potential vulnerability characteristics.

Figure 7 shows the impact of random attacks, degree-centrality descending attacks, and betweenness-centrality descending attacks on the Beibu Gulf sea shipping network. The Beibu Gulf sea shipping network has a strong ability to resist random attacks. Under random attacks, the maximum connectivity subgraph of the Beibu Gulf sea container shipping network decreases much more slowly, with the inhibitory effect on the stability of the maritime transportation in the Beibu Gulf sea area showing an almost linear trend. When the port suffers limited random damage, the transportation efficiency of the Beibu Gulf sea shipping network declines slowly, with the interconnection capability of the network remaining at a relatively high level. For example, even if 34% of ports were attacked, the overall transportation efficiency of the network would only drop by 0.1 percentage points. However, when the proportion of ports attacked exceeds 75%, the efficiency of network transportation begins to decline sharply, and network transportation is greatly affected.



(**a**) (**b**)

Figure 7. Vulnerability of the Beibu Gulf sea shipping network under different attack modes. (**a**) Impact of attack methods on the stability of the Beibu Gulf sea shipping network. (**b**) Impact of attack methods on the transport efficiency of the Beibu Gulf sea shipping network.

However, the Lower Beibu Gulf sea shipping network is extremely vulnerable to deliberate attacks, especially for ports with a high degree of centrality and betweenness centrality. When the ports ranked by degree centrality and betweenness centrality are attacked successively, the connectivity and network efficiency of the Beibu Gulf maritime network rapidly decrease. Notably, when ports are prioritized for removal based on their mediating roles, the connectivity fragmentation of the network accelerates, indicating that these strategically located ports are critical to maintaining the integrity of the maritime network in the Beibu Gulf sea area.

As shown in Figure 8, when the coastal defense port with the highest betweenness centrality is attacked, the stability and transportation efficiency of the network begin to significantly decrease. When the proportion of attack nodes is less than 8.75%, that is, when the top five ports in the intermediary centrality ranking of the Beibu Gulf maritime network are attacked, the performance of the network is not significantly affected by the three load redistribution mechanisms. Subsequently, as the proportion of failed nodes increases, the Beibu Gulf maritime transportation network shows a relatively peaceful trend of decline in resilience under the remaining capacity allocation strategy, demonstrating strong emergency response capabilities.

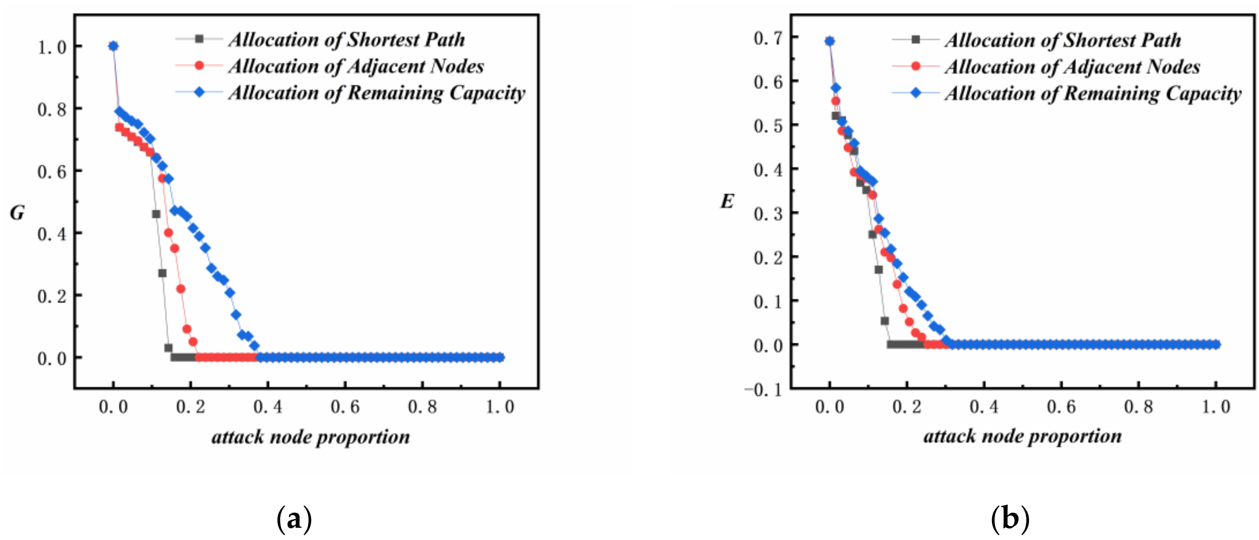


Figure 8. Impact of the load redistribution strategy on the cascading failure of the Beibu Gulf sea shipping network. (**a**) Impact of the load redistribution strategy on the stability of the Beibu Gulf sea shipping network. (**b**) Impact of the load redistribution strategy on the transportation efficiency of the Beibu Gulf sea shipping network.

Overall, the adjacency allocation policy has medium resistance to the network cascading failure mechanism, whereas the shortest route allocation policy has the weakest resistance. Therefore, when the Beibu Gulf sea shipping network is faced with port failure due to emergencies, shipping companies should take appropriate route adjustment measures according to a comprehensive consideration of costs, time expenditures, and other relevant factors and transfer the cargo from damaged ports to other ports. These measures would enhance the overall anti-risk capabilities of the Beibu Gulf sea shipping network.

We take Qinzhou Port in China as an example to illustrate this issue. As an important seaport in southwestern China, Qinzhou serves as a hub for trade between countries with the opening of the Pinglu Canal. Here, it is necessary to predict the consequences of hub port congestion and avoid encountering congestion issues such as the Suez Canal [44] and Panama Canal crises. If Qinzhou Port fails due to external disturbances, Zhanjiang, Haiphong, and Hong Kong could serve as alternative ports to accept goods originally intended for Qinzhou Port. Shipping companies could then adopt appropriate route adjustment plans by analyzing the infrastructure conditions, relative distance, transportation costs, and remaining cargo handling capacity of alternative ports. These measures would mitigate the chain reaction caused by the failure of Qinzhou Port located within the Beibu Gulf sea shipping network.

5. Conclusions

This research introduced a modeling framework that represents the structural properties of a maritime network and identified plausible modes of port failure and three strategies for adjusting port loads, simulating iterative cascading propagation to capture the dynamic behaviors across all ports. A novelty of this approach is that all properties and findings were derived from a very large AIS dataset, which could also facilitate the generalizability of this approach to other regional contexts. The findings of this research offer valuable insights into enhancing network transmission efficiency and bolstering network stability. The Beibu Gulf sea area is the most convenient passage to the sea in southwest China and an important window for in-depth cooperation between China and the ASEAN. Based on the AIS data of ship traffic in the Beibu Gulf sea area in 2019 and 2021, we constructed a maritime transport network model of the Beibu Gulf sea area based on complex network theory and analyzed the corresponding structural characteristics representing the spatial patterns of port centrality and network resistance in the maritime transport network of the Beibu Gulf sea area. The main conclusions of this paper are as follows.

(1) The small-world characteristics and scale-free characteristics of the Beibu Gulf sea shipping network are becoming increasingly significant, with the network structure showing vulnerable characteristics. The numbers of routes, participating ports, and participating countries in the Beibu Gulf maritime network grew from 2019 to 2021, and a large maritime transport network is currently taking shape. However, only a few ports in the network, such as Ho Chi Minh Port, Hai Phong Port, and Chin Zhou Port, have a wide range of contacts, can directly trade with additional regions, and are minimally affected by other ports in the network. Ultimately, imbalanced port development leads to increased network instability.
(2) The container shipping network of the Beibu Gulf sea has a typical "core–edge" ring structure, with an "axle–spoke" network structure taking shape [45]. The "hub–spoke" maritime transportation network is centered around the main transportation routes between hub ports (i.e., "hubs"), supplemented by branch routes connecting hub ports and related feeding ports (i.e., "hubs"), thereby achieving economies of scale and radiating driving effects. Chinese ports have formed the core framework of "Qinzhou Port–Yangpu Port–Hong Kong Port" in the maritime transportation network of the Beibu Gulf sea, and their participation in the whole network has been continuously strengthened. However, the pattern of maritime networks composed of Chinese ports in the Beibu Gulf sea area remains relatively simple, with few participating ports. Here, most of the transportation is concentrated in a few core ports, with most featuring single one-way or two-way connections.
(3) The Beibu Gulf sea shipping network showed strong resilience against emergencies but weak resilience against deliberate destruction. We suggest that the relevant authorities deepen cooperation between ports and shipping, increase the connections between Chinese shipping enterprises and Southeast Asian ports, and expand direct flights between Chinese ports and Southeast Asian ports. Authorities should also continue to strengthen the construction of port facilities and collection and distribution systems and improve the anti-risk capacity of the port itself, as well as formulate alternative port plans; establish prevention and control safety production risk identification mechanisms; effectively protect the network against major safety accidents; and bolster public safety and health events, emergency response capacity, and the overall resilience of the network.

For instance, the COVID-19 outbreak affected Haiphong Port in Vietnam, leading to stringent shutdown measures. These measures had a progressive, cumulative impact on container shipping within the Beibu Gulf sea area and worldwide. However, the precise scope of this impact and the interconnections between its various consequences remain uncertain. Considering Haiphong Port as the initial port to be disrupted, Qinzhou Port and Ho Chi Minh Port appeared to be the most significantly impacted, following an assessment of capacity overload in other ports. Enacting cascading failures and strategies for cargo load redistribution showed that the potential risks associated with the cascading failures at Haiphong Port proliferated across various regions in Asia, including the Beibu Gulf sea.

However, our work provides only a preliminary exploration of the chain effects of port congestion in the Beibu Gulf sea shipping network. Moreover, this study retains certain limitations. In the future, different capacity redundancy coefficients could be established to represent the maximum processing capacity of the port. This work studied only the theoretical capacity of ports, providing insights for stakeholders and those planning the development of new infrastructure to increase the capacity of ports. In addition, when studying the resilience of the Beibu Gulf's marine network, this study simulated only the damage and recovery mechanisms of individual ports in the marine network. Future work could consider the path failures and simultaneous failures of multiple ports to explore the network's resistance to different attacks.

Author Contributions: Conceptualization, M.X., J.C., P.Z., P.P. and C.C.; methodology, M.X., J.C., P.Z., P.P. and C.C.; software, M.X., J.C. and C.C.; validation, M.X., P.Z., P.P. and C.C.; formal analysis, M.X.; resources, J.C. and P.P.; writing—original draft, M.X., J.C., P.Z., P.P. and C.C.; writing—review and editing, J.C., P.Z., P.P. and C.C.; visualization, M.X. and C.C.; supervision, J.C., P.Z., P.P. and C.C.; project administration, J.C. and P.P.; funding acquisition, J.C. and C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Funds of Fujian Provincial for Promoting High Quality Development of Marine and Fisheries Industry (No. FJHYF-ZH-2023-10), National Social Science Fund of China (23&ZD138), this work is supported by a project grant from the National Social Science Fund of China (22AZD108), the Strategic Priority Research Program of the Chinese Academy of Sciences (Category B, Geographic Intelligence, no. XDB0740300), and the Chinese Academy of Sciences President's International Fellowship Initiative (2024PVA0104).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wang, Y.; Xue, C.; Li, H.; Yu, K. Efficiency Measurement and Determinant Factors of Marine Economy in China: Based on the Belt and Road Perspective. *Discret. Dyn. Nat. Soc.* **2021**, *2021*, 5546200. [CrossRef]
2. Huang, Q.; Zhang, X.; Li, Y. Study on the economic effects of China and ASEAN countries from the New International Land-Sea Trade Corridor. *Transp. Policy* **2023**, *139*, 123–135. [CrossRef]
3. Wang, M.; Wang, Y. Evaluating the Strategic Position of the Beibu Gulf, South China Sea. *Coast. Manag.* **2023**, *51*, 1–23. [CrossRef]
4. Cheshmehzangi, A.; Tang, T. *China's City Cluster Development in the Race to Carbon Neutrality*; Springer Nature: Singapore, 2022; pp. 161–173.
5. UNCTAD. *Review of Maritime Transport 2017*; United Nations Publications: New York, NY, USA, 2017.
6. Wendler-Bosco, V.; Nicholson, C. Port disruption impact on the maritime supply chain: A literature review. *Sustain. Resilient Infrastruct.* **2020**, *5*, 378–394. [CrossRef]
7. Ducruet, C. Port specialization and connectivity in the global maritime network. *Marit. Policy Manag.* **2022**, *49*, 1–17. [CrossRef]
8. Liu, C.; Wang, J.; Zhang, H. Spatial heterogeneity of ports in the global maritime network detected by weighted ego network analysis. *Marit. Policy Manag.* **2018**, *45*, 89–104. [CrossRef]
9. Changhai, H.; Shenping, H.; Fancun, K.; Shaoyong, X. Vulnerability analysis of inland waterways network base on complex network theory. *Int. J. Comput. Appl.* **2020**, *42*, 67–75. [CrossRef]
10. Tsiotas, D. The imprint of tourism on the topology of maritime networks: Evidence from Greece. *Anatolia* **2017**, *28*, 52–68. [CrossRef]
11. Chen, J.; Chang, S.; Zhang, P.; Chen, Q.; Peng, P.; Claramunt, C. A Critical Examination for Widespread Usage of Shipping Big Data Analytics in China. *J. Mar. Sci. Eng.* **2022**, *10*, 2009. [CrossRef]
12. Forsberg, S.; Thomas, K.; Bergkvist, M. Power grid vulnerability analysis using complex network theory: A topological study of the Nordic transmission grid. *Phys. A Stat. Mech. Its Appl.* **2023**, *626*, 129072. [CrossRef]
13. Haselhoff, T.; Braun, T.; Fiebig, A.; Hornberg, J.; Lawrence, B.T.; Marwan, N.; Moebus, S. Complex networks for analyzing the urban acoustic environment. *Ecol. Inform.* **2023**, *78*, 102326. [CrossRef]
14. Zhao, J.; Ouenniche, J.; Smedt, J.D. A complex network analysis approach to bankruptcy prediction using company relational information-based drivers. *Knowl.-Based Syst.* **2024**, *300*, 112234. [CrossRef]
15. Tian, S.; Li, S.; Gu, Q. Measurement and contagion modelling of systemic risk in China's financial sectors: Evidence for functional data analysis and complex network. *Int. Rev. Financ. Anal.* **2023**, *90*, 102913. [CrossRef]
16. Zhang, L.; Wen, S. The influence of global gallium trade network dynamics on price: A complex network and panel regression approach. *Resour. Policy* **2024**, *93*, 105091. [CrossRef]

17. Neiva, M.B.; de Oliveira, B.M.; Schmidt, A.M.; Scheibe, V.M.; Milke, J.C.; dos Santos, M.; Yamada, V.M.; Colombo Filho, M.E.; Soares, G.T.; de Araújo Ribeiro, Y.; et al. LICD-10-ORPHA: An Interactive Complex Network Model for Brazilian Rare Diseases. *Procedia Comput. Sci.* **2024**, *239*, 634–642. [CrossRef]
18. Wang, T.; Huang, Y.; Cheng, J.; Xiong, H.; Ying, Y.; Feng, Y.; Wang, J. Construction and optimization of watershed-scale ecological network based on complex network method: A case study of Erhai Lake Basin in China. *Ecol. Indic.* **2024**, *160*, 111794. [CrossRef]
19. Ersoz, C.; Kilic, S.; Aldemir, H.O. Analysis of Turkey's airport network structure and centrality in the opening-out period after the first wave of COVID-19: A complex network approach. *Case Stud. Transp. Policy* **2022**, *10*, 2506–2518. [CrossRef]
20. Song, J.; Ding, J.; Gui, X.; Zhu, Y. Assessment and solutions for vulnerability of urban rail transit network based on complex network theory: A case study of Chongqing. *Heliyon* **2024**, *10*, e27237. [CrossRef]
21. Shi, J.; Liu, Z.; Feng, Y.; Wang, X.; Zhu, H.; Yang, Z.; Wang, J.; Wang, H. Evolutionary model and risk analysis of ship collision accidents based on complex networks and DEMATEL. *Ocean. Eng.* **2024**, *305*, 117965. [CrossRef]
22. Malandri, C.; Mantecchini, L.; Postorino, M.N. A comprehensive approach to assess transportation system resilience towards disruptive events. Case study on airside airport systems. *Transp. Policy* **2023**, *139*, 109–122. [CrossRef]
23. Álvarez, N.G.; Adenso-Díaz, B.; Calzada-Infante, L. Maritime Traffic as a Complex Network: A Systematic Review. *Netw. Spat. Econ.* **2021**, *21*, 387–417. [CrossRef]
24. Ducruet, C. The geography of maritime networks: A critical review. *J. Transp. Geogr.* **2020**, *88*, 102824. [CrossRef]
25. Peng, P.; Yang, Y.; Cheng, S.; Lu, F.; Yuan, Z. Hub-and-spoke structure: Characterizing the global crude oil transport network with mass vessel trajectories. *Energy* **2019**, *168*, 966–974. [CrossRef]
26. Peng, P.; Lu, F.; Cheng, S.; Yang, Y. Mapping the global liquefied natural gas trade network: A perspective of maritime transportation. *J. Clean. Prod.* **2021**, *283*, 124640. [CrossRef]
27. Ducruet, C.; Notteboom, T. The worldwide maritime network of container shipping: Spatial structure and regional dynamics. *Glob. Netw.* **2012**, *12*, 395–423. [CrossRef]
28. Tocchi, D.; Sys, C.; Papola, A.; Tinessa, F.; Simonelli, F.; Marzano, V. Hypergraph-based centrality metrics for maritime container service networks: A worldwide application. *J. Transp. Geogr.* **2022**, *98*, 103225. [CrossRef]
29. Jin, L.; Chen, J.; Chen, Z.; Sun, X.; Yu, B. Impact of COVID-19 on China's international liner shipping network based on AIS data. *Transp. Policy* **2022**, *121*, 90–99. [CrossRef] [PubMed]
30. Lee, S.; Ducruet, C. Spatial Glocalization in Asia-Pacific Hub Port Cities: A Comparison of Hong Kong and Singapore. *Urban Geogr.* **2009**, *30*, 162–184. [CrossRef]
31. Ducruet, C.; Zaidi, F. Maritime constellations: A complex network approach to shipping and ports. *Marit. Policy Manag.* **2012**, *39*, 151–168. [CrossRef]
32. Nguyen, P.N.; Woo, S. Port connectivity and competition among container ports in Southeast Asia based on Social Network Analysis and TOPSIS. *Marit. Policy Manag.* **2022**, *49*, 779–796. [CrossRef]
33. Loveridge, A.; Elvidge, C.D.; Kroodsma, D.A.; White, T.D.; Evans, K.; Kato, A.; Ropert-Coudert, Y.; Sommerfeld, J.; Takahashi, A.; Patchett, R.; et al. Context-dependent changes in maritime traffic activity during the first year of the COVID-19 pandemic. *Glob. Environ. Chang.* **2024**, *84*, 102773. [CrossRef]
34. Vanelslander, T. *Transportation Amid Pandemics*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 153–168.
35. Guerrero, D.; Letrouit, L.; Pais-Montes, C. The container transport system during COVID-19: An analysis through the prism of complex networks. *Transp. Policy* **2022**, *115*, 113–125. [CrossRef] [PubMed]
36. Wu, D.; Yu, C.; Zhao, Y.; Guo, J. Changes in vulnerability of global container shipping networks before and after the COVID-19 pandemic. *J. Transp. Geogr.* **2024**, *114*, 103783. [CrossRef]
37. Xu, Y.; Peng, P.; Claramunt, C.; Lu, F.; Yan, R. Cascading failure modelling in global container shipping network using mass vessel trajectory data. *Reliab. Eng. Syst. Saf.* **2024**, *249*, 110231. [CrossRef]
38. He, Y.; Yang, Y.; Wang, M.; Zhang, X. Resilience Analysis of Container Port Shipping Network Structure: The Case of China. *Sustainability* **2022**, *14*, 9489. [CrossRef]
39. Xu, X.; Zhu, Y.; Xu, M.; Deng, W.; Zuo, Y. Vulnerability analysis of the global liner shipping network: From static structure to cascading failure dynamics. *Ocean. Coast. Manag.* **2022**, *229*, 106325. [CrossRef]
40. Li, J.; Wang, Y.; Zhong, J.; Sun, Y.; Guo, Z.; Chen, Z.; Fu, C. Network resilience assessment and reinforcement strategy against cascading failure. *Chaos Solitons Fractals* **2022**, *160*, 112271. [CrossRef]
41. Jiang, J.; Lee, L.H.; Chew, E.P.; Gan, C.C. Port connectivity study: An analysis framework from a global container liner shipping network perspective. *Transp. Res. Part E Logist. Transp. Rev.* **2015**, *73*, 47–64. [CrossRef]
42. Bombelli, A.; Santos, B.F.; Tavasszy, L. Analysis of the air cargo transport network using a complex network theory perspective. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *138*, 101959. [CrossRef]
43. Newman, M.E.J.; Watts, D.J. Scaling and percolation in the small-world network model. *Phys. Rev. E* **1999**, *60*, 7332–7342. [CrossRef]
44. Wan, Z.; Su, Y.; Li, Z.; Zhang, X.; Zhang, Q.; Chen, J. Analysis of the impact of Suez Canal blockage on the global shipping network. *Ocean Coast. Manag.* **2023**, *24*, 106868. [CrossRef]
45. O'kelly, M.E. A quadratic integer program for the location of interacting hub facilities. *Eur. J. Oper. Res.* **1987**, *32*, 393–404. [CrossRef]