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Vulnerability assessment of International Container Shipping Networks under national-level restriction policies

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ABSTRACT

This study develops a systematic methodology to assess the vulnerability of International Container Shipping Networks (ICSNs) amid national-level restriction policies potentially caused by the increasing international trade disputes and health crises. It designed a holistic vulnerability assessment framework that explores the impact of two disruption scenarios—direct and complete trade restrictions, which incorporates new measures of vulnerability and centrality to evaluate a country's susceptibility to international restrictions and its impact on other countries' ICSNs. Subsequently, correlation and dependence analyses are conducted to explore relationships between vulnerability/centrality and eight international network characteristics, identifying key factors. Finally, an enhanced *k*-means algorithm classifies the impact degrees of various countries' restrictive policies on a country of interest, and examines the effects of both partial and collective disruptions of identified critical countries. Experimental results demonstrate the effectiveness in revealing the varied impacts of different restrictive policies on distinct performance metrics, identifying critical factors that influence vulnerability and centrality, and precisely classifying different countries' restriction impacts to help identify key influential countries. These insights not only deepen understanding of ICSNs under national-level disruptions but also aid in optimizing international shipping from an operational perspective and providing strategic guidance for proactive disruption management from a preventative standpoint.

1. Introduction

Maritime transportation networks are critical for supporting international trade and economic exchanges among countries/regions, with the majority of global merchandise trade transported by sea and processed through ports worldwide (Verschuur et al., 2022; Xin et al., 2024; M. Xu et al., 2024). Despite their vital importance, these networks are increasingly susceptible to a range of uncertainties and frequent disturbances, including natural disasters, geopolitical tensions, and pandemics (Jin et al., 2022; Q. Liu et al., 2023). Such interruptions — distinguished by their destructive, anomalous, and unforeseeable nature — can restrict or even obstruct transport flows, which, in turn, cause substantial economic damages or supply chain breakdown. Prominent examples include the 2011 earthquake and tsunami in Japan that drastically affected the global automotive supply chain (Dui et al., 2021), the economic conflict between the US and China since 2018 that led to the restructuring of global supply chains (Gereffi et al., 2021), the rigorous COVID-19 protocols that resulted in congestion at ports and subsequent shipping delays at major global hubs (Gu and Liu, 2023), and the blockade of the Suez Canal in 2021 that stranded enormous amounts of cargo (Lebedev et al., 2021). These disruptions can significantly impact the economy of any country or region involved in global maritime logistics, particularly those lacking effective countermeasures. Therefore, it is imperative for governments and relevant stakeholders to recognize the impacts of these disruptions on maritime transportation networks beforehand, thereby enabling them to adeptly respond to these challenges and effectively formulate robust mitigation strategies.

Vulnerability assessment acts as a powerful tool for quantifying and documenting a system's susceptibility to incidents or disasters by measuring performance degradation (Zhou et al., 2019). It empowers stakeholders to swiftly evaluate the potential impacts of various disruption scenarios, aiding in the identification of bottlenecks and critical components within a system. Concurrently, it facilitates the development of strategies to bolster the system's resilience against disruptions. In this context, extensive research has been conducted to assess vulnerability across diverse maritime transportation networks. This

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includes the vulnerability assessment of the Global Liner Shipping Network (GLSN) against cascading failures (Xu et al., 2022), the evaluation of shifts in shipping network vulnerability pre- and post-COVID-19 pandemic periods (Wu et al., 2024), and the vulnerability assessment of the Global Container Shipping Network (GCSN) against targeted link disruptions (Viljoen and Joubert, 2016). These studies underscore the effectiveness of vulnerability assessments in understanding network susceptibility to potential risks, facilitating operational decisions that enhance network robustness and ensuring a smoother shipping logistics operation. To this end, conducting a vulnerability assessment is crucial for enhancing preparedness against potential risks faced by a country/region within a complex shipping network.

While important, current maritime transportation network-based research predominantly focuses on the effects of disruptions on the global shipping system (e.g., Bai et al., 2023; Jarumaneeroj et al., 2024, 2023; Wu et al., 2024; Xu et al., 2022). There are comparatively few studies examining the implications of disconnections between countries (the term ’countries’ refers to both countries and regions in this study) on a particular country’s international maritime trade performance. This research gap has become more pronounced in light of escalating geopolitical tensions and global health crises, such as trade wars (Huang et al., 2023) and the COVID-19 pandemic (Li et al., 2021a, 2021b; Poo et al., 2024a), highlighting the prevalence of national-level disconnections. In terms of these disturbances, a country may enforce targeted import and export restrictions on specific countries to safeguard its national interests. Such measures often cause widespread disruptions in the whole network rather than small-scale port disconnections. Despite their profound impacts, the consequences of maritime network disconnections between countries on a country’s international trade have not been thoroughly explored in existing literature. This study, therefore, seeks to address the following critical issues and simultaneously enhance understanding of the impact of country-to-country disconnections, resulting from restrictive policies, on international shipping logistics.

1. How to characterize disconnection scenarios between countries under various restriction policies and across different levels of link disruptions?
2. How to accurately and comprehensively quantify the changes in a country’s international trade performance across different disconnection scenarios, incorporating essential port-route connection information from real shipping service route data?
3. How to identify the critical structural or functional characteristics of a country’s international network that could assist in refining the shipping network design to ensure continued international trade amidst diverse country-to-country disconnection events?
4. How to classify the impact degrees of different countries’ restrictive policies on a country’s international shipping network, facilitating proactive hierarchical management of disruption risks?

To address the identified issues, this study introduces a new methodology for assessing the vulnerability of a country’s International Container Shipping Network (ICSN) amidst disruptions, caused by national link disconnections. Firstly, the Global Container Shipping Network (GCSN) is constructed using real global container shipping service data in 2022. Two types of disruption scenarios — direct restriction and complete restriction policies — are then applied to evaluate each country’s vulnerability under different country-to-country link disruption scenarios. To properly quantify the impacts of these disruptions, new vulnerability and centrality measures are proposed to measure the susceptibility of a country’s ICSN to other countries’ restriction policies and the ability to influence other countries’ ICSNs through the implementation of restriction policies, respectively. Unlike existing measures in the literature, these measures are unique as they take critical elements of the GCSN, including network directionality, link capacity, and transit times, into consideration. Based on these foundations, the study is extended in two significant ways. First, Pearson and Spearman correlation coefficients and conditional entropy are employed to examine the correlations and dependences between a country’s vulnerability/centrality metrics and its respective international network characteristics. The results to this analysis would help identify key factors that support the refinement of network design that concurrently reduces vulnerability while enhancing centrality at the same time. Second, utilizing Mainland China (hereafter referred to as ‘China’ for simplicity) as a case study, the enhanced *k*-means algorithm is adopted to classify other countries based on their impacts on China’s ICSN under different restrictive policies. The impacts of the critical identified countries are further analyzed in great detail, considering both partial and collective link disruptions. It should be remarked that this research employs a combination of methods for vulnerability analysis in a holistic manner for the first time. This contributes to a deeper understanding of a country’s ICSN performance amidst various national-level disconnections. It also assists in optimizing shipping service networks and provides strategic guidance for proactive disruption management in a more sustainable fashion.

The rest of the paper is organized as follows. Section 2 reviews literature related to vulnerability assessments within maritime transportation networks, as well as research gaps and contributions of this present work. Section 3 entails the newly developed vulnerability assessment framework, including the construction of the GCSN, the network disruption models under two different restriction policies, the development of vulnerability and centrality metrics, the analyses of correlations and dependencies, and the classifications of country’s impact degrees. Section 4 presents the experimental results. Discussion of insights, broader implications, and limitations is presented in Section 5. Finally, Section 6 concludes this study and suggests directions for future research.

2. Literature review

Vulnerability — one of essential quantities in assessing transportation systems — is crucial for comprehending the performance mechanisms of maritime transportation networks during disruptions. A substantial body of literature on assessing vulnerability of maritime transportation networks exists, as in Calatayud et al. (2017), Lhomme (2015), Liu et al. (2018), Poo et al. (2024b), and Xu et al. (2022). In addition to vulnerability, related concepts such as robustness, reliability, and resilience are also employed to measure maritime transportation network performance in response to potential internal and external disruptions (Asadabadi and Miller-Hooks, 2020; Bai et al., 2023; Cheung et al., 2020; Li et al., 2022; Poo and Yang, 2024; Wan et al., 2018; Xu et al., 2023). Technically speaking, vulnerability focuses on the extent of a system becoming inoperable under disruptions, while robustness, reliability, and resilience focus more on the system’s ability to adapt and maintain operations (Liu et al., 2023). Despite different terminologies and foci, studies in these domains share common characteristics aiming at measuring alterations in the functional capabilities of maritime transportation networks, especially after disruptions (please refer to Gu et al. (2020) for a thorough review of these concepts in transportation networks). Specifically, evaluating the performance of maritime transportation networks against disruptions necessitates two critical prerequisites: formulating system performance assessment metrics and modeling disruption scenarios (M. Xu et al., 2024). As such, the implementation of the evaluation components within shipping networks from these two critical perspectives will be herein explored in the following subsections.

2.1. Performance assessment of maritime transportation networks

The scholarly field is rich with literature dedicated to the development of robust metrics for evaluating the operational performance of maritime transportation networks under various disruptions. These metrics include the Largest Connected Component (LCC), connected component size, average shortest path length, node degree, clustering coefficient, Closeness Centrality (CC), Degree Centrality (DC), Betweenness Centrality (BC), network efficiency, and motif-based metrics, and the UNCTAD bilateral connectivity index (Bai et al., 2023; Cao et al., 2025; Guerrero et al., 2024; Liu et al., 2018; Saeed et al., 2021; Viljoen and Joubert, 2016; Xu et al., 2022, 2023). Among these performance measures, network efficiency and LCC stand out as prominent metrics in the literature. Particularly, network efficiency, which measures the ease of information transfer within the network, generally employs the reciprocal of the shortest path lengths between node pairs, with shorter paths indicating greater topological efficiency. Owing to its effectiveness, this metric has been extensively applied across maritime networks, including the Maritime Silk Road (Peng et al., 2018; Wan et al., 2021), Maersk shipping line (Liu et al., 2018), and European port network (Liu et al., 2022; Q. Liu et al., 2023). The LCC, on the other hand, measures the size of the largest connected subnetwork, which can be interpreted as the number of ports capable of transporting goods in maritime transportation networks under disruptions. A large LCC signifies a high level of interconnectivity among ports, signaling a smoothly functioning network. Conversely, a small LCC suggests potential segmentation into unconnected parts, impeding cargo transport between some ports. Fluctuations in LCC size reveal the network's vulnerability to disruptions and serve as a robust indicator of network resilience (Bai et al., 2023; Q. Liu et al., 2023).

In reality, maritime transportation networks are directed-weighted networks, rich with information such as network directionality, transit times, and service capacities (Wu et al., 2024). These characteristics significantly influence the functionality of a network. Specifically, the transit time of a link often correlates with the geographical distance between ports, where shorter distances indicate higher transit efficiency. Similarly, greater service capacity between two ports suggests that more cargo can be transported within a given period. To incorporate these effects, adaptations and enhancements to traditional topological metrics have been developed to leverage this valuable information. For instance, Liu et al. (2022) integrated network service capacity into such metrics as DC, CC, and BC to more accurately assess a port's connectivity level. Bai et al. (2023) utilized both travel time and network connection intensity to create an effective weighted efficiency metric through a combination with a network disintegration method (Zhou et al., 2021a). Xu et al. (2024) devised a novel efficiency metric that accounted for not only the topological connectivity but also geographical distance and link weight. Besides these studies, a variety of contemporary indicators have been extensively introduced. Qin et al. (2023) proposed a comprehensive three-dimensional econometric model that incorporated port structure, function, and location to evaluate port-node resilience against external shocks. Wu et al. (2019) employed metrics, including the network's weekly total shipping capacity and average shortest shipping time, to assess the impacts of worldwide main channel disruptions on global container shipping. Liu et al. (2023) proposed a new concept of customer-oriented maritime supply chain resilience, focusing on aspects such as freight service continuity and rate stability, to analyze the impact of the COVID-19 pandemic on supply chains.

While the above metrics significantly refine network performance measurement, numerous challenges remain unaddressed. First, the network functional factors, including network directionality, transit times, and service capacities, are crucial for an accurate evaluation of network performance. Yet, existing metrics often address some of these elements and fail to integrate all essential port-route connection information comprehensively. Second, current metrics tend to measure either the performance of individual ports or entire shipping networks, with no specific focus on assessing the effects of national-level disconnections on a particular country's international trade network. Third, evaluating network connection performance from multiple perspectives, rather than relying on a single aspect, promises to ensure a comprehensive assessment of essential network functions. Therefore, developing advanced metrics that (*i*) incorporate essential port-route connection information and (*ii*) ensure the integrity of network function evaluations from the perspective of a country's international trade network is critical for addressing the challenges posed by national-level link disconnections in international shipping logistics.

2.2. Disruption scenarios in maritime transportation networks

Maritime transportation networks are vulnerable to a wide range of unforeseeable and destructive disruptions at various scales, including local-level events such as terrorism attacks, dockworker strikes, and natural occurrences like fog and typhoons, as well as regional challenges like geopolitical tensions, trade wars, and pandemics (Liu et al., 2023). These disruption scenarios are typically categorized in existing studies as either node (port) failures or link (route) disconnections, with random attacks and deliberate attacks. In this regard, random perturbations mimic unpredictable events like natural disasters, whereas deliberate attacks are akin to intentional actions such as terrorist attacks. For node-based disruptions, ports are targeted according to disruption sequences (or strategies), determined by their importance, as evaluated by both topological and functional metrics. Liu et al. (2023) analyze the resilience of the intra-Europe network against three potential attack strategies: (*i*) targeting ports based on throughput volumes, (*ii*) targeting ports based on DC, and (*iii*) targeting ports based on geographical locations. Likewise, Bai et al. (2023) defined port attack sequences based on weighted BC, CC, and DC. Liu et al. (2018), on the other hand, identified port attack sequences based on global network efficiency and the local efficiency clustering coefficient. Notably, findings by Bai et al. (2023) and Liu et al. (2018) indicate that maritime transportation networks are significantly more vulnerable to intentional attacks than random failures.

Link-based disruptions in maritime transportation networks are as common as port failures in the real world. Viljoen and Joubert (2016) analyzed the vulnerability of the GCSN using two link-based disruption strategies: link betweenness and link salience. Dui et al. (2021) introduced the concept of 'residual resilience' and developed an optimization model to determine the optimal recovery sequence for failed links, thereby rapidly restoring a disrupted maritime network to full operational capacity. Ducruet (2016) simulated the partial disruption of the Suez and Panama canals by removing links, in which over 50 % of traffic was canal-related, to assess their impact on the GLSN. Calatayud et al. (2017) examined the vulnerability of a country's liner shipping services by eliminating its inbound and outbound links.

Despite numerous initiatives mimicking realistic disruption scenarios, these studies often fall short in examining the effects of country-to-country disconnections on a country's international shipping network. Such disruptions are increasingly prevalent in the context of rising international trade disputes and global health crises — these potentially lead to more severe consequences than conventional localized disruptions. However, efforts to address these challenges in the maritime domain remain sparse. Inspired by Li et al. (2021), who investigated the impacts of two entry restriction policies in the air transportation during the COVID-19 pandemic — direct flight suspension and complete entry suspension — this study similarly develops two link disruption scenarios — direct restriction and complete restriction policies — to analyze each country's vulnerability under different country-to-country link disruptions.

2.3. Research contributions

As has been illustrated in the literature, the development of accurate network performance assessment metrics and the modeling of proper disruption scenarios are essential for the precise evaluation of maritime shipping network vulnerability. However, vulnerability assessments of a country's international shipping trade within a global maritime transportation network — especially from the perspective of country-to-country link disconnections — remain insufficiently explored in both metric development and scenario modeling. Additionally, previous studies on maritime transportation networks have seldom conducted analyses related to identifying key factors that significantly influence vulnerability or categorizing the impact degrees from different disruptions — despite their crucial role in enhancing shipping network design and supporting proactive disruption risk management (Tagawa et al., 2022). This study, therefore, presents a groundbreaking effort to holistically examine the vulnerability of a country's ICSN against national-level disruptions, while addressing the abovementioned significant challenges.

In summary, the key contributions of this study are outlined as follows.

1) A holistic vulnerability assessment framework is designed to evaluate the performance of a country's ICSN under two distinct restrictive policies. Unlike traditional vulnerability analyses, this framework focuses more on vulnerabilities of a country's ICSN arising from inter-country link disruptions, thereby deepening insights into a country's ICSN susceptibility to the growing frequency of international disputes and global health crises.
2) Innovative vulnerability and centrality metrics are newly devised to precisely delineate a country's ICSN in the face of perturbations by country-to-country disconnections. These two metrics are refined so that a country's capacity to maintain both connection efficiency and extent is quantified, while seamlessly integrating the impacts of network directionality, link weight, and transit times simultaneously.
3) This study employs both Pearson and Spearman correlation coefficients along with conditional entropy to investigate the correlations and dependences between a country's vulnerability/centrality and its respective international network characteristics. This analysis helps identify key factors that are crucial for refining network design to mitigate vulnerability and enhance centrality at the same time.
4) An enhanced *k*-means algorithm is adopted to classify countries based on their impact degrees on a specific country's ICSN under varying restrictive policies, thereby facilitating the design of hierarchical intervention measures against potential disruption risks. Additionally, the effects of both partial and collective link disruptions of the identified critical countries are examined — this, in turn, provides insights into the focal country's vulnerability across different levels of potential disruptions.

3. Methodology

This section outlines the methodology used for the analysis of a country's ICSN in the face of disruptions from country-to-country disconnections. Section 3.1 presents the fundamental framework for vulnerability assessment in this study, consisting of three essential modules: (*i*) the construction of GCSN, (*ii*) network disruption modeling, and (*iii*) the development of vulnerability and centrality metrics. With the framework in place, it becomes possible to evaluate the vulnerability of each country's ICSN under various inter-country connection disruptions. This will, for the first time, provide an effective tool for countries to analyze their trade dependence on their importers/exporters and aid them in developing protective measures with reasonably good proportion to the level of vulnerability faced by disruptions. Building on the established framework, two additional analyses are undertaken. Section 3.2 examines the correlations and dependences between a country's vulnerability/centrality and its respective international network characteristics. This analysis aims to pinpoint key factors that can reduce vulnerability and enhance centrality of a country's ICSN at the same time. Section 3.3, later, describes the use of refined *k*-means algorithm to classify countries based on their influence when enforcing restriction policies on a specific country. The effects of both partial and collective restrictions by the critical identified countries on a country's ICSN are also analyzed. With this analysis, a particular country would be able to comprehend the impacts of restrictive trade policies beforehand. It also helps in the development of hierarchical interventions mitigating potential disruption risks. Fig. 1 illustrates the overview of our proposed framework, with details in each step.

3.1. Vulnerability assessment framework

3.1.1. Data collection and shipping network construction

Generally, existing studies on shipping network construction rely on two principal types of data: vessel movement data and shipping service route data. Vessel movement data effectively reflects the dynamic nature of ship trajectories, offering detailed insights such as specific sailing routes and timings. However, this type of data involves complex data processing and is characterized by large volumes. In contrast, shipping service route data efficiently provides predetermined routes and ports, focusing exclusively on details directly relevant to cargo transport. This type of data can improve analysis effectiveness by omitting unrelated information and eliminating the need for additional processes such as trajectory cleaning and reconstruction. It therefore attracts more applications in the field (e.g. Bai et al., 2023; Wu et al., 2024; Xu et al., 2024). As a result, this study utilizes the global container shipping service data, sourced from 'BIG SHIP DATA' (www.bluewaterreporting.com), to construct the GCSN. This dataset includes 13,266 records from 2022, each of which contains details such as the original port, departure port, TEUs of cargo service capacity, and transit times from origin to destination. Asymmetrical cargo flows and unbalanced capacities in maritime networks lead to notable disparities in transport times, capacities, and frequencies between ports. Considering the network as directed and accounting for these variations can more effectively mirror the real dynamics of cargo movement. As a result, a real-world, directed-weighted GCSN is created, consisting of nodes (ports) and links (routes) that connect among them. The direction of each link mirrors the sequence of departures along the shipping route between two ports, as determined by the order of port visits. The weight of each link indicates the deployed cargo service capacity between two ports, as determined by aggregating the corresponding cargo service capacities of all container ships traversing the link. The completed GCSN comprises 627 nodes, 3235 linked pairs, and 4174 directed links, encompassing a substantial portion of global ports. Additionally, the network's asymmetric configuration is highlighted by 97.8 % of linked pairs showing unbalanced cargo service capacity and 70.9 % featuring unidirectional connections.

3.1.2. Network disruption modelling

National-level trade disruptions are becoming more prevalent, as driven by increasingly unpredictable events such as geopolitical tensions and pandemics. These disruptions, often resulting from targeted policies like international trade suspensions, national lockdowns, and specific area entry bans, necessitate a deeper understanding of their impacts. To this end, two disruption scenarios are designed based on two policies, inspired by research that investigated the impacts of entry restrictions in air transportation during the COVID-19 pandemic (Li et al., 2021b).

1. ***Direct Restriction Policy.*** When one country imposes a direct restriction policy on another, all direct transportation routes between them are interrupted. However, cargo may still be transported indirectly through a third country. To simulate the effects of this policy, all direct links connecting ports of the two involved countries are removed from the network. An illustrative example is shown in Fig. 2(a), where Country 2 enforces a direct restriction policy on Country 1, resulting in the disconnection of all direct links between them.
2. ***Complete Restriction Policy.*** When a country implements a complete restriction policy on another, cargo transit between the two

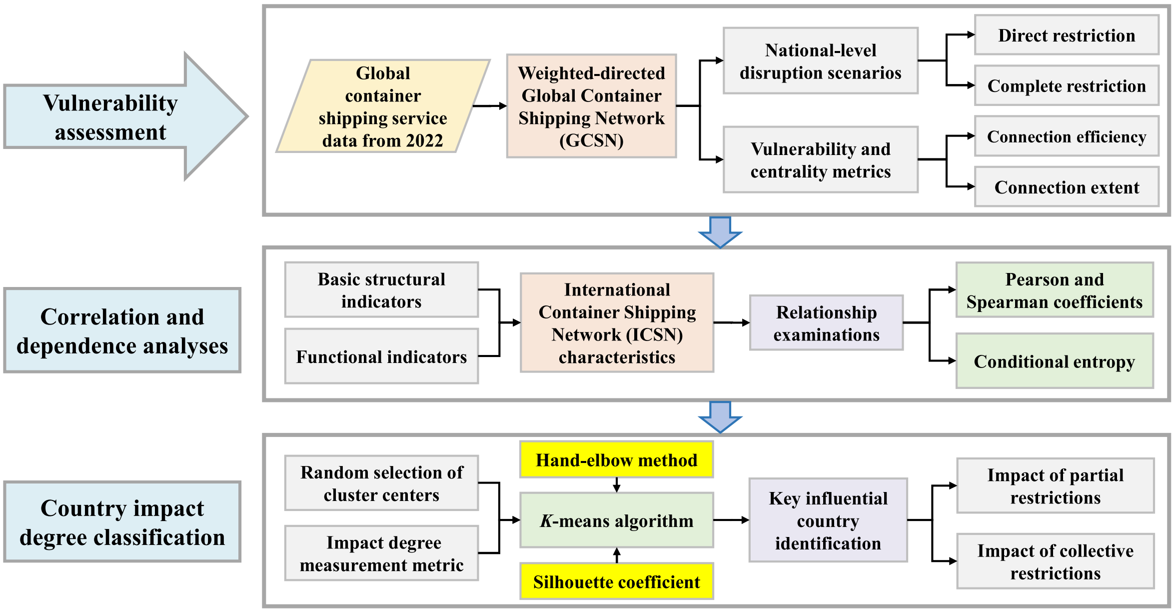

Fig. 1. Research framework.

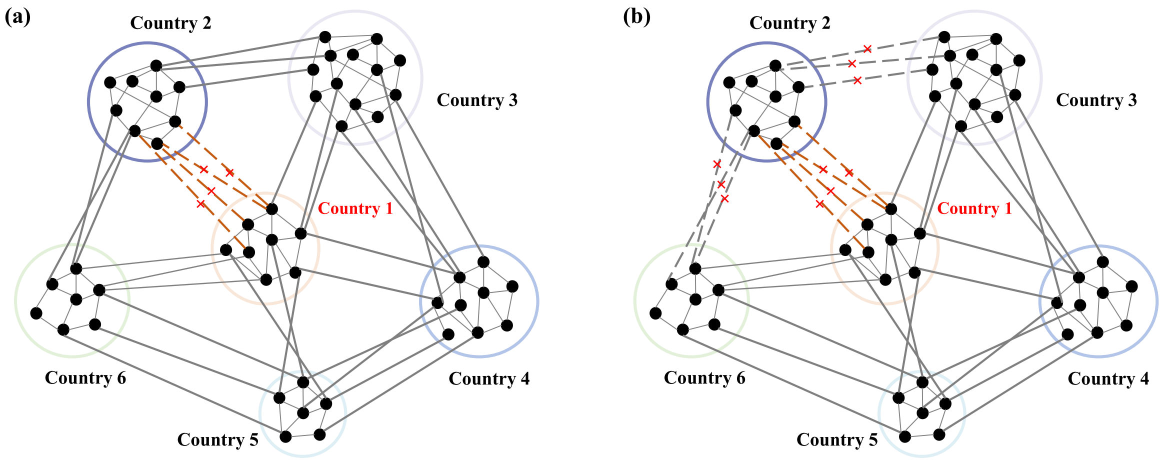

Fig. 2. (a) Illustration of network disruption caused by direct national-level restriction policy; (b) illustration of network disruption caused by complete national-level restriction policy. Note that the black points represent ports that are located in different countries.

countries is entirely prohibited by any means, including transshipments through third countries. Such measures are quite plausible, as seen in situations like the Russia-Ukraine conflict or during the COVID-19 pandemic, where some countries banned both entry and transit of cargo from restricted nations. This policy represents a more severe impact than the direct restriction policy, as it includes the following restrictions: (*i*) banning all direct cargo transportation, (*ii*) preventing cargo transit via third countries, and (*iii*) disallowing any cargo passage through the implementing country to other destinations. To simulate the effects of this policy, all links associated with the enforcing country are severed, thereby providing an accurate assessment of the impacts on the country facing the restrictions. Fig. 2(b) illustrates an example where Country 2 enforces a complete restriction policy on Country 1, resulting in the severance of all its links with other countries to avoid any potential connections with Country 1. The links between Country 2 and Countries 3 and 6 are also severed for calculation purposes. It is important to clarify that this severance is not actual but a methodological setting designed to precisely evaluate the effects on Country 1, rather than reflecting a real disconnection between these countries.

3.1.3. *Vulnerability and centrality metrics*

To evaluate a country's ICSN against cross-border disconnections enforced by restrictive policies, two crucial aspects regarding the network's functions are analyzed: (*i*) connection efficiency, determined by the time required to establish service connections within the network and (*ii*) connection extent, measured by the reachability of node interconnectivity. The former effectively measures the speed of goods transfer between ports, highlighting the focus on timeliness within maritime logistics (Bai et al., 2023). Conversely, the latter helps determine whether the network structure contains viable direct or indirect pathways, thereby illustrating the network's overall accessibility (Estrada, 2012). These metrics are adopted to examine the international connectivity of countries from different aspects, considering critical network properties such as directionality, link weight, and transit times, thereby enhancing the comprehensiveness of the evaluation.

With respect to network connection efficiency, this study employs the inverse of the shortest transit time to measure the spread of information with minimal transit time from one to another port within the GCSN. This method provides enhanced intuitiveness and accessibility compared to traditional shortest path length metrics (Bai et al., 2023). The definition of modified network connection efficiency is outlined in Eq. (1) below:

$$e_{ij} = \frac{1}{t_{ij,min}} \tag{1}$$

where $t_{ij,min}$ represents the minimum directional shipping time from port i to j calculated across all accessible links. From Eq. (1), it is clear that a larger e_{ij} implies greater transmission efficiency from port i to j.

Regarding network connection extent, a connection reachability metric is formulated to determine whether a port can dispatch goods to another port via all potential routes within the GCSN, as outlined below:

$$c_{ij} = \begin{cases} 1, & \text{if there is a reachable path from } i \text{ to } j \\ 0, & \text{if there is not reachable path from } i \text{ to } j \end{cases} \tag{2}$$

where c_{ij} equals 1 if there is a reachable path from port i to j via any potential links within the GCSN and 0 otherwise. Undoubtedly, a greater connection extent among ports simplifies the process of finding routes from one to another port.

Based on the above definitions, the definitions for the international connection efficiency and extent of a country's ICSN are constructed. Mathematically, the international connection efficiency can be defined by the average connection efficiency between ports within a country and all other ports outside the country in the GCSN (Li et al., 2021b; Zhou et al., 2021b), as shown below:

$$DE_p = \left(\frac{1}{|N_p|\cdot|\overline{N}_p|} \sum_{i\in N_p} \sum_{j\neq i, j\in \overline{N}_p} e_{ij} + e_{ji} \right) \Big/ 2 \tag{3}$$

where N_p denotes the set of ports within Country p, while $\overline{N}_p$ defines the set of ports outside Country p, with $|N_p|$ and $|\overline{N}_p|$ denoting the number of ports inside and outside Country p. Similarly, the international connection extent DC_p can be calculated by replacing e_{ij} with c_{ij} in Eq. (3).

It should be remarked that the abovementioned metrics adeptly account for the impact of directionality, acknowledging that transit times or reachability of service paths may differ between transport directions i-j and j-i. Additionally, to address variations in cargo service capacities across links, the DE_p and DC_p metrics are further refined into weighted measures using a network disintegration model, similar to Zhou et al. (2021). This model initially decomposes the original weighted network into multiple unweighted subnetworks and, later, calculates the DE_p and DC_p values of each subnetwork. Finally, DE_p or DC_p of all subnetworks are summed to derive the total weighted values. The formulation of weighted-directed connection efficiency and extend metrics, denoted by $WDEC_{q,l} = \{WDE_{p,l}, WDC_{p,l}\}$, can be illustrated with the equation below:

$$WDEC_p = DEC_{p,1} + DEC_{p,2} + \ldots + DEC_{p,l} \tag{4}$$

where l indicates the number of subgraphs, and $DEC_{q,l} = \{DE_{p,l}, DC_{p,l}\}$ specifies the connection metric values for Country p linked to the lth subnetwork. Note that, the efficacy of the network disintegration model has been validated by comparative studies with unweighted networks, whose details are documented in Bai et al. (2023) and Zhou et al. (2021).

To evaluate the impacts of a country that imposes restriction policies on an underlying country's ICSN, the connection efficiency and extent loss experienced by the latter due to the disruptions is adopted as a vulnerability measure, as shown below:

$$\Delta WDEC_{qp} = 1 - \frac{WDEC_{qp}}{WDEC_p} \tag{5}$$

where $WDEC_p = \{WDE_p, WDC_p\}$ denotes the connection efficiency and extent metric values of Country p before disruption, and $WDEC_{qp} = \{WDE_{qp}, WDC_{qp}\}$ represents the connection efficiency and extent metric values of Country p after being disrupted by link disconnections from Country q. The values of $\Delta WDEC_{qp} = \{\Delta WDE_{qp}, \Delta WDC_{qp}\}$ range from 0 to 1, with a higher value suggesting greater susceptibility to disruptions.

To characterize a country's ICSN in relation to international disruptions, two functional metrics, namely **overall vulnerability and overall centrality**, are further defined. In this regard, overall vulnerability (V_WDEC_p) — as quantified by the average impact of individual disruptions from all other countries on this country in Eq. (6) — measures the susceptibility of a country's ICSN to the restriction policies of individual countries.

$$V\_WDEC_p = \frac{1}{|\Omega| - 1} \sum_{q\neq p, q\in\Omega} \Delta WDEC_{qp} \tag{6}$$

where Ω denotes the set of countries within the GCSN, and $|\Omega|$ is the number of countries.

Overall centrality, on the other hand, evaluates a country's ability to influence other countries' ICSNs through the implementation of restriction policies, as computed by Eq. (7).

$$C\_WDEC_p = \frac{1}{|\Omega| - 1} \sum_{q\neq p, q\in\Omega} \Delta WDEC_{pq} \tag{7}$$

Note that the last two metrics are specifically designed to support a holistic examination of a country's ICSN in the face of national-level disruptions. Related notations and descriptions are given in Table 1.

3.2. *Correlation and dependence analyses*

To study the relationships between a country's overall vulnerability/centrality and its respective international network characteristics, two crucial components must be addressed: selecting appropriate network factors, which necessitates a precise characterization of a country's international network, and conducting comprehensive correlation and dependence analyses, which requires the use of effective techniques and approaches to reveal these relationships.

Table 1
Notations and descriptions used in formulas.

Notations	Descriptions
c_{ij}	Connection extent from port i to j
e_{ij}	Connection efficiency from port i to j
DC_p	International connection efficiency of Country p
DE_p	International connection extent of Country p
DEC_p	International connection efficiency and extent of Country p, $DEC_p = \{DE_p, DC_p\}$
$WDECp$	Weighted-directed international connection efficiency and extent of Country p, $WDEC_p = \{WDE_p, WDC_p\}$
$WDEC_{qp}$	International connection efficiency and extent of Country p after being disrupted by Country q, $WDEC_{qp} = \{WDE_{qp}, WDC_{qp}\}$
$\Delta WDEC_{qp}$	International connection efficiency and extent loss experienced by Country p due to disruptions from Country q
V_WDEC_p	Overall vulnerability of Country p, $V\_WDEC_p = \{V\_WDE_p, V\_WDC_p\}$
C_WDEC_p	Overall centrality of Country p, $C\_WDEC_p = \{C\_WDE_p, C\_WDC_p\}$

Table 2
Description of selected international network indicators.

Types	Indicators	Description
Basic structural indicators	International Cargo Service Capacity (ICSCAO)	The total transported cargo capacity between a country and other countries.
	Number of International Links (NIL)	The number of links connecting a country to other countries.
	Distribution of the International Cargo Service Capacity (DICSC)	The dispersibility of the deployed cargo service capacity between a country and other countries.
	Distribution of the Number of International Links (DNIL)	The dispersibility of the number of links connecting a country to other countries.
	Number of Ports (NP)	The total number of ports within a country.
Functional indicators	Average Weighted-Directed Degree Centrality (AWDDC)	The average Weighted-Directed Degree Centrality for all ports within a country, which incorporates both the network directionality and link weight.
	Average Weighted-Directed Closeness Centrality (AWDCC)	The average Weighted-Directed Closeness Centrality for all ports within a country, which incorporates both the network directionality and link weight.
	Average Weighted-Directed Betweenness Centrality (AWDBC)	The average Weighted-Directed Betweenness Centrality for all ports within a country, which incorporates both the network directionality and link weight.

3.2.1. Network indicators

There are numerous network indicators that can describe the inherent characteristics of a country's ICSN characteristics. In this study, eight indicators are employed, comprising five basic indicators and three functional indicators, whose details are provided in Table 2. The first set of indicators measures the basic structural characteristics of a country's international network, revealing how the international shipping network is structured in terms of ports, routes, and connection weights (i.e., deployed cargo service capacity within each link). The second set of indicators measures the centrality characteristics of ports within a country, reflecting their functional importance within the entire shipping network (Bai et al., 2023). It should be noted that the Distribution of International Cargo Service Capacity (DICSC) is herein quantified by the Herfindahl-Hirschman Index (HHI) (Wang et al., 2020), which measures the dispersion of deployed cargo service capacity between one country and others, as follows:

$$DICSN_p = \sum\nolimits_{v=1,v\neq p}^{|\Omega|-1} {\varphi_{pv}}^2 \tag{8}$$

where φ_{pv} represents Country p's share of cargo service capacity with Country v, which can be calculated using the following formula:

$$\varphi_{pv} = \frac{S_{pv}}{\sum\nolimits_{v=1,v\neq p}^{|\Omega|-1} S_{pv}} \tag{9}$$

where s_{pv} denotes the deployed cargo service capacity between Countries p and v. A lower value of $DICSC_p$ indicates a greater dispersion of deployed cargo service capacity between Country p and other countries. The Distribution of the Number of International Links ($DNIL_p$) can be similarly derived based on HHI, with Country p's share of the number of international links with Country v, represented by δ_{pv}, replacing φ_{pv} in Eq. (8).

3.2.2. Correlation and dependence analyses

Correlation and dependence examinations focus on different perspectives of statistical relationships that provide complementary insights into how a country's international network characteristics influence its network performance amidst national-level disruptions. Specifically, correlation analysis measures the strength and direction of relationships between variables, while dependence analysis examines the causal influence and extent to which one variable depends on others.

With respect to correlation analysis, this study adopts both Pearson and Spearman coefficients. The Pearson coefficient quantifies the strength of a linear relationship between two continuous variables, while the Spearman coefficient detects monotonic relationships, which are not necessarily linear (Zhou et al., 2023). These coefficients range from −1 to 1, where 1 indicates a perfect positive correlation, −1 indicates a perfect negative correlation, and 0 signifies no correlation. To effectively distinguish the degrees of correlation, the following classification is adopted: correlation coefficients $|r| < 0.10$ indicates trivial effects, $0.10 \leq |r| < 0.30$ indicates small effects, $0.30 \leq |r| < 0.50$ indicates medium effects, and $|r| \geq 0.50$ indicates large effects (Cohen, 2013).

Regarding dependence analysis, conditional entropy, derived from mutual information and entropy measures, is employed (Carro et al., 2019). Conditional entropy, denoted by $H(Y|X)$, quantifies the uncertainty of one variable Y given known information about another variable X, which can be computed by the following formula:

$$H(Y|X) = \int dx \int dy \cdot p(x,y) \cdot log \frac{p(y)}{p(x,y)} \tag{10}$$

where $p(x, y)$ represents the joint probability distribution function of variables X and Y, while $p(x)$ and $p(y)$ denote their respective marginal probability distribution functions. Based on Eq. (10), a higher value of conditional entropy indicates greater uncertainty and lower predictability in one variable when the other is known. In contrast, a lower value of conditional entropy suggests greater predictability of one variable given known information about the other. Conditional entropy reaches zero when the value of Y is completely determined by the value of X. Conversely, it equals the entropy of Y when the two variables are independent.

3.3. Classification of country impact degrees

Strategically categorizing foreign countries according to their individual restriction impacts on a country's ICSN is crucial for proactive risk management, especially in facilitating the adoption of tiered intervention tactics. Such a categorization process can be viewed as an unsupervised learning endeavor designed to uncover inherent structural insights within the dataset. The k-means clustering algorithm is especially suited for such a process, due to its simplicity, efficacy, and scalability, operating efficiently without the need for prior knowledge (Liu et al., 2021; Yu et al., 2025). As such, this study utilizes the k-means algorithm to categorize the impact degrees that different countries exert on a country's ICSN through the imposition of individual restriction policies.

The fundamental concept behind the k-means algorithm is as follows. Given a set of n samples, represented by $X = (x_1, x_2, \ldots, x_n)$, that needs to be partitioned into k clusters, the k-means algorithm aims to minimize the Sum of Squared Errors (SSE) between each sample and its corresponding cluster center, as depicted below:

$$SSE = \sum_{j=1}^{k} \sum_{x_i \in C_j} \left\| x_i - u_j \right\|^2 \tag{11}$$

where C_j represents the jth cluster set and u_j denotes the corresponding clustering center of C_j, calculated as follows:

$$u_j = \frac{1}{|C_j|} \sum_{x_i \in C_j} x_i \tag{12}$$

where $|C_j|$ represents the number of samples in C_j.

In applying the k-means algorithm to classify national impact degrees, a critical challenge lies in selecting the appropriate value of k, which represents the number of classification levels, beforehand. To address this concern, both the hand-elbow method and Silhouette Coefficient (SC) are employed to ensure an accurate determination of k.

With respect to hand-elbow method, the SSE serves as a metric to gauge the quality of clustering outcomes. When the value of k is less than the actual number of clusters, increasing k significantly enhances the cohesion within each cluster, leading to a substantial decline in SSE. As the value of k approaches the true number of clusters, further increases in the value of k would result in diminished cohesion, causing a slowdown in the rate of SSE reduction. The plot of SSE against the value of k typically exhibits an 'elbow' shape, and the k-value at the elbow point is chosen as the optimal number of clusters.

As for the SC, it is defined for the ith sample as follows:

$$SC_i = \frac{v_i - r_i}{\max\{r_i, v_i\}} \tag{13}$$

where v_i represents the average distance from x_i to other samples within the same cluster, and r_i signifies the average distance from x_i to all samples in the nearest neighboring clusters. The value of SC_i ranges from -1 to 1, where a coefficient close to 1 indicates a well-clustered result, signifying that samples are well-grouped, while a value near -1 suggests poor clustering, meaning that samples are inappropriately grouped. Following this, the average SC for all samples can be calculated, and the value of k corresponding to the highest average SC signifies the optimal number of clusters.

To further improve the robustness of the k-means algorithm in classifying national impact degrees, two enhancements are implemented. Firstly, since the k-means algorithm can be prone to finding a local minimum in the SSE due to its sensitivity to the initial selection of cluster centers, the algorithm is executed multiple times with randomly chosen cluster centers. With this approach, the sensitivity issue could be largely addressed, while increasing the likelihood of finding a global minimum, or at least ensuring a solution close to the global minimum. Secondly, considering that both connection efficiency and extent are both crucial aspects of a country's ICSN, this study employs a linear weighting formula to combine ΔWDE and ΔWDC, providing a comprehensive measure of a specific country's impact on another country's ICSN, as follows:

$$\Delta V\_WDEC_{qp} = \alpha \cdot \Delta WDE_{qp} + (1 - \alpha) \cdot \Delta WDC_{qp} \tag{14}$$

where α represents a trade-off weighting coefficient, which can be assigned based on the specific demands of state governments and stakeholders. Accordingly, the distance measure in k-means is the difference between the ΔV_WDEC_{qp} values of two sample points.

After classifying the impact degrees of various countries that individually impose restriction policies on a specific country, two scenarios are further devised to investigate the focal country's vulnerability to varying levels of restrictive policies from critical countries identified by the k-means classification. In the first scenario, the link weights (i.e., deployed cargo service capacity) associated with one critical country imposing restrictions on the focal country are gradually reduced to simulate partial restrictions. In the second scenario, connections associated with multiple identified critical countries imposing restrictions on the focal country are severed simultaneously to examine the effects of joint restrictive policies. Evidently, these analyses deepen the understanding of how various types of restrictive measures by critical countries affect the focal country's ICSN.

4. Experimental results and analyses

This section presents the results concerning the effects of country-to-country disconnections on a country's (the term 'countries' refers to both countries and regions in this study) ICSN, along with their respective insights and implications. Section 4.1 details the basic vulnerability and centrality characteristics of each country/region's ICSN. Section 4.2 discusses the correlations and dependences between overall vulnerability/centrality and international network characteristics. Section 4.3 demonstrates the classification results of country impact degrees on the world largest exporter's (i.e. China) ICSN, as well as the examination of effects from partial and collective disruptions on China's ICSN.

4.1. Basic vulnerability and centrality analyses

Utilizing the weight-directed GCSN detailed in Section 3.1, statistical information such as the number of ports, cargo service capacity, and number of links for each country can be identified (See Appendix A for more details). Based on these statistics, Figs. 3 and 4 illustrate the overall vulnerability and centrality for each country under two different restriction policies, with countries listed in descending order based on their international cargo service capacity (*ICSCAO*), i.e., total transported cargo capacity between a country and other countries. Analysis of these figures uncovers several key observations. Firstly, the overall vulnerability metric of each country displays a negative correlation with its *ICSCAO* to a certain extent, whereas the overall centrality metric is positively correlated with *ICSCAO* to some extent. Moreover, the relationship between vulnerability metric and *ICSCAO* exhibits more fluctuation and instability. Secondly, under the direct restriction policy, the US, Singapore, Malaysia, and Saudi Arabia exhibit the highest centrality values, whereas under the complete restriction policy, the US and China hold the highest centrality values. Interestingly, despite China possessing the largest *ICSCAO*, its influence on other countries' ICSNs is not as strong as that of the US, highlighting the US's dominant position in international trade logistics. Lastly, under the complete restriction policy, Singapore's connection efficiency-based vulnerability value, i.e., *V_WDE*, is the lowest (see Fig. 4(a)), likely due to its status as a key international maritime hub, which grants it greater resilience against the restrictive measures of individual countries.

To systematically analyze the differences in the impacts of the two policies on overall vulnerability and centrality, Table 3 details the mean, standard deviation, minimum, and maximum values of these metrics across all countries under each restriction policy. The standard deviation statistics reveal that vulnerability metrics tend to exhibit less variability between countries, while centrality metrics show greater volatility. Notably, while a country may not be able to influence other countries' ICSNs through restriction policies, its ICSN is inevitably affected by the restriction policies of other countries. This is highlighted by the minimum values of *C_WDEC* being closer to 0 compared to those of *V_WDEC*. Additionally, connection efficiency-based metrics are more significantly impacted than connection extent-based metrics, due to their different foci. More formally, connection efficiency metrics prioritize the shortest service connection time, which is significantly prolonged under restriction policies. In contrast, connection extent metrics concentrate on accessibility between ports, which may remain feasible through alternative routes even under restrictions, thanks to the substitution effect among indirect links. Lastly, the overall vulnerability and centrality metrics under a complete restriction policy are approximately four times greater than those under a direct restriction policy, underscoring the need for heightened scrutiny of the complete restriction policy.

4.2. Correlation and dependence analysis results

Tables 4 and 5 present quantitative results from the correlation analyses between vulnerability/centrality metrics and international

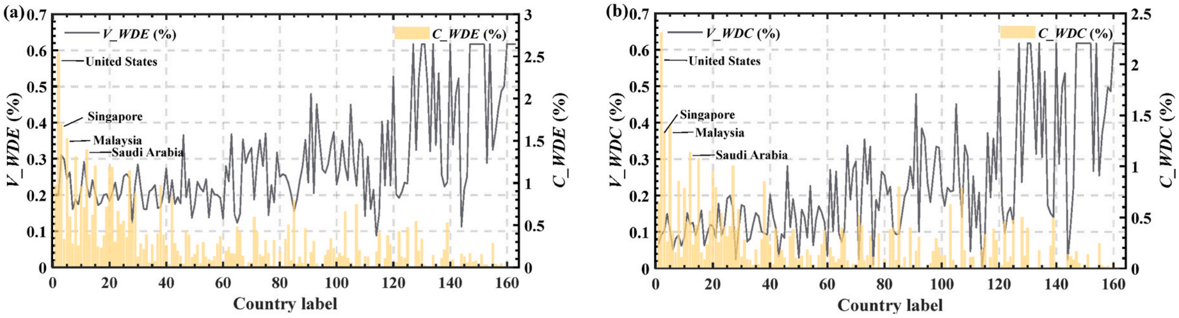

Fig. 3. Overall vulnerability and centrality values of each country/region under direct restriction policy. (a) *V_WDE* and *C_WDE*; (b) *V_WDC* and *C_WDC*.

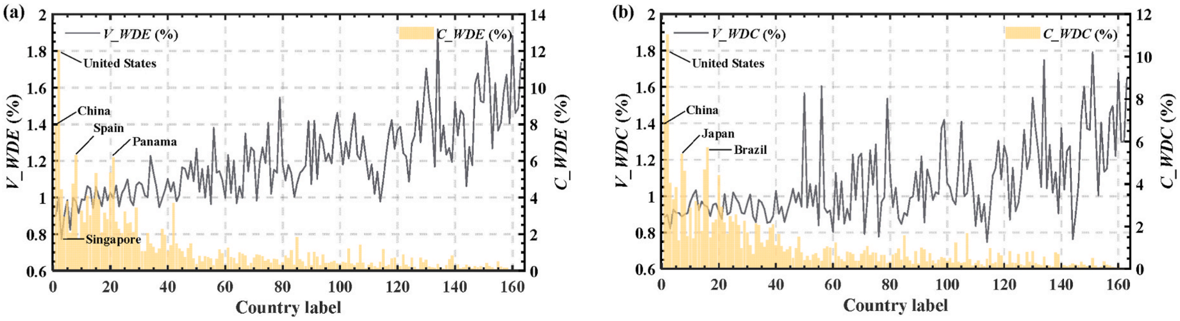

Fig. 4. Overall vulnerability and centrality values of each country/region under complete restriction policy. (a) *V_WDE* and *C_WDE*; (b) *V_WDC* and *C_WDC*.

Table 3
Summary statistics of overall vulnerability and centrality metrics for all countries/regions under two restriction policies.

Metric	Direct restriction policy				Complete restriction policy			
	Mean (%)	Sta	min (%)	max (%)	Mean (%)	Sta	min (%)	max (%)
V_WDE	0.29	0.0014	0.087	0.62	1.21	0.0022	0.771	1.92
C_WDE	0.29	0.0037	0.000	2.55	1.21	0.0161	0.021	12.04
V_WDC	0.23	0.0017	0.002	0.62	1.07	0.0021	0.747	1.79
C_WDC	0.23	0.0032	0.000	2.31	1.07	0.0141	0.033	11.04

Table 4
Pearson and Spearman correlation coefficients between vulnerability/centrality metrics and the eight network indicators under direct restriction policy.

Indicators	Pearson					Spearman				
	V_WDE	*C_WDE*	*V_WDC*	*C_WDC*	Mean (abs)	*V_WDE*	*C_WDE*	*V_WDC*	*C_WDC*	Mean (abs)
ICSCAO	−0.21[a]	0.63	−0.31	0.56	0.43	−0.56	0.62	−0.66	0.53	0.59
NIL	−0.30	0.68	−0.37	0.62	0.49	−0.58	0.59	−0.64	0.52	0.58
DICSC	0.69	−0.46	0.68	−0.43	0.56	0.62	−0.66	0.63	−0.60	0.63
DNIL	0.67	−0.45	0.67	−0.41	0.55	0.57	−0.71	0.62	−0.66	0.64
NP	−0.22	0.48	−0.23	0.44	0.34	−0.20	0.32	−0.22	0.29	0.26
AWDDC	−0.12	0.42	−0.23	0.37	0.28	−0.60	0.61	−0.70	0.52	0.61
AWDCC	−0.39	0.43	−0.49	0.37	0.42	−0.47	0.47	−0.57	0.40	0.48
AWDBC	−0.06	0.39	−0.15	0.36	0.24	−0.54	0.79	−0.67	0.73	0.68
Mean (abs)	0.33	0.49	0.39	0.44		0.52	0.60	0.59	0.53	

[a] Small effects are marked in light blue, medium effects are marked in light green, and large effects are marked in light orange.

network indicators under two restriction policies, which reveal several key findings. Firstly, the correlations of overall vulnerability/centrality metrics with all eight network indicators are notably significant, with no instances of trivial effects ($|r| < 0.10$). Secondly, the Spearman's correlation results are substantially higher than those from Pearson's, suggesting a stronger monotonic relationship in addition to the linear relationship. Thirdly, correlations under the complete restriction policy are significantly higher than those under the direct restriction policy. Lastly, the correlation between centrality metrics and the eight network indicators tends to be stronger than the correlation observed between vulnerability metrics and these indicators. The relationship between vulnerability/centrality metrics and international network characteristics across 163 countries/regions is illustrated in Figs. B1 and B2, aiding in the identification of these findings.

Further analysis of each individual network indicator, along with results shown in Figs. B1 and B2, provides additional insights:

Table 5
Pearson and Spearman correlation coefficients between vulnerability/centrality metrics and the eight network indicators under complete restriction policy.

Indicators	Pearson					Spearman				
	V_WDE	*C_WDE*	*V_WDC*	*C_WDC*	Mean (abs)	*V_WDE*	*C_WDE*	*V_WDC*	*C_WDC*	Mean (abs)
ICSCAO	−0.45	0.76	−0.28	0.75	0.56	−0.80	0.85	−0.56	0.83	0.76
NIL	−0.49	0.90	−0.34	0.88	0.65	−0.78	0.87	−0.61	0.82	0.77
DICSC	0.63	−0.43	0.62	−0.40	0.52	0.71	−0.69	0.67	−0.65	0.68
DNIL	0.60	−0.41	0.61	−0.37	0.50	0.67	−0.71	0.60	−0.66	0.66
NP	−0.30	0.78	−0.24	0.85	0.54	−0.36	0.65	−0.29	0.67	0.49
AWDDC	−0.37	0.32	−0.21	0.29	0.30	−0.80	0.74	−0.55	0.71	0.70
AWDCC	−0.61	0.41	−0.38	0.37	0.44	−0.70	0.58	−0.44	0.58	0.58
AWDBC	−0.27	0.25	−0.16	0.23	0.23	−0.73	0.82	−0.54	0.81	0.73
Mean(abs)	0.47	0.53	0.35	0.52		0.69	0.74	0.53	0.72	

1) ***ICSCAO* and *NIL*:** These indicators have a significant impact on a country's vulnerability and centrality. Countries with higher *ICSCAO* and *NIL* values typically exhibit lower vulnerability and higher centrality.
2) ***DICSC* and *DNIL*:** These indicators also substantially affect vulnerability and centrality. In particular, countries with greater dispersion of deployed cargo service capacity or number of links with other countries exhibit lower vulnerability and higher centrality. This is logical, as greater dispersion lessens a country's dependence on any single country.
3) ***NP*:** This indicator has a weaker influence on vulnerability and centrality compared to the first four indicators. However, countries with more ports can somewhat reduce their vulnerability and improve centrality.
4) ***AWDDC*, *AWDCC*, and *AWDBC*:** These indicators display weaker Pearson correlations but stronger Spearman correlations with vulnerability/centrality metrics. Higher values in *AWDDC*, *AWDCC*, and *AWDBC* correspond to lower vulnerability and higher centrality, highlighting the importance of enhancing the hub position of ports within a country in the GCSN.

These insights indicate that both basic structural and functional indicators are crucial factors in determining the vulnerability and centrality of a country in the network. Rational adjustments and design of international service connections based on these indicators can improve a country's resilience to absorb national-level disruptions and strengthen its centrality in international maritime trade at the same time.

Table 6 presents the conditional entropy values between vulnerability/centrality and the eight network indicators under the two restriction policies, with the last row listing the entropy values of the vulnerability/centrality metrics themselves. It is apparent that almost all conditional entropy values, except those related to *NP* indicators, are significantly lower than the entropy values of the vulnerability/centrality metrics. This indicates a strong dependence between the network indicators and the vulnerability/centrality metrics. Particularly, the conditional entropy values for *ICSCAO*, *AWDDC*, *AWDCC*, and *AWDBC* are equal to or near zero, meaning virtually no uncertainty in the vulnerability/centrality metrics when these network indicator values are known. This strong dependence further underscores the critical role of a country's international cargo service capacity (i.e., *ICSCAO*) and the strategic positioning of its ports in (*i*) determining its ICSN under national-level restriction policies and (*ii*) exerting influence over other countries' ICSNs through the implementation of such policies.

4.3. Classification results of country impact degrees

The refined *k*-means algorithm, with a weight coefficient of 0.5 (i.e., connection efficiency and extent have an equal contribution to a country's ICSN vulnerability), is herein utilized to explore how individual restrictive policies, imposed by various countries, affect China's ICSN. Figs. 5 and 6 illustrate the classification outcomes of the impact degrees from different countries, each individually implementing one of two distinct restriction policies on China. Both Fig. 5(a) and 6(a) identify $k = 4$ as the elbow point, accompanied by very high SC values, confirming $k = 4$ as the optimal number of classification levels. Fig. 5(b) and 6(b) reveal the results of the impact degree classifications under the two policies. The clear hierarchical classification boundaries in these results confirm the applicability and effectiveness of the *k*-means algorithm for classifying impact degrees. Moreover, a higher impact level includes fewer countries, clearly pinpointing the few critical countries with substantial influence on China's ICSN. Fig. 5(c) and 6(c) display the average impact degree within each classification group, highlighting the substantial variability across groups and underscoring the importance of classification in clarifying the interconnections between China's ICSN and those of other countries.

Further insights from Figs. 5 and 6 include:

1) Under a direct restriction policy, only about 10 countries significantly weaken China's ICSN, with the impacts of most others remaining minimal, as evidenced in Fig. 5(c) where the average impact of Level 4 approaches zero. Conversely, a complete restriction policy allows nearly any country to exert some degree of influence on China's ICSN. Even countries lacking direct routes to China could

Table 6
Conditional entropy between vulnerability/centrality metrics and the eight network indicators under direct and complete restriction policies.

Indicators	Direct restriction policy				Complete restriction policy			
	V_WDE	*C_WDE*	*V_WDC*	*C_WDC*	*V_WDE*	*C_WDE*	*V_WDC*	*C_WDC*
ICSCAO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NIL	1.46	1.66	1.46	1.66	1.66	1.66	1.66	1.66
DICSC	0.00	0.22	0.00	0.22	0.22	0.22	0.22	0.22
DNIL	0.42	0.62	0.42	0.62	0.62	0.62	0.62	0.62
NP	4.33	4.57	4.33	4.57	4.57	4.57	4.57	4.57
AWDDC	0.08	0.10	0.08	0.10	0.10	0.10	0.10	0.10
AWDCC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AWDBC	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01
	7.02	7.35	7.02	7.35	7.35	7.35	7.35	7.35

Table 7
Top 20 countries/regions ranked by deployed cargo service capacity with China.

No.	Countries/regions	Service capacity (Weekly TEU)	Number of links	No.	Countries/regions	Service capacity (Weekly TEU)	Number of links
1	South Korea	1,276,831	62	11	Philippines	62,337	38
2	Singapore	854,318	19	12	Panama	47,796	6
3	Hong Kong	796,043	24	13	Indonesia	46,549	11
4	Taiwan	527,706	32	14	Canada	37,462	6
5	United States	492,404	51	15	Mexico	36,597	5
6	Malaysia	379,032	34	16	Netherlands	34,701	2
7	Vietnam	322,562	49	17	Spain	23,395	1
8	Japan	238,666	96	18	United Arab Emirates	20,685	2
9	Australia	66,395	18	19	Saudi Arabia	17,494	1
10	Thailand	64,799	16	20	Papua New Guinea	15,753	2

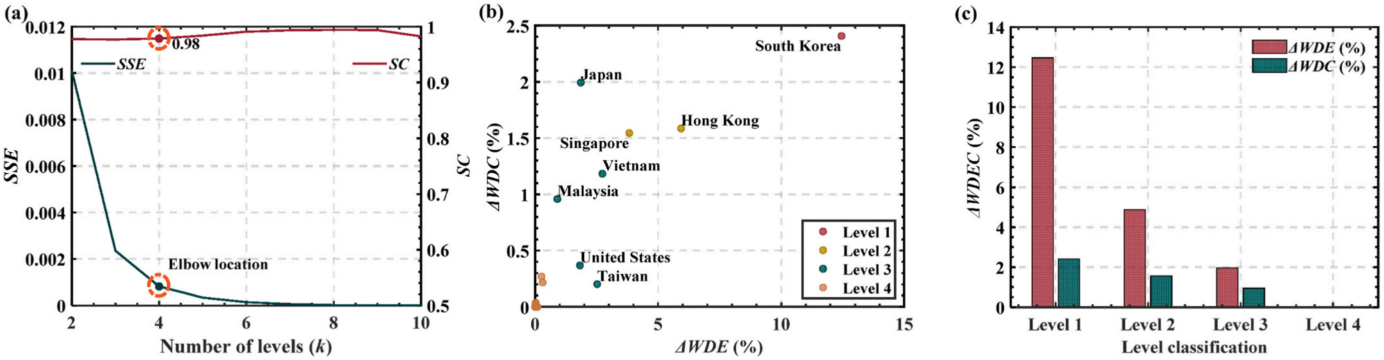

Fig. 5. Classification results for the impacts of individual countries/regions on China's ICSN through the direct restriction policy. (a) determination of classification levels; (b) visualization of impact degree classification results; (c) average impact degree of countries/regions within each classification group.

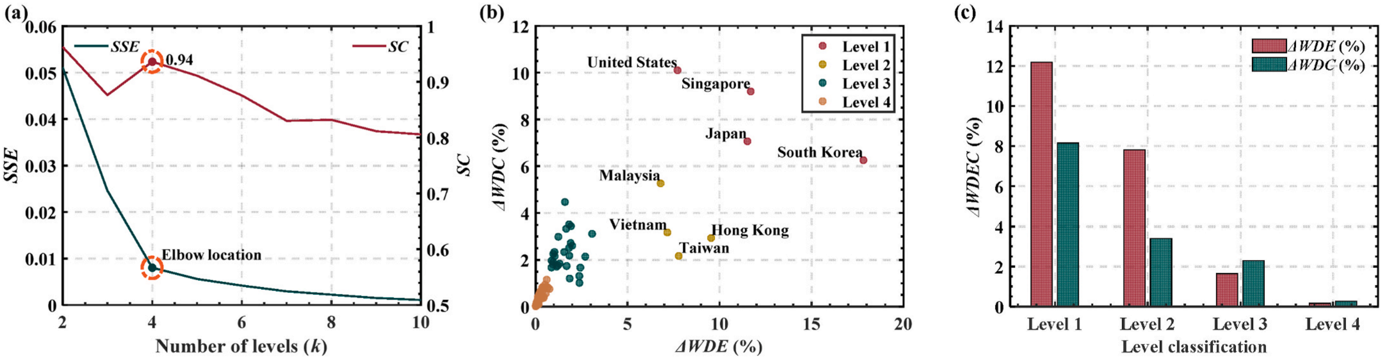

Fig. 6. Classification results for the impacts of individual countries/regions on China's ICSN through the complete restriction policy. (a) determination of classification levels; (b) visualization of impact degree classification results; (c) average impact degree of countries/regions within each classification group.

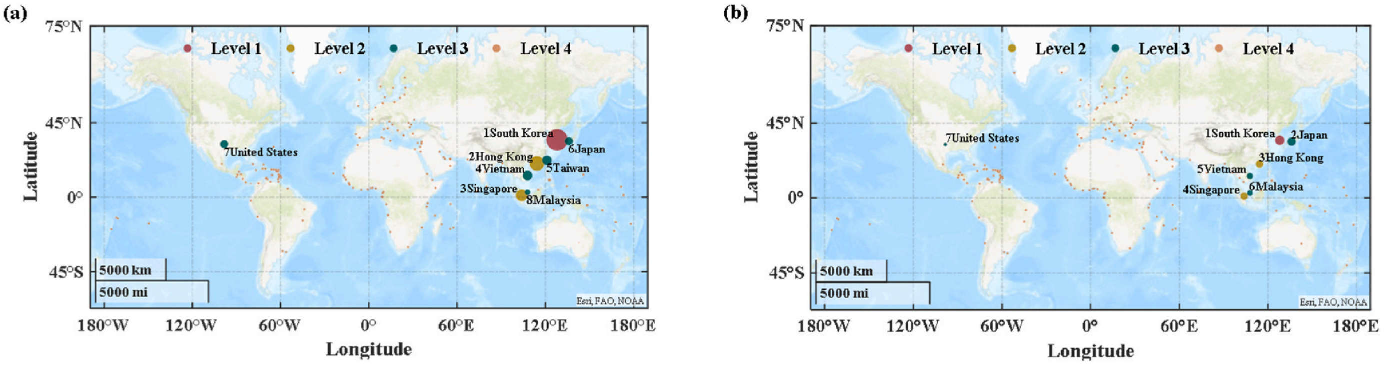

Fig. 7. Geographical distribution of individual countries/regions' impact degrees on China's ICSN through the direct restriction policy. (a) *ΔWDE* and (b) *ΔWDC*.

affect its ICSN, as transfers through these countries are entirely prohibited under such a policy.

2) Under a direct restriction policy, the connection extent metric is significantly less affected than the connection efficiency metric, as evidenced by substantial differences in the scales of the horizontal and vertical axes in Fig. 5(b). This disparity stems from the abundant alternative routes available within China's well-developed international maritime network. Specifically, when one country enforces a direct restriction policy on China, alternative routes through other countries can maintain the connection extent of China's ICSN. The high redundancy and availability of alternative routes enhance the resilience of China's ICSN against disconnections caused by direct suspensions from any single country. However, the connection efficiency metric experiences more substantial degradation, caused by significant increases in the shortest service connection time when alternative routes become necessary due to direct restrictions. In contrast, under a complete restriction policy, this difference is less pronounced because the complete restriction not only disrupts direct connections with China but also eliminates the possibility of transit through the restricting countries within the GCSN.

Figs. 7 and 8 depict the geographical distribution of each country's impact on China's ICSN through the implementation of one of the two restriction policies, with the size of each point reflecting its impact degree. Several noteworthy observations can be drawn from these figures.

1) Countries/regions that critically affect Mainland China's ICSN through direct restriction policies are geographically close to China. Notable examples include South Korea, Japan, Hong Kong, Singapore, and Taiwan, all of which maintain frequent direct connections with China and play vital roles in global container shipping (see Table A1). This observation underscores how geographical proximity significantly enhances commodity trade, reflecting the community characteristics of international trade (Bai et al., 2023; Jarumaneeroj et al., 2024). In contrast, under the complete restriction policy, the distribution of countries with a significant impact on China's ICSN is more spatially dispersed, particularly in terms of connection extent. Countries like Italy, Turkey, and Brazil, despite their geographical distance and limited direct routes with China (None ranked in the top 20 for deployed cargo service capacity with China according to Table 7), have a substantial effect on the connection extent of China's ICSN. Additionally, the countries with well-developed international network systems (see Table A1) markedly affect China's ICSN when imposing complete restriction policy, as they possess extensive international transport links that facilitate connections between China and other countries without direct links to China. Overall, the impact of a direct restriction policy primarily depends on direct routes and geographical proximity between countries, whereas the impact of a complete restriction policy, especially on connection extent, is significantly influenced by the development level of the imposing country's international network.

2) Under a direct restriction policy, South Korea holds the top position in impacting China's ICSN in terms of both connection efficiency and extent, suggesting that a direct restriction imposed by South Korea would lead to the most significant reduction in China's ICSN. Under a complete restriction policy, while South Korea continues to dominate in terms of connection efficiency, the US exerts the greatest impact on China's connection extent. This effect arises because the US not only maintains a substantial frequency of direct connections with China but also serves as a crucial hub that links numerous countries globally. It is noteworthy that both South Korea and Hong Kong, despite having the highest direct international connections with China, ranked first and third respectively (see Table 7), are surpassed by the US and Japan in terms of their individual impact on the connection extent of China's ICSN when imposing complete restrictions (see Fig. 8(b)). This indicates that, while they serve as major direct connectors, they are not as crucial as some of the world's leading developed countries for China's broader connectivity with other countries.

3) Countries distant from China, like Germany, Turkey, Italy, and Brazil, which have few direct connections (see Table 7) but possess well-developed international networks (see Table A1), have a significantly larger impact on China's ICSN under a complete suspension policy compared to a direct suspension. However, the difference in impacts between the two restriction policies for countries geographically close to China, such as Japan, South Korea, Singapore, and Malaysia, is relatively small. This can be attributed to the substantial influence by the latter under the direct suspension policy.

Figs. 9 and 10 illustrate the impacts of restriction measures implemented individually by critical countries on China's ICSN, and vice versa. These figures reveal that individual restrictions by these countries on China lead to declines of 0.9–12.5 % in connection efficiency and 0.2–2.4 % in connection extent under the direct restriction policy, with more substantial declines of 6.8–17.8 % and 2.2–10.1 % under the complete restriction policy. Notably, the radar charts show that the light red areas, representing the impacts of China's individual restrictions on these countries, almost completely overshadow the light purple areas, depicting the impacts of these countries' individual restrictions on China. For example, China's complete restriction measures could decrease South Korea's connection efficiency and extent by up to 51.6 % and 29.0 % respectively, while a complete policy from South Korea could only reduce these metrics in China's ICSN to 17.8 % and 6.3 %. This significant disparity stems from China's well-developed network, which increases other countries' reliance on China and diminishes their inclination to enforce restrictions on China based on their national interests. These observations also underscore the necessity for systematic adjustments and strategic designs in a country's international network to boost its centrality and minimize its susceptibility within the GCSN, thereby facilitating smoother operations in international maritime

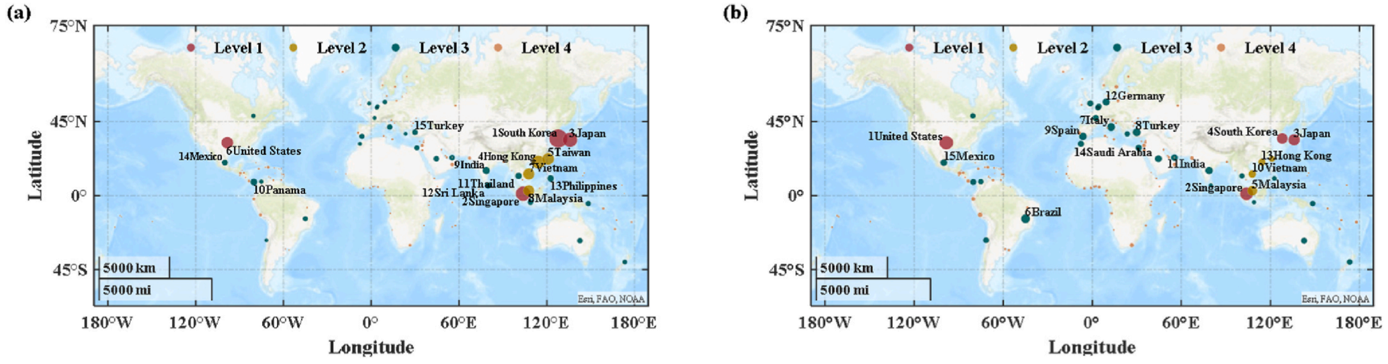

Fig. 8. Geographical distribution of individual countries/regions' impact degrees on China's ICSN through the complete restriction policy. (a) ΔWDE and (b) ΔWDC.

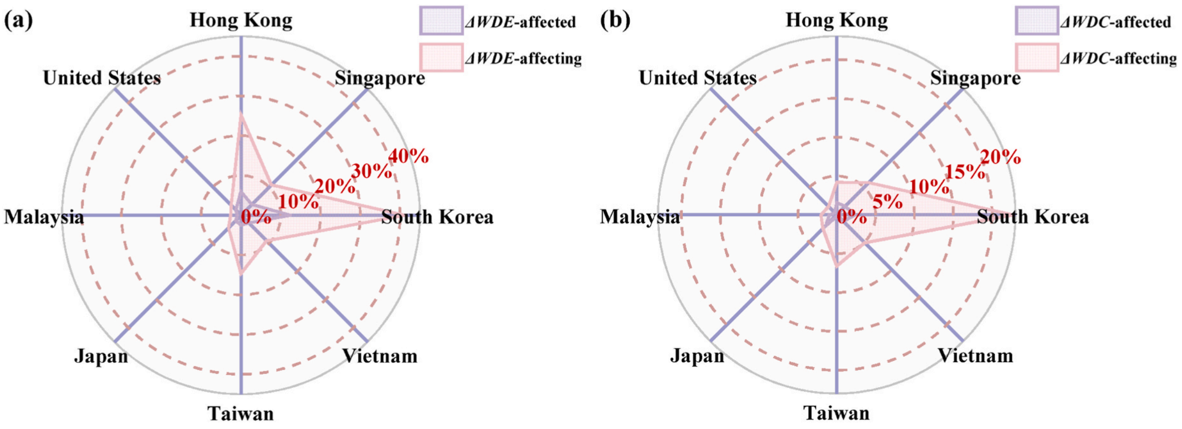

Fig. 9. Impact degrees of direct restriction policy on ICSNs between China and critical countries/regions. (a) *ΔWDE* and (b) *ΔWDC*.

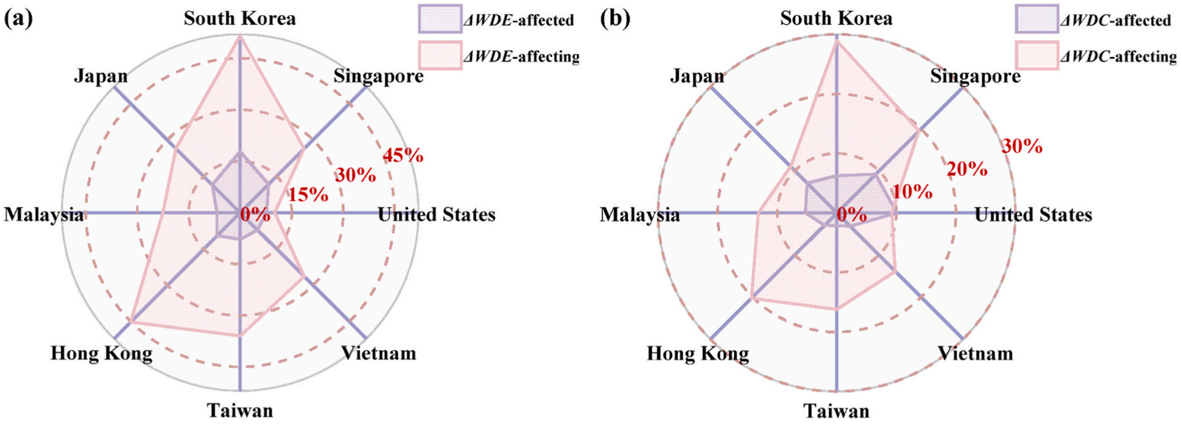

Fig. 10. Impact degrees of complete restriction policy on ICSNs between China and critical countries/regions. (a) *ΔWDE* and (b) *ΔWDC*.

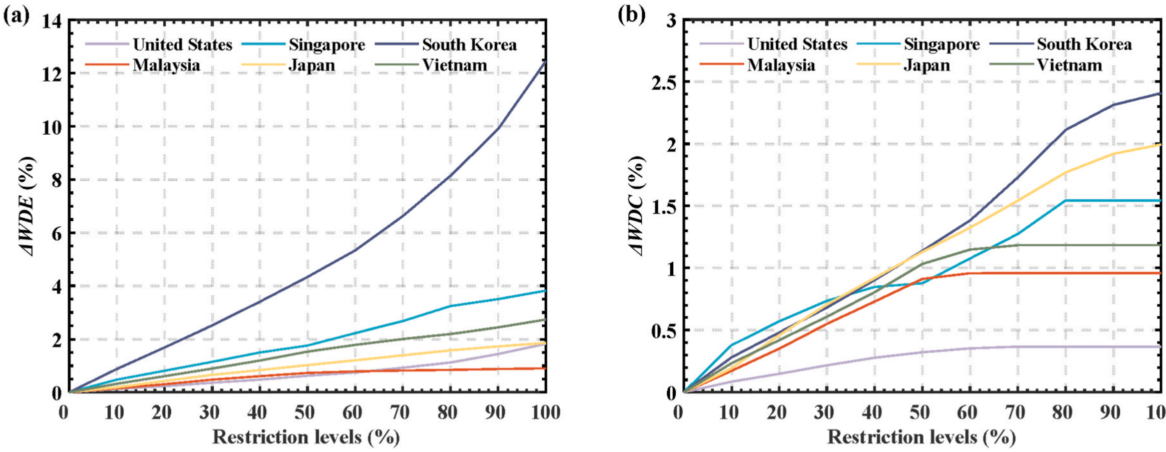

Fig. 11. Variations in impacts on China's ICSN from varying levels of direct restrictions by identified critical countries/regions. (a) *ΔWDE* and (b) *ΔWDC*.

trade.

In some instances, a country may not sever all connections with another but rather impose partial constraints. Consequently, Figs. 11 and 12 showcase the variations in impacts on China's ICSN when six identified critical countries, including the US, Singapore, South Korea, Malaysia, Japan, and Vietnam, individually implement different levels of restriction policies against China. To enforce these partial restrictions, the weights of the edges associated with the country imposing the restrictions and the country facing the restrictions are adjusted proportionally. As the level of restrictions increases, there is a corresponding substantial decrease in the associated edge weight. These figures illustrate that China's connection efficiency performance under the two policies and its connection extent performance under the complete restriction policy generally decrease linearly as restriction levels increase — although some deviations are noted at certain points. Interestingly, a ladder-like pattern emerges in its connection extent under the direct restriction policy, suggesting that increased restriction levels do not consistently diminish China's connection extent. This resilience is

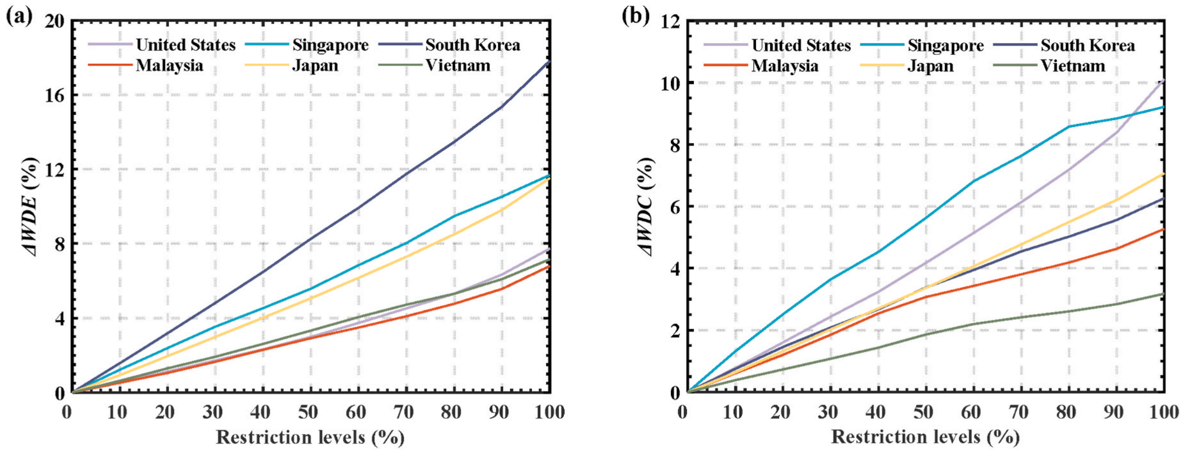

Fig. 12. Variations in impacts on China's ICSN from varying levels of complete restrictions by identified critical countries/regions. (a) *ΔWDE* and (b) *ΔWDC*.

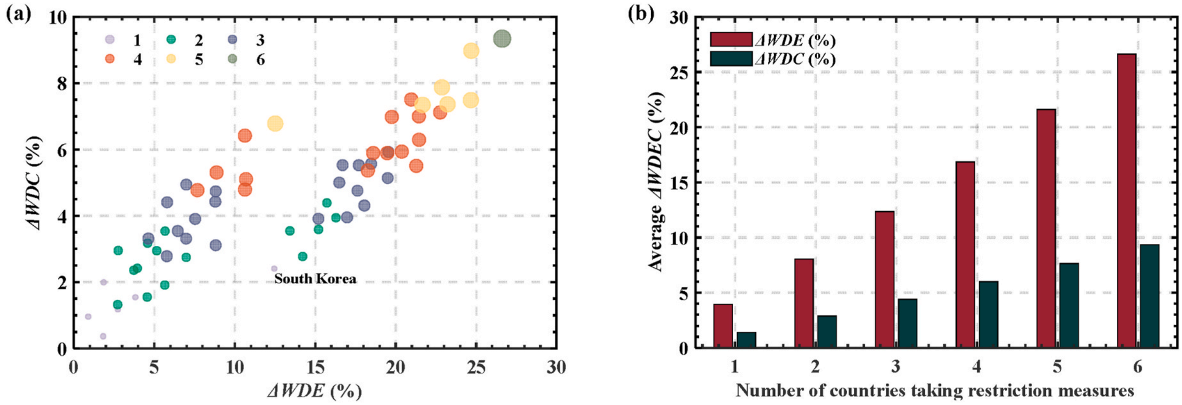

Fig. 13. Collective impacts on China's ICSN when six critical countries simultaneously impose direct restriction policies. (a) Distribution of collective impact degrees; (b) average collective impact degrees with different number of critical countries imposing restrictions.

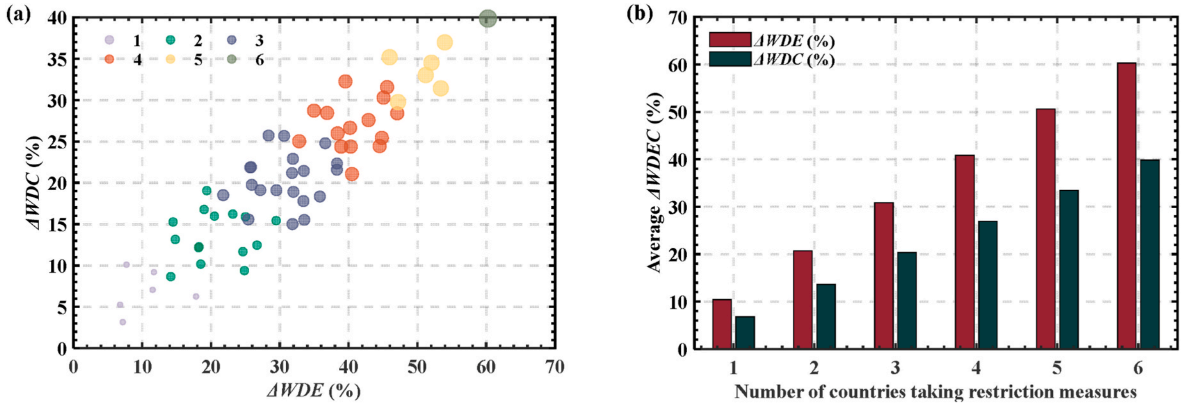

Fig. 14. Collective impacts on China's ICSN when six critical countries simultaneously impose complete restriction policies. (a) Distribution of collective impact degrees; (b) average collective impact degrees with different numbers of critical countries imposing restrictions.

primarily due to the existence of numerous alternative routes within China's well-developed network that help mitigate the effects of direct disconnections. Clearly, this analysis offers valuable insights into the dynamics of China's ICSN amid varying degrees of national-level disconnection.

Finally, Figs. 13 and 14 illustrate the collective effects on China's ICSN when critical countries simultaneously impose various combinations of restriction policies. These figures demonstrate that the effects linearly increase with the number of countries enforcing restrictions. Regardless of the types of implemented restriction policies, the combined impact of these critical countries on China's ICSN is substantial. For instance, when the six countries jointly implement a direct restriction policy, the connection efficiency and extent of China decrease by 26.6 % and 9.3 %, respectively. When these countries jointly adopt a complete restriction policy, these figures dramatically decrease by 60.3 % and 39.9 %. This significant decrease occurs because the joint restriction policy of these critical countries affects not only their direct connections with China but also blocks some transit channels for China to many other countries.

Another interesting observation from Fig. 13(a) is that the joint impact degrees are divided into two distinct clusters with clear boundaries, attributed to South Korea's individual influence on China far exceeding that of other critical countries under the direct restriction policy. The bottom left cluster represents the joint effects of these critical countries excluding South Korea, while the upper right cluster represents their effects including South Korea. Notably, South Korea's individual impact under the direct restriction policy even surpasses the combined impact of other critical countries — due largely to its comprehensive connections with China. Additionally, the collective impact under the complete restriction policy is more than twice that under the direct restriction policy, as evidenced by comparing Fig. 13(b) and 14(b).

5. Discussion, implications, and limitations

The comprehensive results detailed above reveal how the proposed methodology advances understanding of the impacts from large-scale national-level disconnections, resulting from suspension policies, on a country's ICSN. These analyses offer profound political and managerial insights, especially valuable to the international trade sector, as they could help enhance the optimization of international shipping services and, at the same time, provide strategic guidance for proactive risk management. To this end, the increasing prevalence of national-level disconnections, driven by geopolitical tensions and global health crises, further emphasizes the importance of these findings. The primary discussion, contributions and implications to vulnerability analysis from an ICSN perspective are outlined below.

Firstly, this study represents the first exploration of the impacts of country-to-country disconnections on a country's international maritime transport trade. Traditional studies have concentrated on the performance of the global shipping systems or individual ports during disruptions, revealing challenges in developing holistic network function evaluation metrics from the perspective of a country's international shipping trade and in designing various realistic national-level disruption scenarios. However, the newly developed methodology emerges as a powerful tool for assessing the vulnerability of a country's ICSN under two specific national-level restriction policies. Importantly, both overall vulnerability and centrality metrics are devised to accurately gauge a country's ICSN susceptibility to other countries' restriction policies and its ability to affect other countries' ICSNs through the enforcement of restriction policies. Statistical analyses utilizing real container service data effectively reveal the diverse impacts of different restrictive policies on each country's ICSN and the nuances in each country's overall vulnerability and centrality. These insights offer crucial practical significance for stakeholders and policymakers in understanding the vulnerability mechanisms of the international shipping network in response to national-level disruptions.

Secondly, this study provides critical insights for state governments and stakeholders on how well-designed international shipping network structures can reduce vulnerability and boost centrality. According to correlation and dependence analyses in Section 4.2, monotonic relationships among overall vulnerability/centrality and network indicators are identified. These findings offer strategic guidance for refining network system designs on an international scale. Particularly, to construct an international shipping network that is resilient to country-to-country disconnections while influential over other countries' ICSNs, it is essential for state governments and stakeholders to focus on the following strategic areas:

1) The strong correlations and dependences between factors like *ICSCAO*, *AWDDC*, *AWDCC*, and *AWDBC*, and the vulnerability/centrality metrics underscore the critical role of a country's international cargo service capacity and strategic port positioning in maintaining functionality under national-level restrictions and influencing other countries' ICSNs. Governments and stakeholders can increase a country's resilience to direct and complete restrictions by expanding cargo service capacity and upgrading key domestic ports to international hub status. This also simultaneously enhances a country's centrality, thereby increasing its potential to influence other nations' ICSNs.
2) Factors such as *NIL*, *DICSC*, and *DNIL* also substantially influence vulnerability and centrality, as evidenced by the correlation examination results. It underscores that evenly distributing links and capacity among a larger set of trading partners dilutes reliance on any single country. Hence, governments and stakeholders are advised to establish more links with foreign ports and distribute cargo service capacity and the number of links more evenly among different countries. Such diversification protects against unilateral disruptions and strengthens a nation's position in negotiations. Especially for countries with strong connections to only a few high-capacity ports, strategic link dispersion can serve as a cost-effective path to increased resilience.
3) While having more ports can somewhat reduce a country's vulnerability and improve centrality, this factor has proven to be of minimal relevance and dependence in comparison to other indicators. Therefore, it suggests that prioritizing the development of existing high-performing ports and expanding routes to more countries are generally more impactful. These strategic insights are valuable for governments and stakeholders seeking to optimize international shipping service structures efficiently within the constraints of resources and costs.

Thirdly, this study delivers significant benefits for governments and stakeholders by guiding proactive measures for prevention and mitigation of major international disruptions. It employs a precise impact degree classification method to discern which countries significantly affect the targeted countries through the implementation of different restrictive policies. By utilizing China as a test case for analyzing the degrees of impact from various countries, several insights emerge, and corresponding recommendations can be provided:

1) The results highlight that geographic proximity plays a predominant role under the direct restriction policy. As shown in Figs. 5 and 7, countries/regions located near Mainland China (e.g., South Korea, Japan, Hong Kong, Singapore, and Taiwan) exert more pronounced effects on China's ICSN because of frequent direct connections and the short transit distances involved. Conversely, complete restriction widens the pool of influential countries—beyond those with immediate geographical or direct-route ties—by eliminating possible transit through the restricting nations (see Figs. 6 and 8). This explains why countries like Italy, Turkey, and Brazil, despite having limited direct capacity with China, still substantially affect China's connection extent under a complete restriction due to their global hub status or broad networks.
2) The partial and collective disruption scenarios illustrate how multiple countries collectively exert a compounded effect. When critical countries (e.g., South Korea, the US, Singapore, and Malaysia) impose restrictions in tandem, the resulting impact can be far greater than the sum of each individual restriction (Figs. 13 and 14). This synergistic effect demonstrates the importance for policymakers to consider not only bilateral vulnerabilities but also the broader network's structure—especially when multiple high-capacity or high-connectedness nodes collaborate in imposing restrictive measures. Meanwhile, the ladder-like pattern in partial restrictions (Figs. 11 and 12) highlights the importance of route redundancy in mitigating incremental steps of disconnection.
3) The disparity between China's influence on other countries' ICSNs and other countries' influence on China's ICSN (Figs. 9 and 10) reveals that a well-developed network can reduce susceptibility to foreign restrictions while amplifying one's leverage in international

trade. This asymmetry underscores the strategic advantage for nations to strengthen their shipping networks, both in terms of capacity (e.g., *ICSCAO*) and the development of global hub ports (e.g., high *AWDDC*, *AWDCC*, *AWDBC* values).

4) The classification results demonstrate the heterogeneity of different countries' impacts when imposing restrictions. Policymakers can use these insights to prioritize strategic partnerships and sign alternative routing agreements with high-impact countries. Likewise, deploying risk-based contingency plans, particularly with nations such as South Korea, the US, Singapore, and Japan, may help mitigate the most severe potential disruptions.

Lastly, this study can aid in assessing the effectiveness of strategies and policies designed to enhance a country's resilience against disruptions and to support recovery initiatives. The developed methodology enables a direct re-evaluation of a country's ICSN in response to changes in international networks, due to the adoption of new strategies or policies. By comparing initial and follow-up assessments, the efficacy of these strategies or policies can be gauged. Such measures are critical for reinforcing the stability of international shipping logistics. Moreover, improved system resilience further boosts a country's competitiveness and ensures its sustainable engagement in global trade.

Despite these notable insights and implications, certain limitations warrant attention. First, the study focuses primarily on container maritime trade and does not account for other modes of transportation or commodities, which may behave differently under restrictive policies. Second, the static analysis of network disruptions overlooks the dynamic adaptations that shipping lines or governments might implement over time to overcome restrictions, such as rerouting ships and forming new alliances. Currently, most studies focus on how the disruption of a single port impacts nearby ports through rerouting and the selection of alternative hubs (i.e., the cascading effect) (Bai et al., 2023; Cao et al., 2025; Lu et al., 2024). It would be insightful to assess the cascading effect at a national scale, where a large number of transportation routes are rerouted simultaneously due to restrictive policies. This would enhance the understanding of the impact of national-level restrictions. Thirdly, the implications drawn from the comprehensive case analysis predominantly focus on the disruptions at a country level in the target countries. Moving forward, a bilateral analysis between the target and one influential country could be conducted in greater detail to uncover vulnerabilities arising from both port-level and country-level disruptions. This approach would provide a more thorough understanding of the vulnerabilities involved. Lastly, although the methodology accommodates partial restrictions, it assumes uniform proportional weight reductions; real-world scenarios may feature more complex, non-linear disruptions. Therefore, there is a pressing need to develop more advanced models, supported by richer datasets, to more accurately analyze the impacts of national-level disruptions on a country's ICSN.

6. Conclusions

This study, as driven by the challenges and disruptions stemming from escalating geopolitical tensions and global health crises on international maritime transportation networks, develops a novel methodology to assess the vulnerability of a country's international shipping network in the face of national-level disruptions. This methodology distinguishes itself from the existing literature through its new features, including (*i*) the introduction of two national-level disruption scenarios, i.e., direct restriction and complete restriction policies, to simulate their impacts on a country's ICSN, (*ii*) the development of new metrics for both vulnerability and centrality that integrate network directionality, link weight, and transit times, in assessing a country's susceptibility to other countries' restriction policies and its capacity to influence other countries' ICSN, (*iii*) the employment of correlation and dependence analyses to examine relationships between vulnerability/centrality and eight different network indicators, and (*iv*) the introduction of an advanced *k*-means algorithm to pinpoint critical countries, facilitating the design of hierarchical intervention measures against various disruptions. Experimental analyses confirm the efficacy of this methodology in revealing the varied impacts of different restrictive policies on distinct international network performance metrics, identifying crucial factors affecting vulnerability and centrality, and achieving precise classifications of country impact degrees. The discussion and implication analysis further delve into understanding a country's ICSN performance amid various inter-country disconnections, aids in the optimization of international shipping services, and provides strategic guidance for proactive disruption risk management concurrently.

Future research could take several promising paths. Firstly, the factors affecting the vulnerability and centrality of a country's ICSN are multifaceted — involving various aspects of network structure and functionality. Integrating additional relevant factors with the use of advanced quantitative methods like variance sensitivity analysis would allow for a further quantification analysis of the specific impacts of these structural and functional factors on vulnerability and centrality. The new development could facilitate more effective refinement of the international shipping service network. Secondly, although this study concentrates on the collective restrictions imposed by key influential countries on China, future research could broaden the methodology from an applied research perspective. It could incorporate international political dynamics, such as the simultaneous implementation of direct and complete restriction policies by various countries. This would produce more realistic simulations of potential disruptions. Integrating these dynamics would offer additional support to national governments in developing comprehensive emergency preparedness plans, enabling them to address the risks of potential national-level disconnections more sustainably.

CRediT authorship contribution statement

Xuri Xin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Yuhao Cao:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Pisit Jarumaneeroj:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation. **Zaili Yang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Statistical results for top 20 countries

Table A1 lists these statistics for the top 20 countries/regions ranked by cargo service capacity. As shown in Table A1, these countries (the term ’countries’ refers to both countries and regions) rely heavily on international trade for transporting goods. Specifically, 13 out of the 20 countries have international cargo service capacity over 80 percent of their total capacity, and 15 countries of which have over 80 percent of their links dedicated to international connections. Notably, countries like Singapore and the Netherlands are entirely dependent on international shipping trade.

Table A1
Statistical characteristics of the top 20 countries/regions ranked by cargo service capacity.

No.	Countries/Regions	Number of ports	Cargo service capacity (Weekly TEU)			Number of links		
			Total	International	Domestic	Total	International	Domestic
1	Mainland China	29	9,088,834	5,426,345 (60 %*)	3,662,489 (40 %)	617	506 (82 %)	111 (18 %)
2	United States	40	3,767,434	2,248,584 (60 %)	1,518,850 (40 %)	509	384 (75 %)	125 (25 %)
3	Singapore	1	3,193,400	3,193,400 (100 %)	0 (0 %)	135	135 (100 %)	0 (0 %)
4	South Korea	9	2,373,591	2,148,212 (91 %)	225,378 (9 %)	202	184 (91 %)	18 (9 %)
5	Malaysia	9	2,099,949	1,985,550 (95 %)	114,399 (5 %)	193	178 (92 %)	15 (8 %)
6	Hong Kong	1	1,569,458	1,569,458 (100 %)	0 (0 %)	85	85 (100 %)	0 (0 %)
7	Japan	42	1,505,891	797,992 (53 %)	707,900 (47 %)	331	211 (64 %)	120 (36 %)
8	Spain	23	1,458,311	1,206,926 (83 %)	251,385 (17 %)	271	213 (79 %)	58 (21 %)
9	Taiwan	4	1,349,759	1,198,904 (89 %)	150,855 (11 %)	158	148 (94 %)	10 (6 %)
10	Germany	6	1,247,022	1,159,092 (93 %)	87,930 (7 %)	134	127 (95 %)	7 (5 %)
11	Netherlands	4	1,207,356	1,205,806 (100 %)	1550 (0 %)	117	115 (98 %)	2 (2 %)
12	Saudi Arabia	4	1,084,503	1,055,080 (97 %)	29,422 (3 %)	77	74 (96 %)	3 (4 %)
13	India	13	1,042,748	756,551 (73 %)	286,197 (27 %)	117	97 (83 %)	20 (17 %)
14	Belgium	2	1,033,203	1,017,039 (98 %)	16,164 (2 %)	107	105 (98 %)	2 (2 %)
15	Italy	17	1,004,391	767,794 (76 %)	236,597 (24 %)	178	144 (81 %)	34 (19 %)
16	Brazil	17	979,665	392,595 (40 %)	587,071 (60 %)	101	54 (53 %)	47 (47 %)
17	Vietnam	6	951,304	895,257 (94 %)	56,047 (6 %)	146	133 (91 %)	13 (9 %)
18	United Kingdom	13	905,596	900,725 (99 %)	4870 (1 %)	139	134 (96 %)	5 (4 %)
19	United Arab Emirates	4	903,117	792,135 (88 %)	110,982 (12 %)	67	63 (94 %)	4 (6 %)
20	Turkey	13	884,182	508,486 (58 %)	375,696 (42 %)	214	166 (78 %)	48 (22 %)

*The value in a bracket indicates the ratio of international/domestic to total.

Figs. A1 and A2 illustrate the impacts of two distinct restriction policies on the ICSNs of the top 20 countries/regions, denoted by C_1 to C_{20}. Each row in these figures depicts the effects of restrictions imposed by individual countries on the ICSN of a specific country, while each column reflects the impacts of that country’s restrictions on the ICSNs of others. As demonstrated in Fig. A1, the impact of one country imposing a direct restriction policy on another country’s ICSN is typically minor and often negligible. This minimal impact is likely due to the limited number of direct links among countries or the possibility of rerouting goods through third-party countries. In contrast, Fig. A2 shows that the impact of a complete restriction policy, wherein one country completely prohibits cargo transit to and from another, is considerably more severe. Such measures generally result in a significant decline in the targeted country’s ICSN. These findings suggest that a complete restriction policy disrupts a country’s ICSN far more than a direct restriction policy, as it not only impacts direct connections between specific country pairs but also diminishes the overall shipping accessibility of the targeted country to the rest of the world, which is in line with the statement in Section 3.2.

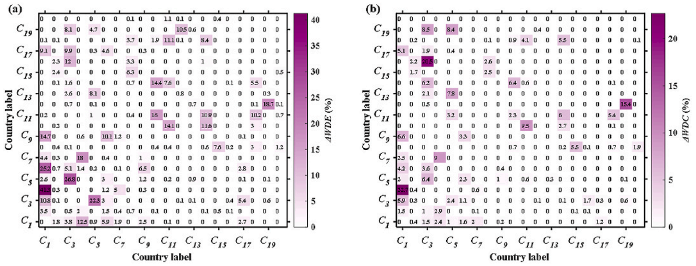

Fig. A1. Impacts of direct restriction policies on the ICSNs of the top 20 countries/regions. (a) *ΔWDE*; (b) *ΔWDC*.

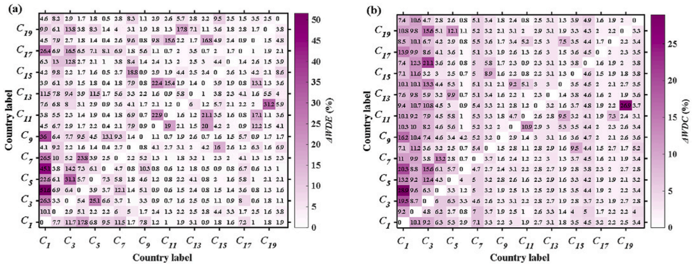

Fig. A2. Impacts of complete restriction policies on the ICSNs of the top 20 countries/regions. (a) *ΔWDE*; (b) *ΔWDC*.

Appendix B. Relationship between vulnerability/centrality metrics and international network characteristics

Figs. B1 and B2 depict the relationship between vulnerability/centrality metrics and international network characteristics (as summarized in Table 2) across 163 countries/regions. Under a direct restriction policy, vulnerability-based metrics demonstrate negative correlations with *ICSCAO*, *AWDDC*, *AWDCC*, and *AWDBC*, and positive correlations with *DICSC* and *DNIL*, while displaying no significant relationship with *NIL* and *NP*. Conversely, centrality-based metrics generally exhibit the opposite relationships: positive correlations with *ICSCAO*, *NIL*, *AWDDC*, *AWDCC*, and *AWDBC*, negative correlations with *DICSC* and *DNIL*, and no significant relationship with *NP*. The correlation trends under the complete restriction policy are similar to those under the direct restriction policy but tend to show more pronounced positive and negative correlations.

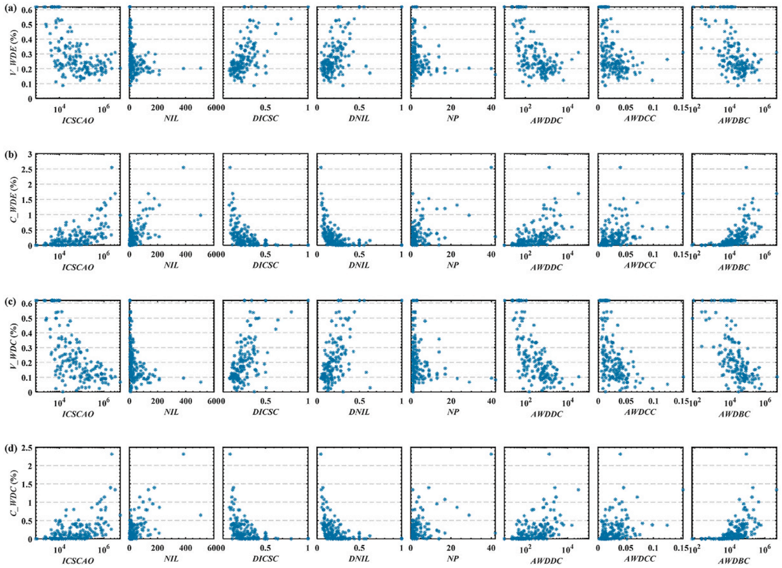

Fig. B1. Relationships between vulnerability/centrality metrics and international network indicators under direct restriction policy. (a) *V_WDE*; (b) *C_WDE*; (c) *V_WDC*; (d) *C_WDC*.

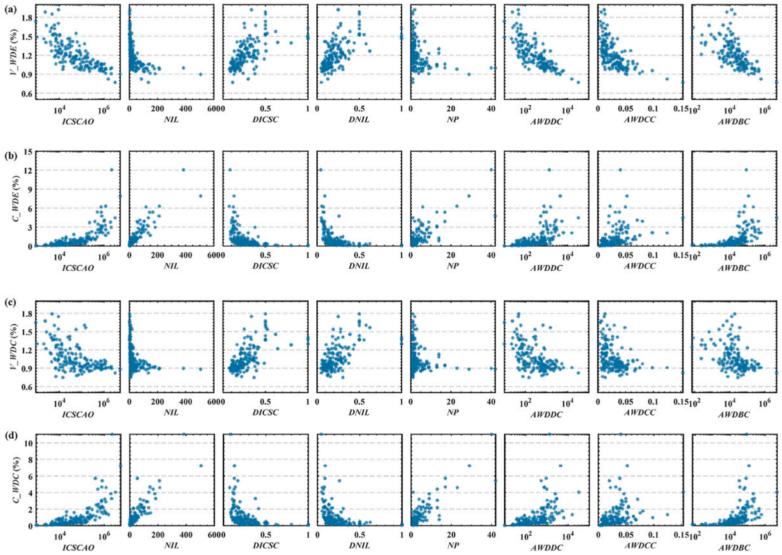

Fig. B2. Relationships between vulnerability/centrality metrics and international network indicators under complete restriction policy. (a) *V_WDE*; (b) *C_WDE*; (c) *V_WDC*; (d) *C_WDC*.

Data availability

Data will be made available on request.

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