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# Assessing the Connectivity Reliability of a Maritime Transport Network: A Case of Imported Crude Oil in China

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**Abstract:** Crude oil transportation is a vital component of the global energy supply, and the global Crude Oil Maritime Transportation Network (COMTN) plays a crucial role as a carrier for crude oil transportation. Once the network faces attacks that result in the failure of certain routes, a severe threat is posed to the crude oil supply security of importing countries. Therefore, it is crucial to evaluate the reliability of the COMTN. This study proposes a model for evaluating the reliability of the imported COMTN by analyzing the impact of node failures. Firstly, the network is constructed using complex networks (CNs) theory, with ports, canals, and straits as nodes, and shipping routes as directed edges. Secondly, based on the Weighted Leader Rank algorithm, a comprehensive evaluation metric for CNs is established, and a node importance assessment model is developed to rank the nodes accordingly. Thirdly, a case study is conducted using China's imported COMTN as an example, evaluating the connectivity reliability (CR) under random and deliberate attack scenarios. Finally, measures and recommendations are provided to enhance the CR of China's imported COMTN. The findings indicate that deliberate attacks pose a greater threat, and reliability varies across maritime routes, with the Americas route exhibiting higher reliability compared to the Middle East and Southeast Asia routes. The results of this study can provide relevant recommendations for policy makers. The model proposed in this study can also be applied to other countries and regions to assess the connectivity reliability of their local COMTNs and develop appropriate measures for the results.

**Keywords:** maritime transport; maritime safety; crude oil imports; transport network; connectivity reliability

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## 1. Introduction

Energy is a critical foundation and driving force for economic and societal advancement. Insufficient energy resources or constraints in their availability can exert a profound influence on a country's security and impede national economic development [1,2]. Experiencing rapid economic growth, China has witnessed a relentless upsurge in energy demand. According to data from the National Bureau of Statistics, China's external reliance on crude oil reached 72% in 2021 [3,4]. Maritime transport constitutes the pre-dominant mode of crude oil transportation in China, surpassing pipeline and railway transportation [5]. As a result, several key maritime routes have emerged as the essential framework for China's crude oil import network [6]. The COMTN plays a pivotal role as a crucial carrier for crude oil transportation. In the event of an attack causing the failure of specific nodes within the network, a significant threat is posed to a country's security regarding the supply of crude oil [7].

The maritime transport of imported crude oil begins at the ports of various source countries, proceeding through a series of straits and canals before arriving at the designated destination ports [8]. Within China's imported COMTN, these ports, canals, and straits constitute a series of interconnected nodes. However, various factors, including political turbulence at regional borders and geopolitical maneuvering, can contribute to uncertainties and instabilities in these associated nodes [7]. For example, heightened tensions between the USA and Iran could lead to the closure of the Strait of Hormuz. The Malacca Strait region experiences frequent pirate attacks, while the Suez Canal could be obstructed by a stranded cargo vessel. Such events can result in the closure and vulnerability of specific nodes within the network, disrupting their functionalities within the COMTN. Studying the connectivity and reliability of the COMTN holds crucial importance.

Currently, the majority of research on the imported COMTN concentrates on the effects of oil price fluctuations, with limited analysis and research on the reliability of the imported COMTN. Extensive research achievements have been made in studying the reliability of transport networks in domains such as urban roads and aviation. However, there is a need to expand the research scope to include maritime transport networks (MTN) for imported crude oil. This study aims to bridge the gaps by employing the CN method and drawing insights from existing studies on transport network connectivity and reliability. By developing an assessment model, this study will comprehensively evaluate the connectivity and reliability of the imported COMTN, contributing to a deeper understanding of its performance.

## 2. Literature Review

### *2.1. The Research of MTN*

In the study of the MTN, researchers primarily focus on aspects such as network resilience, robustness, and trade patterns. The resilience of the transport network structure is the network's ability to absorb disruptions, maintain its fundamental functionality, and recover within an acceptable time and cost [9]. Wu et al. [10] proposed an assessment framework to assess the resilience of the MTN and applied it to the container MTN of the Maritime Silk Road (MSR). This framework successfully identified weak points within the network, providing valuable insights for risk management in maritime transport. Mou et al. [11] utilized AIS data to construct the COMTN and applied CNs to assess its resilience. The research findings provided valuable insights for route design, and other related aspects. Based on post-disaster analysis, Dui et al. [12] developed a novel method with which to optimize the management of remaining resilience in Multi-Transshipment ports and shipping routes, offering new insights into the establishment and maintenance of international trade routes. Wan et al. [13] proposed a risk-based recovery method to assess the effectiveness of several recovery strategies in mitigating disruptions in the Logistics Service Network (LSN). The results demonstrated that the choice of recovery strategy depends on the LSN's structure and specific requirements during the recovery process. This research would contribute to the establishment of a more resilient LSN. Yang and Liu [14] examined the variation characteristics and node resilience of the shipping routes network of the MSR under external shocks. Based on CNs and employing the MSR network as a case study, the study identified key nodes and vulnerable nodes, providing recommendations and measures so as to ensure structural resilience in MTN.

In terms of network robustness, Peng et al. [15] utilized CNs to design statistical indicators and evaluate the robustness of three representative cargo shipping networks under four attack strategies, including random attacks, as well as intentional attacks, based on degree, betweenness, and flux centrality. Liu [16] conducted research and simulation on the robustness of the coal and iron intermodal transportation network. The study involved simulating the complete process of network construction, network attack and network restoration. Through the simulation, the study proposed optimization measures to improve network performance and resilience, laying the groundwork for network risk mitigation. Xu et al. [17] presented a new cascade model for the Global Liner Shipping Network (GLSN) and applied this model to an empirical GLSN dataset. The findings offered valuable managerial insights into preventing or alleviating the propagation of port congestion within the GLSN. Deng et al. [18] developed a network model for marine accidents along the Chinese coastal areas. The robustness analysis of the CNs provided valuable insights into risk prevention, the interruption of risk propagation, and a reduction in maritime accidents. Guo et al. [19] utilized CNs and scenario analysis methods to perform a robustness analysis of both the traditional shipping network and the Arctic shipping network. The findings demonstrated that the higher stability and the regular operation of the Arctic shipping network had the potential to reshape the global geographical landscape.

In the context of maritime trade, researchers have employed data mining techniques to reveal the structural features [20], the evolution mechanisms [21], the changing patterns and the evolutionary modes of maritime trade networks [22]. Through the construction of maritime trade networks, researchers seek to gain insights into the evolving patterns of maritime trade and thus enable a better understanding of the shifts in maritime trade. Specifically, Hao et al. [23] developed a global fossil energy flow network, where countries serve as nodes, to investigate the dynamics of fossil energy trade. The research findings highlighted the pivotal role of specific trade relationships in fossil energy trade and revealed the formation of major trade clusters. Moreover, the study employed CN indicators and traffic flow analysis to capture the evolutionary models of maritime trade and the distribution patterns and dynamics of energy flows. Yu et al. [20] conducted an analysis using AIS data to investigate the potential connections between oil price fluctuations, traffic flow changes, and the topological structure of the MTN. The study also explored whether oil price volatility drives structural changes in the tanker shipping network and provided support for national policies related to tanker transport. Additionally, Mou et al. [24] investigated the correlation and cargo flow patterns of maritime trade modes along the regions of the MSR through various types of MTN. Furthermore, Peng et al. [25] utilized AIS trajectories to construct a global COMTN, revealing a complex hub-and-spoke structure and identifying the top three global hub ports. Based on the findings, targeted recommendations can be provided to ensure the security of the COMTN.

### 2.2. Connectivity Reliability

The concept of CR originated in road transport networks and refers to the likelihood of a transport network being able to maintain a normal level of service when affected by disruptions; this is used as a measure of network reliability, with a particular focus on the binary state of a network segment—connected or disconnected [26]. However, the binary approach fails to fully reflect the existence of multiple states within a system, leading researchers to undertake additional methods [27]. At present, various algorithms, such as Boolean algebra, connectivity probability, the cut-set method, and the approximation method, have been used to solve the problems of CR. With the continuous advancement of research, the theory of CR has given rise to various network feature analysis methods in the context of different transport networks. For example, Wu et al. [28] introduced a novel indicator of network CR, demonstrating its effectiveness in studying the Nanjing subway network. Furthermore, CR has also been employed as an objective or constraint in system optimization, finding applications in post-disaster rescue operations [29], road network design [30], and transport route selection [31], among other areas.

In the domain of MTN, Wang et al. [32] established a bi-objective programming model that considers CR and transport cost as constraints to optimize crude oil transport routes. The study examined the effects of parameter variations on route selection, transportation costs, and CR, offering valuable insights for decision makers planning crude oil transport. Lu et al. [33] employed uncertain variables to accurately describe the connectivity status of each node in the COMTN after extreme events occur. Moreover, uncertainty theory is introduced to assess the reliability of the network's connectivity. Additionally, a highly reliable path selection model is established for the uncertain COMTN. This model ensures the timely delivery of crude oil even in the event of extreme occurrences, providing decision makers with a reliable basis for selecting appropriate paths after such events take place. Wang et al. [34] introduced vine copula to assess the CR of key nodes in the COMTN when evaluating the interdependencies among various unexpected events. The study focused on the Malacca Strait as an example. By constructing the joint distribution of various unexpected events using vine copula, the research results could provide corresponding measures for countries with nodes in the network to cope with unexpected events. Vega et al. [35] conducted a study to examine the maritime connectivity between Ireland and the European continent, utilizing stated preference (SP) experimental data to develop a modelling approach with which to analyze route selection in these regions. The findings made significant contributions to the formulation of transport policies for shipping in Ireland. Wen et al. [36] developed a model for evaluating the reliability of the MTN using joint entropy and multiscale factors. The model was applied to the MTN between Asia and Europe, demonstrating its effectiveness and suitability. The research outcomes offered valuable guidance to decision makers involved in MTN planning.

### *2.3. Research Gaps and Contributions*

Based on the existing literature, research on the connectivity and reliability of transport networks has predominantly concentrated on urban road networks, with limited studies specifically examining the MTN, particularly in the context of crude oil shipping. Among the studies conducted so far, the indicators used to evaluate the reliability of the COMTN have been relatively simplistic, leaving room for improvement in the accuracy of the models. Additionally, the network structure and service functionalities of the COMTN differ significantly from those of road transport networks. Therefore, there is a need to examine the connectivity and reliability of the imported COMTN from a distinct perspective. This study aims to make the following contributions:

(1) An integrated assessment index for node importance is established and a method to identify key nodes in COMTN is developed to facilitate the prioritization of critical nodes within the network.
(2) A model of CR specifically designed for the COMTN is developed. This model evaluates the overall reliability of the network and the reliability of individual routes within it. By overcoming the shortcomings of relying solely on a single index to capture the potential issues within the network, this model offers a comprehensive and objective analysis of the CR of the imported COMTN.
(3) Analysis of the effects of different attacks on the imported COMTN is carried out. This includes assessing the reliability of different maritime transport routes when subjected to attacks and examining the impacts resulting from the failure of critical nodes. Based on these findings, targeted and effective countermeasures and recommendations are formulated to address the issue of network collapse following the failure of specific nodes.

## 3. Methodology

### *3.1. Topology Features of CNs*

Complex network theory has garnered significant attention in the exploration of the MTN. The imported COMTN plays a significant role in the global maritime transport system and encompasses essential elements including ports, straits, canals, shipping routes, and vessels [37]. The imported COMTN is structured as a comprehensive MTN system. The nodes represent the original ports in oil-exporting countries, straits, and canals. The edges of the network represent the shipping routes between ports and the corresponding canals and straits. However, the imported COMTN displays properties of CNs due to various factors, including geographical variations in the world's straits and canals, changes in oil-importing countries, and the specific characteristics of crude oil shipping. The following section introduces several topological characteristics of CNs.

(1) Degree of nodes

Degree $K_i$ of node $i$ is considered one of the fundamental statistical indicators in CNs, referring to the number of nodes directly connected to node $i$. The degree of a node can indicate its importance within a network, with a higher degree corresponding to a greater level of importance [38]. In the context of directed networks, the degree of a node can be further classified into in-degree and out-degree, based on the direction of the edges. In-degree represents the number of edges pointing towards a particular node from other nodes in a network, and it is denoted as $K_i^{in}$; its calculation equation is presented as Equation (1). Out-degree represents the number of edges pointing towards other nodes from a particular node, and it is denoted as $K_i^{out}$; its calculation equation is presented as Equation (2):

$$K_i^{in} = \sum_{j=1}^{N} a_{ji} \tag{1}$$

$$K_i^{out} = \sum_{j=1}^{N} a_{ij} \tag{2}$$

In the equation, $a_{ij}$ represents whether nodes $i$ and $j$ are directly connected; if there is a connection between node $i$ and node $j$, $a_{ij} = 1$. Otherwise, $a_{ij} = 0$. Similarly, $a_{ji}$ represents whether node $j$ and $i$ are directly connected; if there is a connection between node $j$ and node $i$, $a_{ji} = 1$.

(2) Node strength

The node strength is a significant geometric measure in weighted networks, distinguishing them from unweighted networks. It resembles the concept of degree in unweighted networks and serves as a topological parameter for assessing the importance of nodes. In weighted networks, the node strength is defined as the sum of the weights of all edges connected to node $i$. The equation for calculating the node strength is given in Equation (3). The interpretation of the node strength may vary across different CNs. In the case of the imported COMTN, the node strength denotes the transport capacity of a specific site or facility in terms of crude oil handling and distribution [39].

$$S_i = \sum_{\mathrm{j} \in T_{\mathrm{i}}} w_{ij} \tag{3}$$

In the equation, $S_i$ is the strength of the node $i$, $T_i$ is the set of neighboring nodes of node $i$, and $w_{ij}$ is the weight of the edge connecting node $i$ and node $j$.

(3) Betweenness centrality

Betweenness centrality is an approach utilized for assessing the significance of nodes within a network. It reflects the extent to which a node acts as a bridge or intermediary in connecting other nodes [40]. In this study, betweenness centrality is quantified as $C_b(k)$. Its calculation equation is presented as Equation (4).

$$C_b(k) = \frac{1}{(n-1)(n-2)} \sum_{i \neq j \neq v_i, i<j} \frac{g_{ij}(k)}{g_{ij}} \tag{4}$$

In the equation, $g_{ij}$ denotes the number of the shortest paths from node $i$ to node $j$, and $g_{ij}(k)$ denotes the number of the shortest paths from node $i$ to node $j$ through node $k$.

(4) Eigenvector centrality

The importance of a node is influenced by both its degree, which accounts for the number of adjacent nodes, and the importance of those adjacent nodes. The more significant the connected adjacent nodes are, the more important the node itself becomes. Eigenvector centrality is a measurement used in CNs to assess the importance of a node [41], overcoming the limitations of solely relying on the degree value to determine the importance. It assigns a relative score to each node on the principle that connections to nodes with high scores contribute more to a node's score than connections to nodes with low scores (given an equal number of connections). The centrality of the feature vectors is calculated as shown in Equation (5).

$$C_E = x_i = c\sum_{j=1}^{N} a_{ij}x_j \quad (5)$$

where $x_i$ represents the centrality score of node $i$, c is a constant of proportionality, and $N$ is the total number of nodes. When, and only when, $i$ is connected to $j$, $a_{ij} = 1$; otherwise, $a_{ij} = 0$.

### 3.2. Node Importance Assessment Model

The imported COMTN is a directed and weighted special CN. In general transportation networks such as urban road networks, container shipping networks, and aviation networks, nodes are closely connected through edges, resulting in a higher level of network connectivity compared to the COMTN. Relying solely on topological characteristics like the node degree is insufficient to accurately identify important nodes in transport networks. The importance of a node is influenced by the position and the importance of its neighboring nodes in the network. As a result, this study use a comprehensive evaluation index to identify and rank important nodes in the imported COMTN.

The evaluation process involves multiple steps. Firstly, the Weighted Leader Rank algorithm is employed to initially identify crucial nodes by computing metrics such as the node degree, node strength, etc. These metrics provide valuable insights into the importance of nodes within the network. Secondly, to ensure fair comparison and accurate identification, the metrics are standardized, facilitating a consistent evaluation across different nodes. Lastly, by combining the two identification methods, a comprehensive evaluation model for the importance of nodes in the imported COMTN is constructed.

#### 3.2.1. Weighted Leader Rank

Considering the impact of the importance of neighboring nodes on the identification of crucial nodes, this study adopts eigenvector centrality to address this issue. Eigenvector centrality takes into account both the number of neighboring nodes and the importance of those neighboring nodes, providing a comprehensive assessment of a node's importance within the network. In order to rank the importance of nodes in CNs, this study utilizes the Weighted Leader Rank algorithm, which incorporates eigenvector centrality. The network structure of the Weighted Leader Rank algorithm is illustrated in Figure 1.

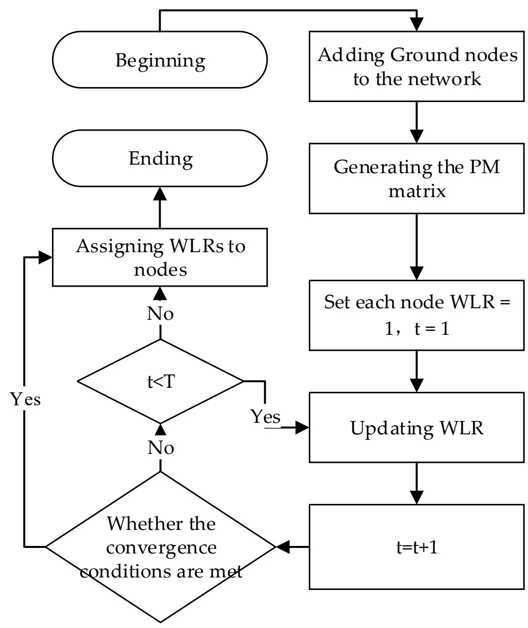


**Figure 1.** Flow chart of Leader Rank algorithm.

The Leader Rank algorithm incorporates the concept of a "Ground" node into the existing network $DiG = (N, DiE)$, creating a directed network $DiG = (N+1, DiE+2N)$ with $N+1$ nodes. The bidirectional connections between the Ground node and other nodes ensure a strongly connected graph, effectively preventing the presence of isolated nodes in CNs and ensuring algorithm convergence. Additionally, to capture the inherent structural characteristics of nodes within the network, the Leader Rank algorithm utilizes a biased random walk algorithm instead of a standard random walk algorithm. It allows nodes to receive a portion of their weights from the Ground node, reflecting their importance in relation to other nodes. The algorithmic calculations are represented by Equations (6)–(11):

$$PM = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} & d_{1g} \\ d_{21} & d_{22} & \cdots & d_{2n} & d_{2g} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} & d_{ng} \\ d_{g1} & d_{g2} & \cdots & d_{gn} & d_{gg} \end{bmatrix} \tag{6}$$

$$d_{ji} = \begin{cases} (k_i^{in}),\ j \to i, j = g \\ 1,\ j \to i, i = g \\ 0, \text{Others} \end{cases} \tag{7}$$

In the equation, $PM$ represents the transfer probability matrix, $d_{ji}$ represents the transfer probability of node $i$ to node $j$, and $\left(k_i^{in}\right)$ is the degree of entry of the node.

$$WLR_i(t+1) = \sum_{j=1}^{N+1} \frac{d_{ji}}{\sum\limits_{k}^{N+1} d_{jk}} WLR_j(t) \tag{8}$$

$$WLR(t) = [WLR_1(t) \quad WLR_2(t) \quad L \quad WLR_n(t)] \tag{9}$$

$$J = \|WLR(t+1) - WLR(t)\|_F \leq e \tag{10}$$

$$g_i = WLR_i(t_{end}) = WLR_i(t_{end}) + \frac{WLR_g(t_{end})}{N} \tag{11}$$

In the equation, $t$ is the number of iterations, $J$ indicates the convergence condition, $e$ is the threshold of convergence, $t_{end}$ indicates the last iteration, and $WLR_i$ is the importance score of the node. For ease of presentation, the results of the scores based on the Leader Rank algorithm are indicated by $g_i$ in this study. Equation (8) is the iterative equation for the importance score of each node, Equations (9) and (10) are the judgment conditions for the convergence of the algorithm, and Equation (11) is the final importance score of each node.

### 3.2.2. Comprehensive Assessment Indicators

Based on the aforementioned analysis, this section considers the node degree, node strength, node position, and the importance of neighboring nodes to construct a comprehensive evaluation index. In the comprehensive index, the degree value of node $K_i$ can be represented by the number of nodes directly connected to node $i$. Considering the characteristics of the imported COMTN, the calculation of the node strength $d_i$ is presented in Equation (12).

$$d_i = \frac{o_i}{O} \tag{12}$$

In the equation, $d_i$ is the work intensity of node $i$, $o_i$ is the volume of crude oil transported by node $i$, and $O$ is the total volume of crude oil transported by the maritime network.

The computation of betweenness centrality $C_b(k)$ is defined by Equation (4). Subsequently, the values of $K_i$, $d_i$, $C_b(k)$, and $g_i$ are normalized and computed, resulting in value $C_i$, as indicated by Equations (13) and (14).

$$x = \frac{x - min_V(x)}{max_V(x) - min_V(x)} \tag{13}$$

In the equation, $x$ indicates the value to be normalized, $min_V(x)$ denotes the smallest value of $x$ in the set $V$, and $max_V(x)$ denotes the maximum value of $x$ in the set $V$.

$$C_i = \left(K_i{}^* + d_i{}^* + C_b(k)^* + g_i^*\right)/4 \tag{14}$$

In the equation, $K_i{}^*$ represents the normalized result of the node degree value, $d_i{}^*$ represents the normalized result of the node strength, $C_b(k)^*$ denotes the normalized result after the quantification of the betweenness centrality, and $g_i^*$ represents the normalized result of the Leader Rank algorithm result.

### *3.3. Modelling Network Connectivity Reliability*

This study focuses on the imported COMTN, specifically examining the network's ability to ensure the safe completion of crude oil transport tasks from source ports to destination ports. The primary purpose of the imported COMTN is to securely transport crude oil cargo from the ports of the importing country to the destination ports at a reasonable cost and time. The successful and safe transport of crude oil cargo from the origin port to the destination port is an important indicator for assessing the connectivity and reliability of the MTN.

The connectivity and reliability of the MTN fundamentally play a fundamental role in determining whether the cargo can arrive at its destination safely and on time. The imported COMTN begins at the ports in different regions and is connected to destination ports through a series of straits and canals. Throughout this process, the network nodes are vulnerable to various extreme events such as uprisings, wars, piracy, terrorism activities, natural disasters, and other disruptive incidents. As a result, the affected nodes face the risk of paralysis or targeted attacks, leading to potential network disruptions and disconnections.

To address these challenges, this study aims to propose a comprehensive model for assessing the connectivity and reliability of the imported COMTN. This model will consider the various risk factors and potential disruptions that can affect the network's functionality. By evaluating the network's connectivity and reliability, this model will contribute to a better understanding of the network's vulnerabilities and assist in formulating effective strategies to mitigate risks and enhance the overall resilience of the imported COMTN.

#### 3.3.1. Network Connectivity Reliability Model

In the field of CNs, the connectivity and reliability of a network are typically evaluated through metrics such as the relative size of the largest connected subgraph after various attacks [42], network efficiency [43], and connectivity [44]. These indicators serve as benchmarks for assessing the network's ability to maintain connectivity under different circumstances. However, these methods are not applicable to the COMTN where connectivity is required between origin–destination ($OD$) pairs rather than between all pairs. To address this issue, this study establishes models of CR under two attack modes: random attacks and deliberate attacks. The main objective is to analyze the CR of designated $OD$ pairs, the CR of maritime routes, and the overall CR of the entire imported COMTN when certain nodes are unable to provide normal shipping network services due to being disconnected.

The following are the prerequisites for constructing the model of CR:

(1) The nodes in the model are assumed to have two states: fully operational or completely failed.

(2) The edges connecting the nodes, i.e., the shipping routes, are assumed to be in normal condition.
(3) The node failures are independent of other port nodes, and the destination nodes are considered immune to failure.

Based on the given conditions, the explanations for the CR of the imported COMTN, including the *OD* pairs, shipping routes, and the entire MTN, are provided below.

(1) The *OD* pairs of CR: This refers to the probability of maintaining connectivity between *OD* pairs in the network when certain nodes are completely disconnected.
(2) The shipping route of CR: The imported COMTN is divided into several shipping routes based on the geographical distribution of ports in importing countries. The specific shipping route of CR is defined as the weighted average of the CR of all *OD* pairs within that route when some nodes in the network are completely disconnected. The weights correspond to the share of crude oil transport undertaken by each *OD* pair.
(3) CR of the entire imported COMTN: It represents the weighted average of the CR of all *OD* pairs in the network when some nodes are completely disconnected. The weights are determined by the share of crude oil imports carried by each *OD* pair.

3.3.2. Model Construction under Different Attack Modes

Random attack refers to the probability-based random disruption of nodes in a network. This attack type represents the random failure of any node in the network, which can occur due to various factors such as natural disasters, regional or national political unrest, or labor strikes. Random attacks are used to evaluate the adaptability and the COMTN of CR when nodes fail randomly.

Deliberate attack refers to the intentional failure of network nodes based on their importance ranking, as described in Section 3.2. This involves the targeted disruption of nodes in a specific order, starting from the most critical and progressing to the least critical. Deliberate attacks include activities such as piracy, terrorism, and military actions driven by geopolitical interests among major nations. The objective of deliberate attacks is to inflict maximum damage and the complete disconnection of the imported COMTN. The analysis of deliberate attacks enables the network's stability to be assessed by examining how CR changes when specific vital nodes fail.

(1) Constructing a random attack model

A random attack model is constructed to simulate the scenario in which nodes in the crude oil shipping network are randomly attacked with a certain probability. This situation typically arises due to factors such as a lack of knowledge about the network or inherent network malfunctions.

The process starts from the initial state of the crude oil shipping network and employs Monte Carlo simulation to randomly disable network nodes. The number of nodes being attacked gradually increases from 1 until all nodes in the network are completely disabled. Drawing insights from the theory of CNs, the reliability of the network is evaluated based on criteria derived from graph theory's analysis of CR [45]. Here are the steps involved in constructing the random attack model, as indicated by (1)–(4):

(1) Construction of the imported COMTN.

A MTN for imported crude oil, denoted as $G(V,E)$, is constructed, where $V = \{v_1, v_2, v_3 \ldots v_n\}$ is the set of nodes and $E = \{e_1, e_2, e_3 \ldots e_m\}$ is the set of edges. The number of network nodes is $n = |V|$, and the number of edges is $m = |E|$. $(v_i, v_j)$ represents the existence of a directed edge between node $v_i$ and node $v_j$, and pointed by node $v_j$ to node $v_j$.

(2) Construction of the adjacency matrix.

Within the MTN $G(V,E)$, comprising a total of $n$ nodes, it is possible to construct an $n \times n$ adjacency matrix $A = (a_{ij})_{m \times m}$. The connection relationship between any two nodes in the MTN is represented by matrix $A = (a_{ij})_{m \times m}$. If there is a directed edge from node $i$ to node $j$, the value of element $a_{ij} = 1$, otherwise, $a_{ij} = 0$.

(3) Computation of the reachable matrix.

According to the CR criterion in graph theory, for a matrix, $S = \left(S_{ij}\right)_{m\times m} = \sum_{h=1}^{m-1} A^k$. If all elements in the matrix are non-zero, then $G$ is a connected graph; otherwise, $G$ is a disconnected graph.

$$A^k = \left(a_{ij}^{(k)}\right)_{m\times m} \tag{15}$$

$$\left(a_{ij}^{(k)}\right) = \sum_{h=1}^{m} a_{ih}^{(k-1)} a_{hj} \tag{16}$$

In Equations (15) and (16), $a_{ij}^{(k)}$ represents the path from node $i$ to node $j$ after $k$ steps. If $\sum_{k=1}^{m-1} a_{ij}^{(k)} = 0$, it indicates the absence of a connection between nodes $i$ and $j$ in the network. By replacing the non-zero elements in matrix $S$ with 1, while keeping the zero elements unchanged, the reachability matrix $P = \left(p_{ij}\right)_{m\times m}$ can be obtained in Equation (17).

$$P_{ij} = \begin{cases} 1, v_i \text{ is connected to } v_j, v_i, v_j \in V \\ 0, \text{Others} \end{cases} \tag{17}$$

In the analysis, the Monte Carlo algorithm is applied to generate random failed nodes. Afterwards, the network's adjacency matrix is updated considering the failed nodes. The reachable matrix is then computed using the Boolean matrix method. By employing the reachable matrix of the imported COMTN, the CR between the source node and the destination node can be determined.

(4) Construction of a CR model under random attack mode.

A model of CR is constructed to evaluate the connectivity of China's imported COMTN under random attacks. The model is expressed by Equations (18)–(20). The CR of each maritime shipping route within the imported COMTN can be assessed based on the CR between each $OD$ pair in the network.

$$R = \sum_{u=1}^{n} w_u r_u \tag{18}$$

$$r_u = \frac{x_u}{K} \tag{19}$$

$$R_\partial = \sum_{u=1}^{q} w_u r_u \tag{20}$$

In Equations (19)–(21), $r_u$, $R_\partial$, and $R$ represent the CR between $OD$ pairs, the route CR, and the network CR. $K$ is the number of simulations, $x_u$ is the number of connections between the $u$th $OD$ pair in $K$ simulations, $q$ and $n$ are the number of $OD$ pairs within a given route and across the network, and $w_u$ is the weight of the $u$th $OD$ pair.

(2) Construction of the random attack model

The CR of the imported COMTN is evaluated by employing a random node failure strategy. This strategy assesses the reliability between different $OD$ pairs in the network when nodes fail randomly. Drawing inspiration from the determination of the sample size in parameter estimation [46], a simulation is conducted 1000 times to ensure a network CR with a 95% confidence level and an error below 0.01. Figure 2 depicts the flowchart for simulating random node failures.

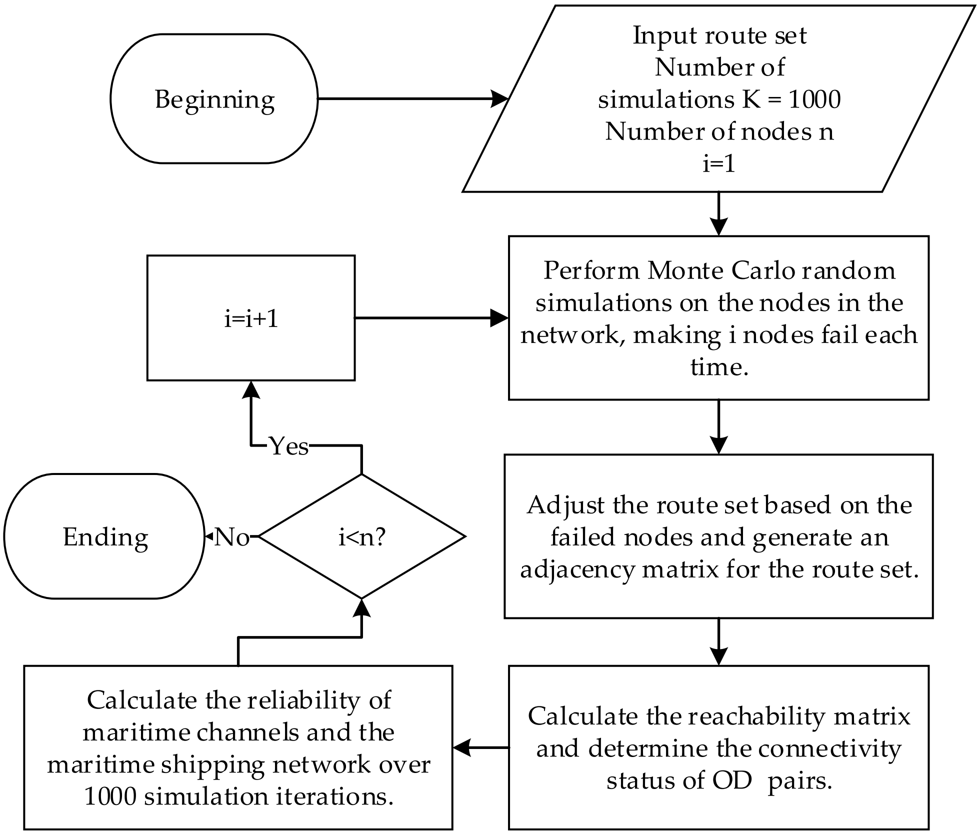


**Figure 2.** Flow chart of random attack failure simulation.

(3) Construction of the deliberate attack model

According to the assessment model for node importance outlined in Section 3.2, the nodes are ranked in descending order based on their importance. Subsequently, the network's CR is recalculated by systematically attacking the nodes one by one until all nodes have been attacked. Deliberate attacks are carried out by the attackers using the network information already available. In this section, the minimum disjoint path sets algorithm [47] is employed to compute the CR of the imported crude oil network under deliberate attacks. The calculation equations are presented in Equations (21)–(24).

Let $L_1, L_2 \cdots L_m$ represent the set of all minimum paths for any given $OD$ pair in the imported COMTN. Based on the principle of disjointness, the CR between the $OD$ pairs is calculated as the product of the reliabilities of individual paths within the set $R_{o,d}(G)$.

$$R_{o,d}(G) = pr(L_1 + L_2 + \cdots + L_m) \tag{21}$$

From the disjoint equation, the following can be calculated:

$$L_1 + L_2 + \cdots + L_m = L_1 + \overline{L_1}L_2 + \overline{L_1L_2}L_3 + \cdots + \overline{L_1L_2} + \cdots + \overline{L_{m-1}}L_m \tag{22}$$

In Equation (23), the terms are disjoint, and the following can be concluded:

$$R_{o,d}(G) = pr(L_1) + pr(\overline{L_1}L_2) + pr(\overline{L_1L_2}L_3) + \cdots + pr(\overline{L_1L_2} + \cdots + \overline{L_{m-1}}L_m) \tag{23}$$

Based on the concepts of disjointness and theorem, if sets $L_i$ and $L_j$ contain some common elements, then $\overline{L_i}L_j = \overline{L_i - L_j}L_j$, where $\overline{L_i - L_j}$ represents the "Boolean intersection" of elements present in $L_i$, but not in $L_j$.

By applying the principle of disjointness to simplify Equation (23), the following can be obtained, as indicated in Equation (24):

$$\begin{aligned} R_{o,d}(G) = pr(L_1) + pr(\overline{L_1}L_2) + pr(\overline{L_1L_2}L_3) + \cdots + pr(\overline{L_1L_2} + \cdots + \overline{L_{m-1}}L_m) \\ +pr(\overline{L_1 - L_mL_2 - L_m} + \cdots + \overline{L_{m-1} - L_m}L_m) \\ = pr(L_1) + pr(\overline{L_1 - L_2})pr(L_2) + pr(\overline{L_1 - L_3L_2 - L_3})pr(L_3) + . \\ +pr(\overline{L_1 - L_mL_2 - L_m} + \cdots + \overline{L_{m-1} - L_m})pr(L_m) \end{aligned} \tag{24}$$

By utilizing Equation (24), the CR for each *OD* pair in the imported COMTN can be computed based on the vulnerability of nodes to attacks. To calculate the CR of individual routes within the entire network, Equations (18) and (20) can be applied, following the same random attack model.

(4) Solution of the deliberate attack model

The imported COMTN is intentionally attacked, simulating the deliberate failure of nodes. The nodes are initially ranked based on their importance. Then, the simulation proceeds by sequentially attacking them in descending order, which causes the targeted nodes to fail. It should be noted that the remaining nodes, which have not been attacked, have a normal operation probability of 0.95 [48]. Figure 3 shows the flow chart of the deliberate failure simulation.

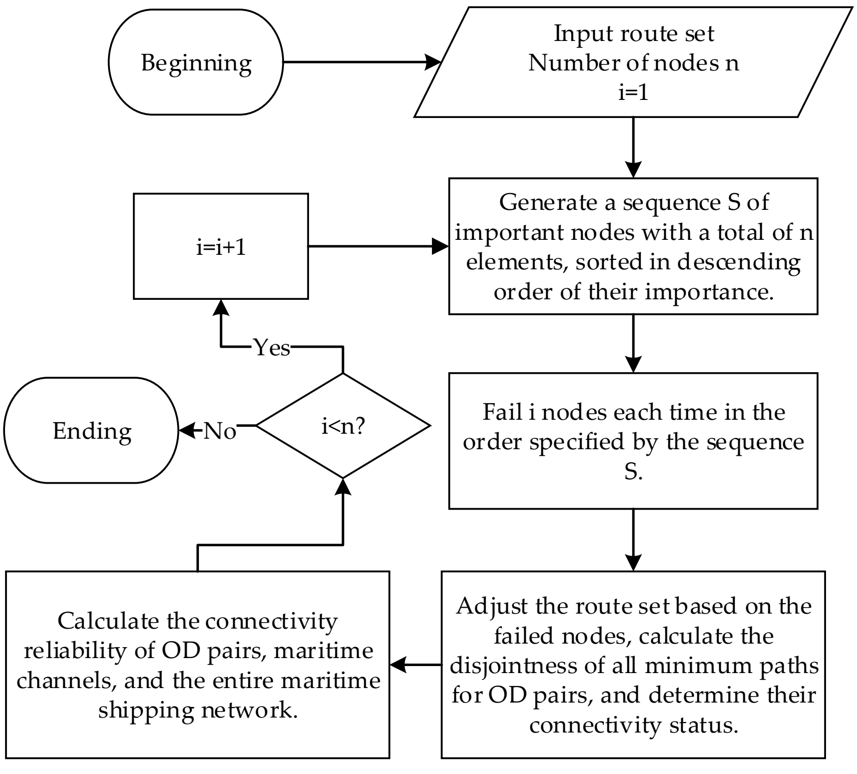


**Figure 3.** Flow chart of selective attack failure simulation.

## 4. Calculation Results and Discussion

This study aims to provide an accurate analysis of the current state of connectivity and reliability in China's imported COMTN, specifically focusing on the network under the "Belt and Road" initiative. To achieve this, the study considers the geographical distribution of China's crude oil source countries and established the actual imported COMTN. By using node importance evaluation indicators and a constructed reliability model, the study calculates the connectivity and reliability of each *OD* pair in China's COMTN under both random attacks and deliberate attacks. Furthermore, the study assesses the connectivity and reliability of individual maritime routes and the entire maritime network by taking into account the assigned crude oil maritime transport shares for each *OD* pair.

### 4.1. China's Imported COMTN

In 2021, China imported $5.13 \times 10^8$ tons of crude oil, with the Middle East, Russia, Africa, and the Americas being the four major regions accounting for 50.0%, 16.0%, 13.0%, and 15.0% of the market share. Since China's crude oil imports from Russia are transported by pipeline, Russia's market share is not considered in this paper. Additionally, China also imported 4.0% of its crude oil from Europe and Southeast Asia during the same year [49]. In addition to crude oil imports from Russia, Kazakhstan, and Mongolia, which are transported via land routes, all other imports of crude oil to China rely entirely on maritime transport. Due to the impact of global circumstances and the progress of the Belt and Road Initiative in recent years, China's primary sources of imported crude oil have undergone changes, resulting in fluctuations in the import volumes. Based on the distribution and import volumes of crude oil sources in 2021, China's imported COMTN has been established. This network primarily consists of three major routes: Middle East to China, Africa to China, and the Americas to China. The major source countries for crude oil imports in the Middle East region include Saudi Arabia, Iraq, Oman, Kuwait, the United Arab Emirates, and Qatar. In Africa, the primary countries are Angola, Congo, Libya, and Sudan. In North and South America, the main countries are the USA, Brazil, and Colombia. Norway and the UK are the primary countries in Europe, while Malaysia serves as the main source country for crude oil imports in Southeast Asia.

In the China's imported COMTN, the major straits and canals include the Sunda Strait, the Strait of Hormuz, the Suez Canal, the Lombok Strait, the Strait of Gibraltar, the Panama Canal, the Bab el-Mandeb Strait, the Taiwan Strait, the Strait of Malacca, and the Bashi Strait. The loading ports of crude-oil-exporting countries and the unloading ports in China serve as two types of nodes in the MTN for China's crude oil imports. The set of nodes $V = (v_1, v_2, \cdots, v_n)$ in the China's imported COMTN consists of 27 nodes, including representative crude oil loading ports in the 16 major source countries mentioned earlier, the Ningbo-Zhoushan Port representing China's crude oil unloading port, as well as the aforementioned straits and canals. Among the 27 nodes, 16 nodes represent the loading ports of the source countries. China's imported COMTN consists of 16 *OD* pairs. The nodes are represented as shown in Table 1. Table 2 presents the nodes, the respective shares of crude oil imports, and the associated maritime transport routes for each *OD* pair. By utilizing the developed reliability model, the CR of the five transport routes within China's imported COMTN, as well as the overall network connectivity, can be computed.

To model China's imported COMTN under the "Belt and Road" initiative, an adjacency matrix is utilized. Taking Table 2 as an example, if there is a shipping route between port, canal, and strait nodes, the corresponding value in the adjacency matrix is set to 1; otherwise, it is set to 0. The visualization of the adjacency matrix is presented in Figure 4.

**Table 1.** Node name and abbreviation.

| Serial Number | Node Number | Serial Number | Node Number |
|---|---|---|---|
| 1 | Strait of Malacca (SOM) | 15 | UK |
| 2 | Taiwan Strait (TS) | 16 | Angola (AN) |
| 3 | Bashi Strait (BS) | 17 | Saudi Arabia (SA) |
| 4 | Sunda Strait (SS) | 18 | Congo (CG) |
| 5 | Lombok Sela (LS) | 19 | Malaysia (MA) |
| 6 | Strait of Hormuz (SOH) | 20 | Iraq (IR) |
| 7 | Strait of Gibraltar (SOG) | 21 | Libya (LI) |
| 8 | The Mandab Strait (TMS) | 22 | Kuwait (KU) |
| 9 | Suez Canal (SC) | 23 | ARE (AR) |
| 10 | Panama Canal (PC) | 24 | US |
| 11 | Brazil (BR) | 25 | Sudan (SU) |

**Table 1.** *Cont.*

| Serial Number | Node Number | Serial Number | Node Number |
|---|---|---|---|
| 12 | Oman (OM) | 26 | Qatar (QA) |
| 13 | Norway (NO) | 27 | China (CN) |
| 14 | Colombia (CO) | | |

**Table 2.** Composition and share of China's crude oil imports maritime network.

| Crude Oil Maritime Transport Access | Crude Oil Imports Source Countries | Crude Oil Imports Routes | Import Share |
|---|---|---|---|
| Middle East–China Route | Saudi Arabia | Port of origin—SOH—SOM/SS/LS—TS/BS—CN | 21.5% |
| | Iraq | | 11.5% |
| | United Arab Emirates | | 6.3% |
| | Kuwait | | 6.7% |
| | Qatar | | 2.0% |
| | Oman | Port of origin—SOM/SS/LS—TS/BS—CN | 13.0% |
| Africa–China Route | Angola | Port of origin—Cape of Good Hope -SOM/SS/LS—TS/BS—CN | 8.0% |
| | Congo | | 3.0% |
| | Libya | Port of origin—SC—TMS—SOM/SS/LS—TS/BS—CN; Port of origin—SOG—Cape of Good Hope—SOM/SS/LS—TS/BS—CN | 1.0% |
| | Sudan | Port of origin—TMS—SOM/SS/LS—TS/BS—CN | 3.0% |
| America–China Route | Brazil | Port of origin—PC—CN; Port of origin—Cape of Good Hope—SOM/LS/SS—TS/BS—CN | 6.0% |
| | Colombia | | 2.0% |
| | USA | Port of origin—CN | 4.0% |
| Europe–China Route | Norway | Port of origin—SOG—SC—TMS—SOM/SS/LS—TS/BS—CN; Port of origin—Cape of Good Hope—SOM/SS/LS—TS/BS—CN; Port of origin—CN | 2.4% |
| | UK | | 1.6% |
| South East Asia–China Route | Malaysia | Port of origin—TS/BS—CN | 8.0% |

Note: data sources, https://www.eia.gov/international/analysis/country/CHN, (accessed on 25 May 2023).

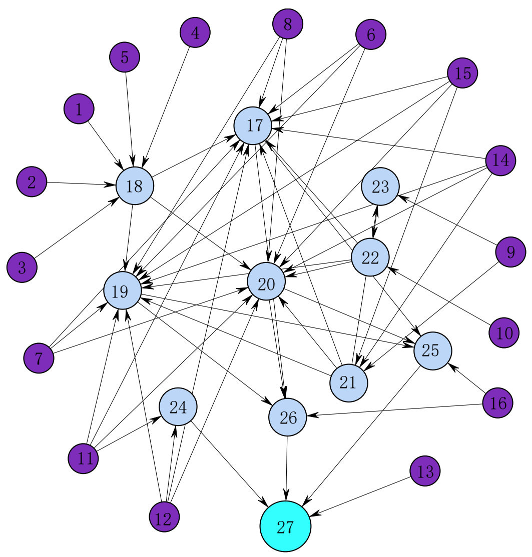


**Figure 4.** China's imported COMTN.

## *4.2. Significant Node Ranking Results*

In this study, the concept of node workload intensity refers to the share of crude oil maritime transport that a specific node bears. Different nodes have different capacities to accommodate various vessel sizes. Tankers are classified into Aframax, Handy, Very Large Crude Carrier (VCLL), Panamax, Suezmax, and Ultra-Large Crude Carrier (ULCC) types. VCLL and ULCC vessels are unable to pass through the Suez Canal, while Aframax, Suezmax, VCLL, and ULCC vessels cannot pass through the Panama Canal. Consequently, the selection of nodes for certain crude oil shipping routes, such as those originating from Libya or Latin America, is influenced by vessel compatibility. In this study, to accurately determine the workload intensity of each node, careful consideration is given to the different vessel types utilized for different *OD* pairs. This approach enables a more precise identification of critical nodes. Assuming an equal number of vessels are available for different routes and considering the varying cargo capacities of these vessels, it can be calculated that the amount of crude oil maritime transport through the Strait of Gibraltar is approximately 1.44 times that of the Suez Canal. Taking the Libya–China *OD* pair as an example, there are two shipping routes available. The aforementioned ratio can be used to allocate the share of crude oil handled by each node. A similar method is employed to allocate the crude oil maritime transport share among nodes for other pairs. Additionally, this study assumes an equal distribution of crude oil maritime transport through the Taiwan Strait and the Bashi Strait. These considerations ensure a comprehensive assessment of node workload intensity and facilitate the accurate analysis of the network's performance.

### 4.2.1. Degree, Node Strength, Betweenness Centrality, Leader Rank Algorithm Results

Using the node importance evaluation model outlined in Section 3.2 and referring to Table 1, the importance scores of the nodes within China's imported COMTN can be obtained and are presented in Table 3.

**Table 3.** Node importance score.

| Node | Degree | Work Intensity | Centrality | Leader Rank |
|---|---|---|---|---|
| SOM | 12 | 0.855 | 0.027 | 2.840 |
| SOH | 8 | 0.480 | 0.046 | 1.360 |
| SS | 12 | 0.093 | 0.027 | 2.840 |
| LS | 12 | 0.093 | 0.027 | 2.840 |
| TS | 5 | 0.468 | 0.015 | 3.620 |
| BS | 5 | 0.468 | 0.015 | 3.620 |
| SOG | 7 | 0.023 | 0.015 | 0.970 |
| TMS | 5 | 0.047 | 0.018 | 1.030 |
| BR | 4 | 0.060 | 0.000 | 0.388 |
| OM | 3 | 0.130 | 0.000 | 0.388 |
| NO | 4 | 0.024 | 0.000 | 0.388 |
| CO | 4 | 0.020 | 0.000 | 0.388 |
| UK | 4 | 0.016 | 0.000 | 0.388 |
| AN | 3 | 0.080 | 0.000 | 0.388 |
| SA | 1 | 0.215 | 0.000 | 0.388 |
| CG | 3 | 0.030 | 0.000 | 0.388 |
| PC | 3 | 0.025 | 0.003 | 0.780 |
| SC | 3 | 0.021 | 0.006 | 0.890 |
| IR | 2 | 0.080 | 0.000 | 0.388 |
| MA | 1 | 0.115 | 0.000 | 0.388 |
| LI | 2 | 0.010 | 0.000 | 0.388 |
| KU | 1 | 0.067 | 0.000 | 0.388 |
| AR | 1 | 0.063 | 0.000 | 0.388 |
| US | 1 | 0.040 | 0.000 | 0.388 |
| SU | 1 | 0.036 | 0.000 | 0.388 |
| QA | 1 | 0.014 | 0.000 | 0.388 |

The imported COMTN in China is comprised of several *OD* pairs. Table 3 reveals that the port nodes at the starting points of the routes have equal importance scores. However, as the nodes move closer to the endpoints, nodes such as Taiwan and the Bashi Strait exhibit higher importance scores. Among these nodes, the straits hold relatively greater importance compared to the canals.

#### 4.2.2. Comprehensive Assessment Indicators

Based on the node importance evaluation model outlined in Section 3.2.2, and by utilizing Equation (14), the importance scores and ranking of each node within China's imported COMTN are presented in Table 4 and Figure 5.

**Table 4.** The comprehensive evaluation index results.

| Node | Scores | Ranking | Node | Scores | Ranking |
|---|---|---|---|---|---|
| SOM | 0.879 | 1 | CO | 0.052 | 14 |
| TS | 0.738 | 2 | UK | 0.052 | 14 |
| BS | 0.738 | 2 | AN | 0.052 | 14 |
| SS | 0.705 | 3 | SA | 0.047 | 17 |
| LS | 0.705 | 3 | CG | 0.041 | 18 |
| SOH | 0.575 | 6 | MA | 0.035 | 19 |
| SOG | 0.264 | 7 | IR | 0.023 | 20 |
| TMS | 0.256 | 8 | LI | 0.017 | 21 |
| SC | 0.142 | 9 | KU | 0.012 | 22 |
| PC | 0.113 | 10 | AR | 0.012 | 22 |
| BR | 0.064 | 11 | US | 0.006 | 24 |
| OM | 0.064 | 11 | SU | 0.006 | 24 |
| NO | 0.058 | 13 | QA | 0 | 26 |

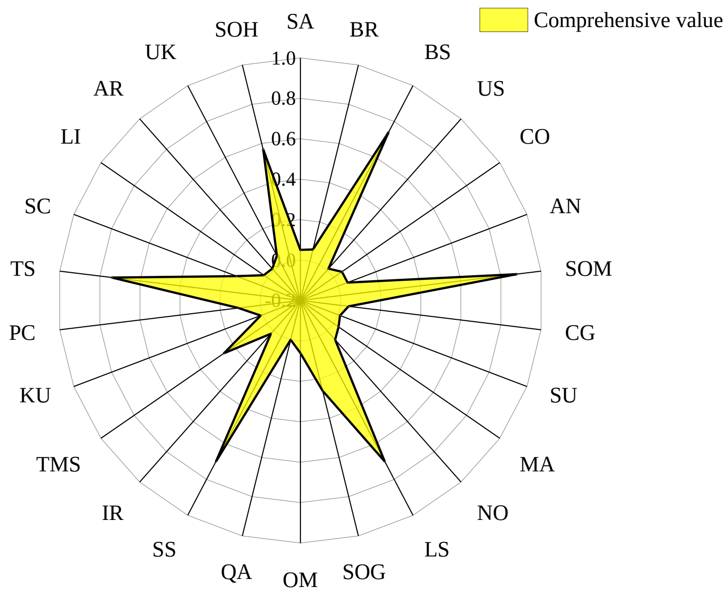


**Figure 5.** The comprehensive evaluation indicators.

### 4.3. Reliability Results and Analysis

#### 4.3.1. Random Attack Results and Analysis

Based on the random attack model and solution process outlined in Section 3.3, where the simulation count is set at $K = 1000$, the number of failed nodes gradually increases from 1 to 26. Figures 6 and 7 depict the fluctuations in CR for China's imported COMTN, as well as for each individual crude oil maritime transport route.

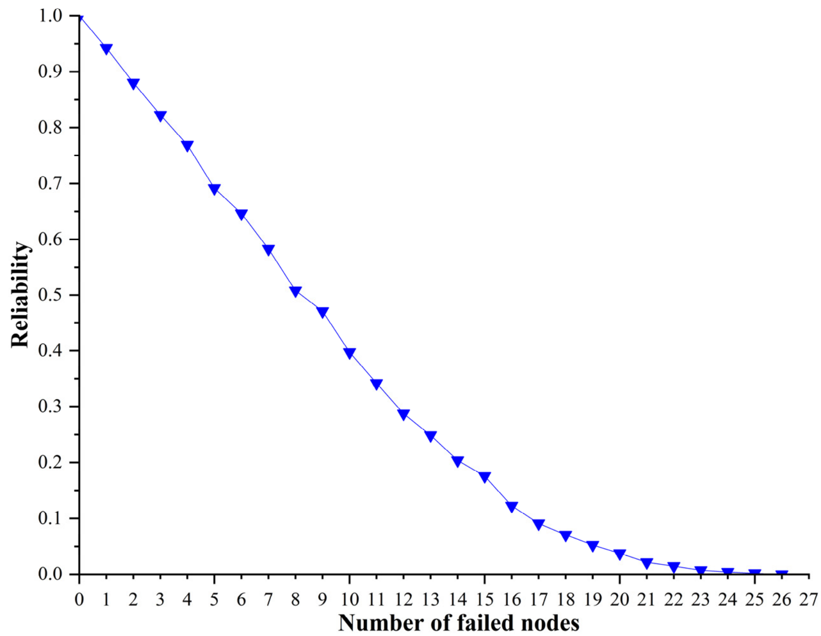


**Figure 6.** Reliability of the shipping network of China's imported crude oil under random attacks.

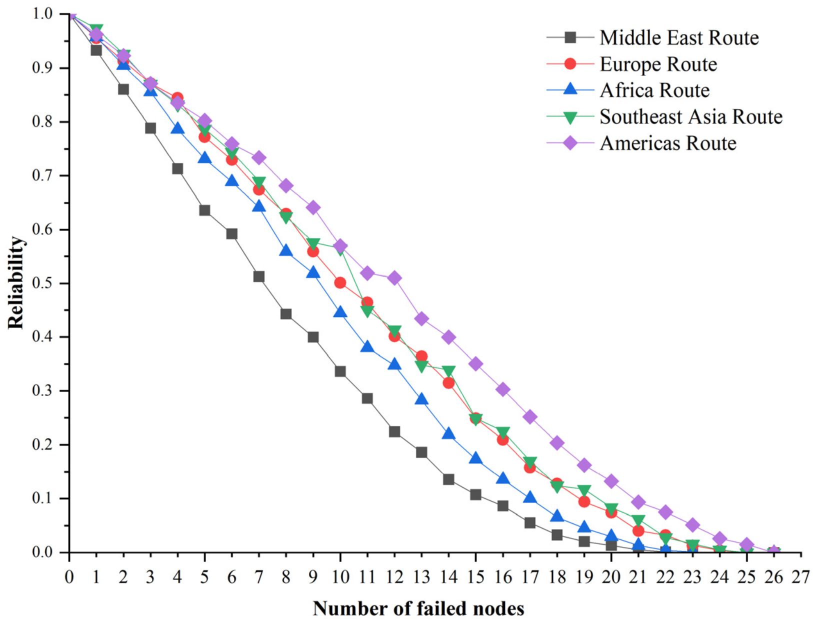


**Figure 7.** Reliability of communication between crude oil shipping routes under random attacks.

According to Figure 6, random attacks on nodes result in an increasing number of failures within the network, leading to a gradual decline in CR. When only one node fails, the CR of China's imported COMTN reaches 0.932. However, as the number of failed nodes gradually increases to seven, the reliability drops to 0.533, approximately half of its initial value. This means that when a random attack targets and simultaneously disrupts the majority of nodes in the network, the CR of the network is compromised, posing a threat to the security of crude oil imports. However, in practical scenarios, conducting such random attacks on nodes dispersed globally would incur significant costs. Consequently, when facing random attacks, China's imported COMTN still maintains a relatively high level of reliability.

According to Figure 7, it is evident that among the five crude oil maritime transport routes, the Middle East route exhibits relatively lower levels of CR, while the Americas route, Southeast Asia route, and Europe route are comparatively more reliable. This discrepancy can primarily be attributed to the fact that the Middle East route necessitates passage through both the Strait of Malacca and the Strait of Hormuz for all OD pairs, while the security conditions in these two straits are notably deficient. Within the Americas route, crude oil from Brazil and Colombia can be transported directly to Chinese ports via the Panama Canal. Additionally, crude oil imports from the USA can take advantage of a route that traverses the Pacific Ocean, with the possibility of making a refuelling stop in Hawaii, before reaching coastal ports in China. Importantly, these routes bypass the need to pass through the Strait of Malacca or the Strait of Hormuz. The African and European routes also avoid the need to pass through the Strait of Hormuz, while the Southeast Asia route offers a direct route to Chinese ports by traversing either the Taiwan Strait or the Bashi Strait. The CR of these routes lies between that of the Middle East and Americas routes.

### 4.3.2. Deliberate Attack Results and Analysis

Based on the deliberate attack model and solution process described in Section 3, the nodes are attacked in a sequential manner based on their importance. After each attack, the CR of China's imported COMTN is recalculated, leading to changes in the CR of the network and its individual maritime transport routes, as depicted in Figures 8 and 9.

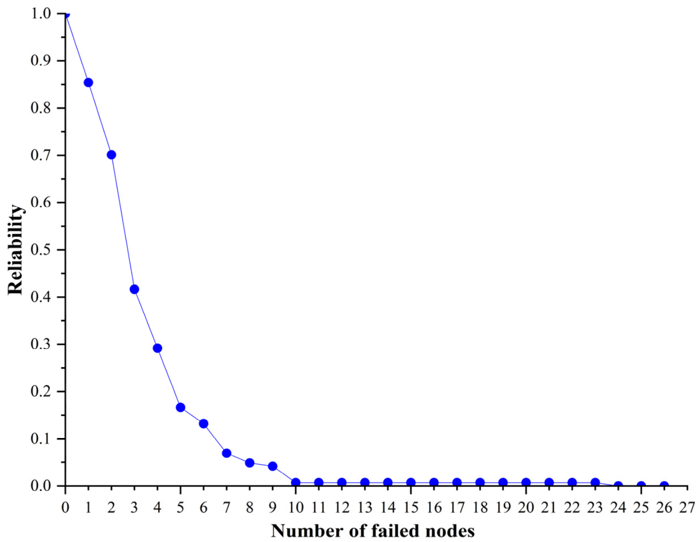


**Figure 8.** Reliability of China's crude oil imports shipping network under deliberate attacks.

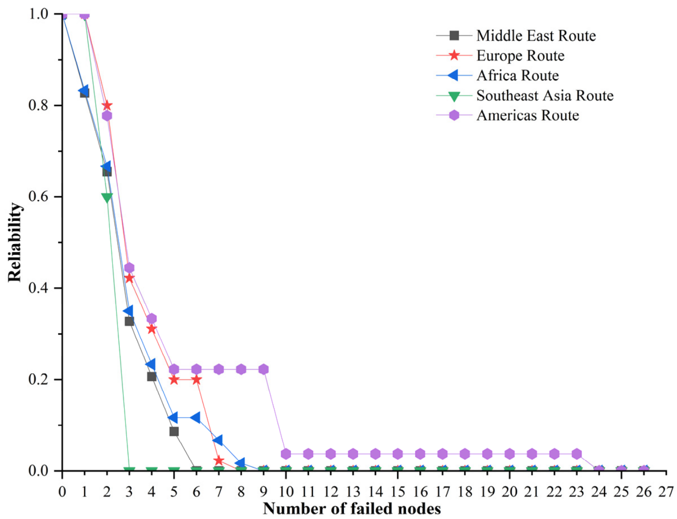


**Figure 9.** Connectivity reliability of crude oil shipping routes under deliberate attack.

When nodes are deliberately attacked, the targeted nodes are typically those with higher importance rankings. These nodes often serve as critical points in each crude oil maritime transport route, resulting in a rapid decline in the CR of the network and the network's ability to withstand attacks. Deliberate attacks prioritize the targeting of highly important nodes, causing a disconnection of numerous interconnecting links and greatly reducing the network's overall CR. Consequently, the functionality of China's imported COMTN is compromised, leading to network paralysis.

According to Figure 9, when the highly important node, the Strait of Malacca, is targeted, its failure does not significantly affect the network's overall CR. This is due to the availability of alternative nodes such as the Sunda Strait and the Lombok Strait, which serve a similar purpose. Consequently, the network maintains a CR of 0.854. However, when the Taiwan Strait is targeted, the network's CR decreases to 0.701, representing an 18.0% decline. At this stage, attacking the Taiwan Strait affects other maritime routes to varying degrees. The Americas route, because direct shipping from the USA to China is possible and there are routes passing through the Panama Canal, remains unaffected. The subsequent targeting of the Sunda Strait even leads to a further decrease in CR, reaching 0.290. At this time, the Lombok Strait remains the only functioning alternative to the Strait of Malacca, contributing to the ongoing deterioration of CR. Finally, continuing to attack the Lombok Strait results in a minimal CR of 0.160. Most connections within the network are severed, leaving only the Americas route for transport between the USA and Latin American countries, either via the Panama Canal or through direct routes to China.

Subsequently, continuing to deliberately attack the Strait of Gibraltar, the Strait of Hormuz, and the Strait of Mandeb would have consequences on the routes connecting the Middle East, Africa, and Europe. These actions would influence the distribution of crude oil transport among various routes, leading to a considerable decrease in the network's CR, which would plummet to 0.042. When the attack reaches the Panama Canal, only the transport of crude oil from the USA continues in the Americas route, while the network connectivity in the European route becomes virtually non-existent, resulting in a mere 0.007 reliability. Eventually, after targeting the nodes located in ports in the UK, Norway, and the USA, the entire network becomes completely severed, with a CR of 0, indicating a complete disconnection. The results show that the higher reliability of the Americas route is mainly due to the fact that there are many different shipping lanes to choose from on this route. Vessels have a wider choice of shipping lanes than on other routes, so if one node is attacked on this route, the vessel can choose another node.

In China's imported COMTN, each maritime route is characterized by its own set of critical nodes. Consequently, when different nodes are selected and targeted for attack, the CR among the various crude oil maritime transport routes varies. Although the Malacca Strait holds the highest importance ranking within the entire network, its impact on the CR of the five routes is relatively insignificant due to the availability of alternative straits such as the Sunda Strait and the Lombok Strait, which can function as substitutes when the Malacca Strait is compromised. With the exception of the Southeast Asia route, the CR of the remaining routes remains at around 0.900. The key nodes in the Southeast Asia route are the Strait of Malacca and the Taiwan Strait. As these two nodes are successively attacked, the CR in Southeast Asia drops abruptly to below 0.100, while the CR of other maritime transport routes decreases by over 50.0%. When the Sunda Strait is further attacked, the Southeast Asia route is practically severed. With the exception of the Americas route, the CR of the Europe, Africa, and Middle East routes drops to 0.100. Continuing the attack on the final alternative to the Malacca Strait, namely the Lombok Strait, results in the complete paralysis of the Middle East and Africa routes. However, due to the Americas route's capacity to reach China via the Panama Canal or directly, and the European route's ability to utilize the Arctic route for direct access to China, both routes maintain a certain degree of CR and remain relatively stable. Until the attack reaches the Panama Canal, the reliability of the Americas route is only 0.007, almost completely severing the route. Further attacks on the port nodes result in a complete loss of connectivity, reducing the reliability of all routes to 0. As a result, the entire imported COMTN to China becomes entirely non-functional, rendering it inoperative.

4.3.3. Comparison of the Results and Analysis of the Two Attack Patterns

The utilization of different attack modes on the nodes within China's COMTN yields distinct effects on the network's connectivity and reliability. Figure 10 presents a comparative visualization depicting the network's connectivity and reliability under two specific attack modes.

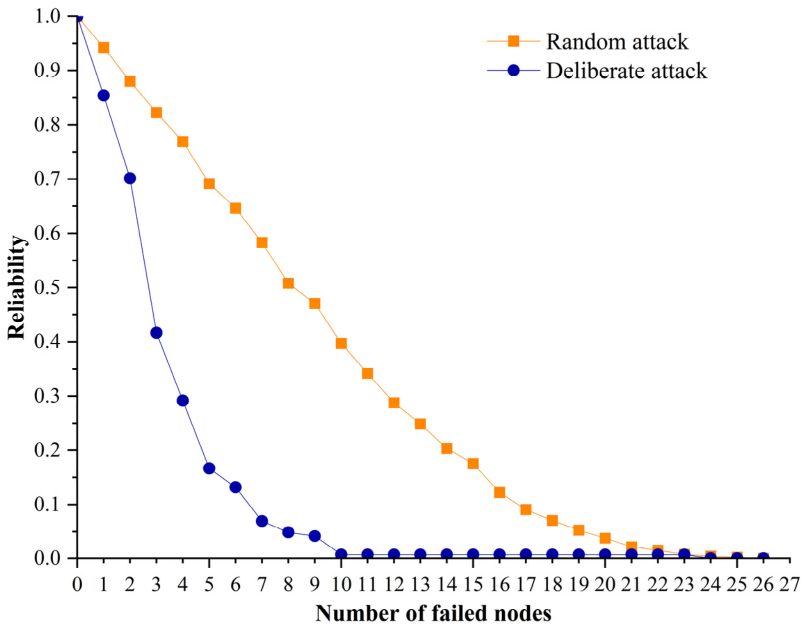


**Figure 10.** Reliability of Chinese crude oil shipping network connectivity under different attack modes.

Analysis of Figure 10 reveals significant disparities in the connectivity and reliability of China's imported COMTN under different attack modes. When deliberately attacking the nodes in China's imported COMTN, there is a substantial decrease in network connectivity and reliability. Specifically, by selecting to attack critical nodes such as the Malacca Strait, Taiwan Strait, and Bashi Strait, which account for 11.0% of the total nodes, the network's connectivity and reliability decrease to 0.422, representing less than half of the original reliability. This indicates a significant deterioration in the overall connectivity and reliability of the MTN.

In comparison, random attacks require targeting the failure of 8 nodes, which constitutes approximately 30.0% of the total nodes, in order to achieve a connectivity and reliability level similar to that of deliberate attacks on the Malacca Strait, Taiwan Strait, and Bashi Strait. By the 6$^{th}$ deliberate attack, the connectivity and reliability of China's COMTN have already decreased to 0.132. Random attacks would require targeting approximately 15 nodes to reduce the network's connectivity and reliability to around 0.100. With the 10$^{th}$ deliberate attack on a specific node, the network's connectivity and reliability plummet to 0, resulting in a complete disruption of China's COMTN. If random attacks persist and target 21 nodes, the entire network would be rendered completely paralyzed.

Deliberate attacks refer to the actions initiated by the attacking party, targeting high-importance nodes within the network. These nodes play a crucial role in maintaining the connectivity and reliability of China's imported COMTN. When key nodes across different routes are targeted, significant changes occur in the network's structure, resulting in a higher likelihood of disconnections and disruptions. On the other hand, in the case of random attacks, the probability of attacking important nodes by chance is relatively low, and the network requires the failure of a significant number of nodes to experience a complete breakdown. Consequently, when the attacking party possesses relevant information about China's imported COMTN and deliberately targets its critical nodes, the overall network will suffer substantial damage, posing a significant threat to energy security and the stable supply of crude oil.

### 4.4. Measures and Recommendations

Similar to the results of Lu et al. [33] and Li et al. [50], this study shows that China's COMTN is relatively reliable under random attacks. However, when facing selective attacks, the connectivity reliability of the network significantly declines, posing a considerable threat to the security of crude oil imports. The American route exhibits the best connectivity reliability in such scenarios. While Lu et al.'s [33] research identified the Middle East route as having the worst connectivity reliability, our study finds the Southeast Asian route to be the least reliable. This difference can be attributed to the fact that this study consider China's crude oil import maritime routes more comprehensively and use a more sophisticated and integrated evaluation model to rank the important nodes. The findings of this study serve as a valuable reference for regions heavily reliant on maritime crude oil transportation. We recommend conducting analyses based on the latest and most complete local data to support the security of the COMTN.

Based on the analysis of the CR of China's imported COMTN in the context of the BRI, the following measures and suggestions are proposed to enhance the network's CR:

(1) Strengthen emergency management measures at key points and give focused protection.

The Strait of Malacca, the Strait of Bab-el-Mandeb, and the Strait of Hormuz are significant nodes in China's imported COMTN. These nodes play a crucial role in ensuring the overall connectivity and reliability of the network and have substantial implications for the maritime transport interests of multiple stakeholders, leading to a high possibility of being targeted by attacks. To ensure China's energy security, promote economic development, and maintain social stability, it is necessary to proactively establish preventive and contingency plans. The responsible authorities should enhance monitoring and early warning capabilities, formulate emergency response protocols, and minimize potential losses in the event of attacks on these critical nodes.

(2) Exploring alternatives at key maritime nodes and tapping new transport routes.

Presently, countries in Southeast Asia and Europe are actively responding to China's Belt and Road Initiative, and it would be prudent to consider increasing the import share through European and Southeast Asian routes. The Americas route exhibits a relatively higher CR, and considering international circumstances, expanding the import share of crude oil from Latin American regions is possible. Furthermore, it is recommended that China accelerates its exploration of new transport routes to reduce dependency on key maritime nodes and establish a diversified transport network. For example, by leveraging the Belt and Road Initiative, efforts should be made to foster the development of China–Europe rail transport, deepen collaboration with the Pakistani government, facilitate the construction of the Gwadar Port, and establish direct shipping routes between China and the Middle East region.

(3) Responding positively to international cooperation and exhibiting the power of China.

The regional distribution of nodes in China's imported COMTN is complex, and the strategic importance of key nodes encompasses the interests of multiple stakeholders, affecting the status of these crucial points. It is not appropriate for China to solely rely on its own capacities to maintain the smooth operation of these vital nodes. Instead, China should proactively engage in international cooperation, such as the Belt and Road Initiative (BRI), and leverage its leadership role. At the same time, fostering collaborative partnerships with the countries hosting these nodes is essential to achieve mutual benefits. By adopting this approach, China can safeguard the secure navigation of its oil tankers while receiving the support of pertinent nations, facilitating the successful implementation of early warning systems and emergency preparedness. Furthermore, it is also crucial to deepen collaboration with pertinent international organizations, effectively leveraging China's proactive role as a permanent member of the United Nations Security Council. Correspondingly, China should actively participate in escort operations to maintain maritime security and promote the implementation of relevant international regulations.

## 5. Conclusions

This study applies CNs and reliability theories to analyse the CR of China's imported COMTN under different attack modes. As a result, an indicator system for identifying the importance of network nodes is established, determining the importance of each node within the network. A CR model is developed to assess the impact of random and deliberate attacks on China's imported COMTN. The analysis results indicate that the two attack modes exhibit some variations in their impact on the CR of the MTN. Specifically, the deliberate attack mode poses a greater threat to the network's CR compared to the random attack mode.

By analysing the CR of the five maritime transportation routes in the Middle East, Africa, the Americas, Europe, and Southeast Asia, it is observed that the Americas route exhibits a relatively better CR in both attack scenarios. The Middle East route demonstrates the lowest CR in the random attack mode, while the Southeast Asia route faced the lowest CR in the deliberate attack mode.

Based on the findings, appropriate measures to mitigate the potential paralysis of MTN have been proposed. It is advisable to prioritize the development of early warning systems and emergency response protocols for critical nodes, while also exploring novel approaches for crude oil transport. Additionally, proactive efforts should be made to foster cooperative relationships among nations and international organizations, leveraging China's global influence to effectively combat challenges such as piracy, maritime terrorism, and adverse weather conditions. The proposed CR model in this study provides valuable insights for relevant authorities to identify critical nodes within the COMTN, offering scientific guidance to ensure the security of China's crude oil imports. At the same time, based on this model, this study can also be extended to other countries. According to the corresponding data, replacing the nodes in the network for other countries could be based on the process used in this study to obtain the CR of the COMTN.

However, this study has certain limitations. On the one hand, it focuses solely on node failures and does not consider the impact of edge failures on the CR of maritime network. On the another hand, the network analyzed in this study is static and does not take into account possible changes that may occur due to geopolitical events, technological advancements, economic conditions, oil spills, congestion, and other factors. Therefore, future research should concentrate on investigating edge attacks and evaluating the influence of edge failures on the CR of maritime network. Improving the model to adapt to dynamic changes in the network is essential. Furthermore, exploring the effects of different shipping routes on the overall reliability of the imported COMTN is also a promising way for further investigation.

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