



Research Article

Analysis of the maritime network and ports in Vietnam

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Article information	Abstract
Received: November 26, 2025 Revision: March 20, 2026 Accepted: March 27, 2026	This study investigates the structure and connectivity of Vietnam's maritime network using Complex Network Analysis. The analysis is based on scheduled liner shipping service data obtained from the Vietnam Shipping Gazette for June 2023, covering services operated by 32 international shipping companies. A weighted maritime network consisting of 75 seaports and 146 shipping routes is constructed, in which ports are represented as nodes, shipping routes as links, and sailing frequency as link weights. Network-level metrics, including network density, average clustering coefficient, and average shortest path length, together with port-level degree, betweenness, and strength centrality measures, are applied to evaluate network structure and port roles. The results show that Vietnam's maritime network is sparse and highly centralized, with Ho Chi Minh and Hai Phong acting as dominant gateway hubs. Low network density and clustering, combined with a long average path length, indicate limited redundancy and strong hub dependence, suggesting structural vulnerability to disruptions. The findings provide a quantitative basis for assessing maritime network performance and resilience in emerging maritime economies.
Keywords Maritime networks; Vietnam ports; Network analysis; Centrality measures; Global trade connectivity	

1. Introduction

Maritime shipping is a fundamental pillar of global trade, accounting for the majority of international merchandise flows by volume and underpinning global value chains (Kanrak et al., 2023). Owing to its strategic geographic location along major East-West shipping routes and its growing integration into global production networks, Vietnam has emerged as an increasingly important maritime nation in the Asia-Pacific region. Over the past two decades, export-oriented industrialization, rapid manufacturing growth, and rising foreign direct investment have significantly increased Vietnam's dependence on an efficient and resilient port and shipping system to sustain economic development and international competitiveness (Blancas et al., 2014).

Vietnam's seaport system has expanded rapidly in both scale and functional complexity, reflecting sustained growth in trade volumes and industrial output (Ministry of Transport of Vietnam, 2023). In 2022, Vietnamese seaports handled approximately 733 million tons of cargo, marking a substantial increase compared with previous years and highlighting the growing role of ports in national logistics chains (VietnamPlus, 2022). Although comprehensive official statistics for subsequent years are still being consolidated, preliminary industry assessments suggest that cargo throughput continued to rise in 2023 and 2024 as global trade recovered from the COVID-19

pandemic and Vietnam strengthened its position within regional production networks (UNCTAD, 2023).

Despite this expansion, Vietnam's maritime shipping system exhibits structural challenges that remain insufficiently examined at the system level. Cargo flows are heavily concentrated in a small number of major gateway ports, particularly Ho Chi Minh and Hai Phong, while many secondary and regional ports operate with limited direct connectivity to international shipping routes, resulting in uneven network integration (Ministry of Transport of Vietnam, 2023). Such concentration may improve short-term efficiency through hub-and-spoke operations but also raises concerns regarding network vulnerability, limited redundancy, and resilience to disruptions such as congestion, extreme weather events, or geopolitical shocks (Ducruet et al., 2018).

Existing studies on Vietnam's maritime sector have predominantly focused on port performance, logistics efficiency, hinterland connectivity, and comparative competitiveness with regional hubs (Nguyen et al., 2023). While this literature provides valuable insights into the operational and economic dimensions, it largely overlooks the structural properties of Vietnam's maritime network as a complex system, including network topology, hub dependence, and the distribution of connectivity across ports (Notteboom & Rodrigue, 2005). Consequently, port development strategies and infrastructure investments are often formulated without systematic, network-based evidence to evaluate system-wide vulnerability and resilience (Ducruet & Zaidi, 2012).

Complex Network Analysis (CNA) has been widely applied in international maritime research to investigate shipping connectivity, hub formation, and network resilience across global and regional shipping systems (Ducruet & Zaidi, 2012). These approaches enable researchers to assess both structural connectivity and traffic intensity, revealing patterns of concentration and interdependence that conventional port performance indicators do not capture (Kaluza et al., 2010). However, the application of CNA to Vietnam's maritime shipping system remains limited, particularly in studies that integrate weighted and unweighted network measures, despite the country's increasing exposure to global supply-chain uncertainty (Ducruet et al., 2018).

The present study addresses the problem of insufficient network-level understanding of Vietnam's maritime shipping system (UNCTAD, 2023). Specifically, it seeks to examine how ports are interconnected, identify which ports function as dominant hubs or intermediaries, and analyze how the overall network structure influences efficiency and vulnerability within the national port system (Notteboom et al., 2022). By adopting a comprehensive network-oriented approach, the study aims to analyze the structural characteristics of Vietnam's maritime network, identify key hubs, regional ports, and feeder ports, and assess the implications of these structural features for system resilience and evidence-based maritime policy and planning (Ducruet & Zaidi, 2012).

To achieve these objectives, the study addresses the following research questions: What are the main topological characteristics of Vietnam's maritime network? Which ports play central roles as hubs or intermediaries within the network? What do these network characteristics imply for the efficiency and vulnerability of Vietnam's maritime shipping system? The analysis covers a network of 75 seaports, including major Vietnamese ports and their directly connected international counterparts. Within this network, ports can be broadly classified into hub ports with high connectivity and traffic intensity, regional ports serving domestic or sub-regional markets, and peripheral feeder ports that depend on hub ports for access to global shipping routes.

The study constructs a weighted maritime network using scheduled services from the Vietnam Shipping Gazette for June 2023, modelling ports as nodes, shipping routes as links, and sailing frequency as link weights. Key complex network measures are applied to assess both network structure and port-level roles. The results show that Vietnam's maritime network is sparse and highly centralized, relying heavily on a small number of hub ports that support cost-effective transshipment but also increase vulnerability to disruptions due to limited redundancy. These findings highlight the need to enhance connectivity among secondary ports and diversify routing options to improve

network resilience, and they contribute system-level, network-based evidence to support more balanced and sustainable maritime and port development policies in Vietnam.

2. Literature review

2.1. Maritime transport and Vietnam's port system

Vietnam plays a significant role in the global supply chain, especially amid the expansion of trade agreements such as the Regional Comprehensive Economic Partnership (RCEP) and the EU-Vietnam Free Trade Agreement (EVFTA) (Kikuchi et al., 2018). Vietnam's maritime industry is vital for connecting with markets in other regions, contributing to its rapid industrial growth and export-driven economy (Greve & Hansen, 2024). Vietnam's Doi Moi reforms, initiated in the 1980s, transformed its economy into a market-oriented one, including the maritime sector. This change has bolstered Vietnam's attractiveness as a key maritime hub (Nguyen & Dinh, 2024).

Vietnam has invested heavily in developing major port complexes, especially in Ho Chi Minh, Cai Mep-Thi Vai, and Hai Phong. This assesses how ports serve as nodes for domestic distribution and international shipping, focusing on trends in cargo volume, container handling, and infrastructure upgrades. The northern ports (Hai Phong and Cai Lan) primarily serve trade with China and East Asia. Hai Phong is the largest northern port, located near Hanoi, and has expanded significantly to accommodate larger cargo volumes. Ports in the central region (Da Nang and Quy Nhon) primarily support domestic trade and smaller international routes (Nguyen & Notteboom, 2016). They are strategically positioned to serve industries in the central provinces, although they handle lower cargo volumes than the northern and southern ports. Southern Vietnam is the heart of Vietnam's port activity, with Ho Chi Minh and the Cai Mep-Thi Vai complex serving as primary ports for export activities (Nguyen et al., 2020). The southern cluster supports industries in the Ho Chi Minh metropolitan area and serves as a transshipment point due to its proximity to major shipping lanes.

However, Vietnam's maritime shipping industry faces several challenges. Some ports near urban areas experience congestion due to high cargo volumes and limited infrastructure (Huu & Ngoc, 2021). This leads to logistical bottlenecks, increased costs, and delays, particularly during peak trade seasons. Efficient transportation between ports and inland areas remains a challenge. While the government has invested in road and rail infrastructure, Vietnam's inland logistics are still developing, limiting efficient cargo movement between manufacturing zones and ports (Banomyong et al., 2015). Vietnam's ports face stiff competition from well-established maritime hubs, such as Shanghai, Hong Kong and Singapore, which benefit from established transshipment networks, economies of scale, and advanced infrastructure. This makes it challenging for Vietnamese ports to attract larger carriers without offering similar efficiencies. The maritime sector is a main source of greenhouse gas emissions, and Vietnam is increasingly focusing on sustainability. Some issues, such as coastal erosion, pollution from port activities, and climate vulnerability, pose additional challenges for Vietnamese ports, particularly those located in low-lying areas (Givental & Meredith, 2016).

Vietnam's maritime transport system is a cornerstone of its international trade, with seaborne cargo accounting for the vast majority of export-import volume. Studies on Vietnam's ports have historically focused on infrastructure capacity, growth in cargo throughput, and regional imbalances among major port clusters (e.g., Ho Chi Minh-Cai Mep-Thi Vai and Hai Phong) (Nguyen et al., 2020; Nguyen & Notteboom, 2016). Nguyen, Park, and Yeo's analysis of port networks in the Ho Chi Minh area highlights the dominance of southern ports in cargo handling and underscores persistent challenges in hinterland connectivity and logistical efficiency (Nguyen et al., 2020).

2.2 Theoretical framework for maritime network analysis

Previous studies have applied several theoretical perspectives to analyze maritime and port systems, including port competition theory, port regionalization, and logistics and supply-chain frameworks. These approaches primarily focus on market behavior, hinterland expansion, and

operational efficiency, but are less effective in capturing the structural and relational characteristics of maritime connectivity.

Complex network theory provides a robust alternative by modelling ports as nodes and shipping routes as links, allowing quantitative evaluation of connectivity, hierarchy, and systemic vulnerability (Watts & Strogatz, 1998; Barrat et al., 2004). This framework has been extensively applied in maritime transport research to identify hub-and-spoke structures, central ports, and network resilience (Hu & Zhu, 2008; Ducruet & Notteboom, 2012).

Given the objective of this study- to analyze the structural characteristics of Vietnam's maritime connectivity- network analysis is adopted as the primary theoretical framework, as it is well established in the literature and directly aligns with the research questions.

2.3 Network analysis in maritime and port studies

Network-based studies of global and regional maritime systems consistently show that container shipping networks are highly centralized, with a small number of hub ports exhibiting high betweenness centrality (Ducruet & Zaidi, 2012; Wang et al., 2022). Benchmark values reported in the literature typically indicate moderate clustering and short average path lengths, reflecting small-world properties at both global and regional scales.

In Southeast Asia, network analysis has been used to examine port competitiveness, hub dominance, and regional integration. However, Vietnam is frequently treated as a peripheral component within broader regional systems rather than as the main unit of analysis (Nguyen & Woo, 2021). Port-level network studies focusing specifically on Vietnam remain limited, and existing work often relies on throughput or policy indicators rather than formal network topology.

2.4 Connectivity indices: LSCI, PLSCI, and network-based measures

Maritime connectivity is commonly assessed using UNCTAD's Liner Shipping Connectivity Index (LSCI), which provides a national-level measure based on shipping services, vessel size, and carrier deployment (UNCTAD, 2024). More recently, UNCTAD introduced the Port Liner Shipping Connectivity Index (PLSCI) to capture port-level differences in connectivity.

While these indices enable standardized comparisons, they do not explicitly represent port-to-port relational structures or identify intermediary dependencies. Network-based approaches complement LSCI and PLSCI by modelling direct interactions among ports, allowing deeper analysis of connectivity hierarchy and structural vulnerability. Accordingly, this study adopts a network analysis approach while acknowledging PLSCI as a relevant alternative metric.

The literature reveals three key gaps. First, Vietnam-specific port-level maritime network analyses remain scarce. Second, existing studies rarely benchmark Vietnam's network characteristics against established global or regional standards. Third, prior research often lacks clarity in distinguishing maritime connectivity from overall logistics or hinterland efficiency. This study addresses these gaps by conducting a port-level network analysis of Vietnam's deep-sea maritime shipping system, benchmarking key network metrics against the international literature, and explicitly defining the analytical scope as a single-layer maritime network.

3. Research methodology

3.1 Research design and analytical framework

This study applies Complex Network Analysis (CNA) to examine the structure and connectivity of Vietnam's maritime network. The analytical focus is strictly on maritime shipping services, rather than on overall multimodal logistics performance. Within this framework, ports are modelled as nodes, and scheduled maritime shipping routes between ports are modelled as edges. The approach allows for the identification of key hub ports, network vulnerabilities, and structural characteristics of Vietnam's maritime connectivity.

The network is analyzed as a weighted and undirected graph, where link weights represent the frequency of scheduled sailings between ports during the study period. This structure enables the simultaneous assessment of both topological connectivity and traffic intensity.

3.2 Data sources and data collection

The empirical analysis is based on secondary shipping schedule data obtained from the Vietnam Shipping Gazette, a specialized maritime shipping publication. The dataset covers June 2023 and includes scheduled services operated by 32 international shipping companies calling at Vietnamese ports. The raw dataset contains information on origin ports, destination ports, shipping companies, service routes, and sailing frequency (the number of scheduled sailings during the study period). From this information, a maritime network was constructed comprising 75 ports (both Vietnamese and foreign ports directly connected to Vietnam) and 146 shipping routes.

3.3 Data pre-processing and quality-control procedures

To enhance data validity and reliability, several quality-control checks were conducted prior to network construction.

- Port name standardization- Port names were harmonized to avoid duplication caused by spelling variations or alternative naming conventions.
- Route verification- Duplicate service listings and circular routes were identified and removed.
- Outlier inspection- Abnormally high or low sailing frequencies were manually checked against original schedule records.
- Consistency checks- Directional inconsistencies in reported services were resolved by treating routes as undirected links when reciprocal services existed.

While the study relies on a single primary data source, the observed network structure and hub-dominance patterns are consistent with findings from prior maritime network studies and international connectivity indicators reported in the literature.

3.4 Network construction and input variables

The shipping network was constructed using nodes representing individual seaports included in the shipping schedules, edges (links) denoting the existence of at least one scheduled shipping service between two ports during the study period, and edge weights as the total number of scheduled sailings between each pair of ports, reflecting route intensity.

An adjacency matrix was generated to represent port-to-port connectivity, and a weighted matrix was created to incorporate sailing frequency. These matrices served as the direct input for the complex network analysis. All computations and network metrics were calculated using the R statistical software, ensuring analytical transparency and reproducibility.

3.5 Network measures and interpretation

To evaluate both network-level structure and port-level roles, this study employs a set of standard CNA measures, summarized in **Table 1**. At the network level, network density measures the proportion of actual shipping routes relative to all possible routes. A low density indicates a sparse network with reliance on a limited number of hub ports. The average clustering coefficient captures the extent to which ports tend to form tightly interconnected groups. Low values suggest limited direct inter-port connectivity and a hub-and-spoke structure. Average shortest path length represents the average number of connection steps required to travel between any two ports. Larger values imply longer routing chains and potentially higher transit times.

At the port level, degree centrality indicates the number of direct shipping connections a port maintains, reflecting its immediate connectivity and operational importance. Betweenness centrality measures how often a port lies on the shortest paths between other ports, capturing its role as an

intermediary or transshipment hub. Strength centrality accounts for the total sailing frequency of routes connected to a port, reflecting the intensity of shipping activity rather than merely the number of connections.

Together, these measures provide complementary insights into structural vulnerability, hub dependence, and the functional roles of individual ports within Vietnam's maritime network.

Table 1 Statistical measures.

Measure	Description	Function
Network density	Fraction of the total number of edges to the maximum possible number of edges.	$p(G) = \frac{m(G)}{n(n-1)}$
Average clustering coefficient	The average fraction of the number of pairs of a node's neighbors that are connected by links to the maximum possible links between them.	$C = \frac{1}{n} \sum_{i=1}^n \frac{m_i}{k_i(k_i-1)/2}$
Average shortest path length	The average number of connection steps along the shortest paths for all possible pairs of nodes.	$L = \frac{1}{n(n-1)} \sum_{i \neq j}^n d(i,j)$
Degree centrality	The sum of the number of links that are connected to a node.	$C_D(i) = \sum_{j=1}^n a_{ij}$
Betweenness centrality	The sum of the shortest paths passing through a given node.	$C_B(i) = \sum_{s \neq i \neq t} \frac{\sigma_{s,t}(i)}{\sigma_{s,t}}$
Strength centrality	The sum of the weights of links that are connected to a node.	$S(i) = \sum_{j=1}^n w_{ij} a_{ij}$

Where

m is the number of edges,

n is the number of nodes,

n_k is the number of nodes with degree k ,

a_{ij} is a binary value, 1 is nodes i and j are connected; 0 is otherwise,

$\sigma_{s,t}(i)$ is the number of the shortest paths from nodes s to t pass through node i ,

$\sigma_{s,t}$ is the number of the shortest paths from nodes s to t ,

$d(i,j)$ is the connection steps from nodes i and j ,

k_i is the degree of node i , and

w_{ij} is the weight of a link that connects between nodes i and j .

This study models connectivity strictly within the blue-water (deep-sea) maritime network. Hinterland transport modes, including road, rail, and inland waterways, are not included in the network representation. As a result, the centrality and efficiency metrics reported in this study reflect maritime-network importance rather than overall port or logistics-system efficiency, which is also influenced by hinterland capacity and congestion. It is important to note that this study adopts a static network perspective, capturing shipping connectivity at a single point in time. Seasonal fluctuations, dynamic route adjustments, and longer-term structural changes are not examined. Moreover, while

maritime connectivity is analyzed in detail, multimodal hinterland connections (road, rail, and inland waterways) are not explicitly modelled Saha et al. (2004). These factors are recognized as critical determinants of overall port performance and represent important directions for future research.

4. Results and discussion

4.1 Network structural properties

Figure 1 illustrates the global maritime network for Vietnam, comprising 75 ports and 146 shipping routes. Beyond demonstrating Vietnam's participation in global maritime trade, the figure reveals several important structural characteristics of the network that directly affect connectivity, resilience, and strategic positioning.

The network exhibits a highly centralized hub-and-spoke structure, with a small number of Vietnamese ports acting as dominant gateways linking Vietnam to the global maritime system. These ports handle a large share of international connections, while most other Vietnamese and foreign ports occupy peripheral positions with limited direct links. This pattern indicates strong dependence on core hubs for international accessibility and reinforces their critical role in maintaining network continuity.

The spatial dispersion of links highlights Vietnam's asymmetric global connectivity. Dense connections are observed with major Asian hubs, reflecting Vietnam's deep integration into regional production networks in East and Southeast Asia. In contrast, links to Europe and North America are fewer and more elongated, suggesting reliance on indirect routing through intermediary hubs rather than extensive direct services. This structure is typical of emerging maritime economies that are globally connected but regionally anchored.

The absence of dense local clusters among Vietnamese ports in **Figure 1** suggests limited lateral connectivity within the national port system along deep-sea shipping routes. Rather than forming tightly interconnected regional subnetworks, most ports connect vertically to major hubs. This configuration enhances efficiency for long-distance trade but reduces redundancy, increasing vulnerability to disruptions at key gateway ports.



Figure 1 Shipping network in Vietnam.

Source: Authors

4.1.1 Network density

The calculated network density of 0.0263 indicates that only 2.63 % of all possible port-to-port connections are realized. This value is substantially lower than densities reported for regional liner shipping networks, which typically range between 0.05 and 0.15, depending on geographic scope and data resolution (Ducruet & Notteboom, 2012; Jiang et al., 2015; Wang et al., 2022). Compared with these benchmarks, Vietnam's maritime network is highly sparse.

Such sparsity implies strong reliance on a limited number of hub ports for connectivity. In Vietnam, this pattern is consistent with empirical observations showing cargo concentration at Ho Chi Minh, Cai Mep-Thi Vai, and Hai Phong, while many smaller ports operate with limited direct international services (Nguyen et al., 2020; Hu et al., 2022). For example, congestion episodes at Cat Lai Port during peak export periods have disrupted national logistics flows, forcing cargo rerouting and increasing dwell times (Huu & Ngoc, 2021).

It is important to note, however, that low maritime network density does not automatically imply systemic fragility. In practice, Vietnam mitigates maritime sparsity through multimodal redundancy, including road, rail, and inland waterway connections that link ports to the hinterland (Banomyong et al., 2015; Nguyen & Notteboom, 2016). Therefore, the vulnerability identified here should be interpreted as maritime-topological vulnerability, not overall logistics system fragility.

4.1.2 Clustering coefficient

The Vietnam maritime network has an average clustering coefficient of 0.00578, which is markedly lower than values typically reported for regional port networks, which typically range from 0.1 to 0.3 (Ducruet & Zaidi, 2012). This indicates a very low level of local interconnectedness among ports. This suggests that ports connected to a common port are rarely connected to each other, reflecting a sparse network structure dominated by direct hub-to-port connections rather than dense local clusters.

While this result is consistent with the observed hub-and-spoke configuration of international liner shipping networks, it is also strongly influenced by limitations in the data scope (Ducruet & Notteboom, 2012). In particular, excluding Inland Waterway Transport (IWT) and barge-based feeder routes significantly affects the measured clustering coefficient. In Southern Vietnam, especially within the Cai Mep-Thi Vai-Ho Chi Minh port cluster, a substantial share of cargo is transshipped via barges operating along inland waterways. These feeder connections create dense local interlinkages that are not represented in the current network model (Nguyen et al., 2021).

Consequently, the reported low clustering coefficient should not be interpreted as evidence of weak functional integration within Vietnam's port system, but rather as a reflection of a network focused solely on deep-sea and international shipping routes. Inclusion of IWT and feeder services would likely increase local clustering, particularly in the southern port cluster, and provide a more accurate representation of Vietnam's multimodal maritime-riverine transport topology (Nguyen & Woo, 2022).

4.1.3 Average path length

The network exhibits an average path length of 9.642, meaning that, on average, nearly 10 connection steps are required to link any two ports within the network's largest connected component. This value is substantially higher than those typically reported for regional or liner-based maritime networks, which often exhibit small-world properties with average path lengths of 2.5 - 4.0 (Ducruet & Zaidi, 2012).

Rather than indicating a computational error, this elevated value reflects the network's structural characteristics and analytical scope. Specifically, the network comprises 75 globally distributed ports connected by only 146 shipping routes, resulting in very low density (0.0263) and a pronounced hub-and-spoke configuration. Many peripheral ports are connected to the network

exclusively through a small number of dominant hubs (Ho Chi Minh and Hai Phong). This thereby increases the number of intermediary steps required to traverse the network (Jiang et al., 2015).

Unlike dense regional shipping or liner service networks commonly analyzed in the literature, the present network captures Vietnam's extended global maritime connectivity, including long-distance and infrequently served routes. In such sparse, geographically dispersed networks, high average path lengths are a well-known and expected outcome of limited redundancy and weak lateral connectivity among peripheral nodes (Banomyong et al., 2015).

This result highlights structural vulnerability rather than inefficiency alone. A high average path length indicates a strong dependence on central hubs and limited alternative routing, suggesting that disruptions at key ports could significantly increase travel distances or fragment connectivity. Enhancing direct links among secondary ports or strengthening regional subnetworks could reduce path lengths and improve overall network resilience.

4.2 Port analysis

4.2.1 Degree centrality

Degree centrality measures how many ports are directly connected to a given port via shipping routes. This study presents the top five ports with the largest degree centrality. Ho Chi Minh is the most connected port, with 67 degrees. This suggests that the port has direct shipping routes to 67 other ports, implying that it plays a crucial role in the network. It also significantly influences cargo flow. Hai Phong ranks second, with a higher degree centrality of 61, which is also an important port in the network. However, this port is slightly less connected than Ho Chi Minh.

Vung Tau and Da Nang rank third and fourth, with 9 and 8 degrees, respectively. They have fewer connections than Ho Chi Minh and Hai Phong. This reflects a more regional or specialized role in the network, with fewer direct routes to other ports. Hong Kong and Busan rank fifth, each with a degree centrality value of six. Although Hong Kong and Busan are the world's major ports, their roles in the Vietnam shipping network are lower. This indicates that the network focuses more on Vietnam's domestic and regional connections than on global ones. However, they are still important in this network.

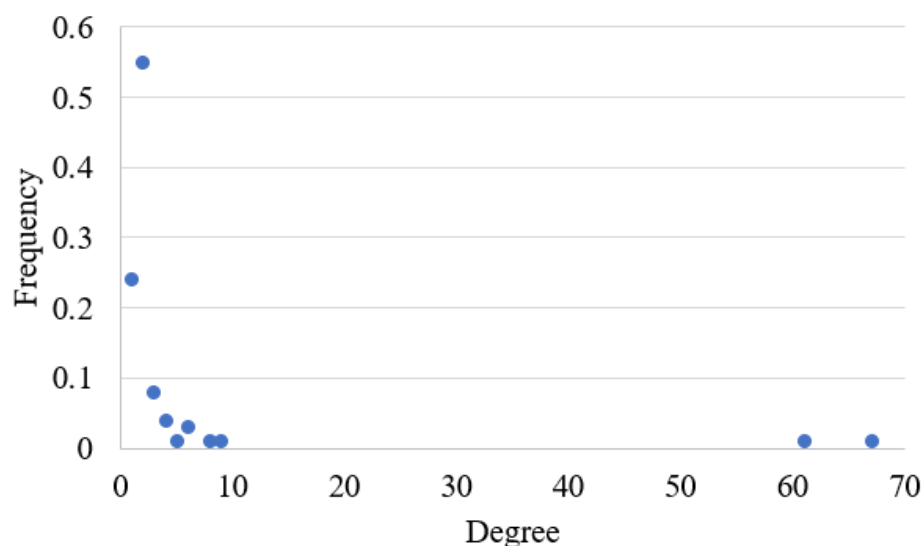


Figure 2 Degree distribution of ports.

Figure 2 illustrates the degree distribution of ports in the network. Most ports have a low degree, while a small number of ports have a high degree. This implies that the network exhibits a scale-free property, with some ports serving as highly connected hubs, whilst most ports have fewer

connections. 24 % of ports have one degree, and 55 % of ports have two degrees. Ports with 3 degrees account for 8.00 % of the total, and ports with four degrees account for 4.00 %. Only one port has five degrees, and two ports have six degrees. Interestingly, ports at 8 degrees, 9 degrees, 61 degrees, and 67 degrees are connected by the same proportion, 1.00 %. This indicates that a small number of ports are central ports or major hubs. A large number of low-degree ports suggests that most ports have fewer connections. They may serve niche shipping routes, be more regional than international, or act as hubs.

From the above, Ho Chi Minh and Hai Phong are key hub ports in the network, followed by Vung Tau, Da Nang, Hong Kong, and Busan. These ports play an important role in domestic and international shipping. They also facilitate significant trade volume. Vung Tau and Da Nang might serve as specific regional markets or specialized functions within the network. This contributes to Vietnam's overall maritime infrastructure. Low-degree ports could be interesting areas for expanding connectivity and becoming more competitive in global trade. The degree of centrality of ports helps inform strategic decisions about where to invest in infrastructure, improve connections, or develop new shipping routes to optimize the efficiency and effectiveness of the network.

4.2.2 Betweenness centrality

The top five ports with the largest betweenness centrality are Hai Phong, Ho Chi Minh, Vung Tau, Chennai, and Hong Kong, with values of 807.16, 609.83, 300.33, 84.00, and 33.50, respectively. This indicates that these ports play a critical intermediary role within the network. Hai Phong is a major port in Northern Vietnam, playing a crucial role in linking domestic and international trade routes. It has the largest betweenness centrality, reflecting that it is an important transit port for shipments within the network. It also facilitates the cargo flow between various destinations. Hai Phong's strategic location is near Hanoi, the capital city. This amplifies its importance in local and global shipping.

Ho Chi Minh is the largest city in Vietnam and is a significant economic hub. Ho Chi Minh City Port serves as the main gateway for trade in Southern Vietnam. Its high betweenness centrality indicates that it is a key intermediary in the network, handling a large volume of shipments. It also serves as a critical connection between Southeast Asia and the border trade market.

Vung Tau is another crucial port in Southern Vietnam, strategically located at the mouth of the Mekong River Delta. This makes the port an important access point for shipping routes. Its high betweenness centrality indicates that the port plays a critical role in linking various routes, especially those that involve coastal and inland waterway trade.

Chennai is a major port in India. The port is included in the analysis due to its connectivity to the shipping network in Vietnam. The port's betweenness centrality indicates that it serves as a regional hub, connecting South Asia with Southeast Asia and facilitating trade between the two regions.

Hong Kong is one of the busiest ports in the world and serves as a major transshipment hub in Asia. It is included in the analysis because this network analysis aims to highlight its role in linking Vietnam's shipping routes. Although this port's betweenness centrality is lower than that of the ports mentioned above, it remains an important port for international trade.

Table 2 presents the distribution of betweenness centrality for ports in the network. 90.67 % of ports have a betweenness centrality of 0, indicating that they are not on the shortest paths between other pairs of ports. These ports are not intermediary or transit points for marine traffic. They are also peripheral and less critical in linking the network. The very small number of ports has betweenness centrality greater than zero, with individual ports having high values. This shows a skewed distribution, indicating that the network is highly centralized: a few key ports handle most of the traffic and serve as the primary connections between other ports. Consequently, most ports depend on a small number of hub ports to access the wider network. This structure represents both vulnerability when hubs face disruption and efficiency under normal operating conditions.

Table 2 Betweenness centrality distribution.

Betweenness centrality	Number of ports	Share of total (%)
0	68	90.67
9.50	1	1.33
30.00	1	1.33
33.50	1	1.33
84.00	1	1.33
300.33	1	1.33
609.83	1	1.33
807.16	1	1.33

4.2.3 Strength centrality

Strength centrality reflects the frequency of sailing on shipping routes connecting ports. The top five ports with the highest strength centrality are Ho Chi Minh (683), Hai Phong (556), Singapore (418), Yantian (105), and Hong Kong (92). This indicates the ports' significant role in the network based on the volume and intensity of links. Ho Chi Minh and Hai Phong have the highest strength centrality, indicating that they are central hubs with substantial trade intensity and cargo volume. Therefore, these ports are well-connected and handle significant shipping traffic. This reinforces their importance in regional and global trade. The high centrality of Ho Chi Minh and Hai Phong also indicates that Vietnam is emerging as an important player in the network, likely due to its growing manufacturing base and strategic location in Southeast Asia.

Singapore ranks third in strength centrality, indicating its important role in global trade, with a large volume of cargo passing through it. Singapore's connectivity and the intensity of its trade routes contribute to its strategic importance in international shipping. Yantian and Hong Kong rank fourth and fifth, and are major gateways for exporting from the Pearl River Delta. This highlights the fact that they facilitate trade, particularly within Asia.

94.67 % of ports have a strength centrality of 1 - 100, which is relatively low, suggesting they are less significant or intense. Only four ports have strength centrality greater than 100, indicating they are the most significant in the network, with strong links or strong influence. Thus, they are the main hubs that handle substantial marine traffic or trade volume.

The extreme concentration of degree, betweenness, and strength centrality at Ho Chi Minh and Hai Phong aligns with findings from other Southeast Asian maritime networks (Nguyen & Kim, 2024; Wang et al., 2022). Benchmarking against these studies confirms that Vietnam's network is more centralized than those of Singapore or Malaysia, where secondary hubs play stronger intermediary roles.

Practically, this means that disruptions at these two ports, such as congestion, labor shortages, or climate-related flooding, can have disproportionate national impacts. Historical congestion at Cat Lai Port and seasonal flooding in northern ports provide empirical examples of such risks (Huu & Ngoc, 2021; Duc Thanh et al., 2021). At the same time, ports such as Da Nang and Vung Tau, which exhibit moderate centrality, represent viable candidates for strategic capacity expansion to reduce hub dependency.

5. Implications

The network analysis reveals several Vietnam-specific and empirically grounded implications for maritime policy, infrastructure planning, and network resilience. The implications below are

derived directly from the observed high average path length (9.642), extreme centrality concentration, low clustering coefficient (0.00578), and hub-dependent topology of Vietnam's maritime network.

5.1 Reducing excessive path length through targeted direct links

The unusually high average path length indicates that many ports are connected only through multiple intermediary hubs, primarily Ho Chi Minh and Hai Phong. This structure increases transit time, cost, and systemic vulnerability. To reduce excessive path length, policymakers should prioritize developing direct services between Vietnamese secondary ports (e.g., Da Nang, Quy Nhon, and Vung Tau) and major regional hubs in Northeast and Southeast Asia (e.g., Busan, Shanghai, Kaohsiung, and Singapore). Establishing selective direct routes would shorten network distances, reduce dependency on a single gateway, and improve Vietnam's position within regional supply chains.

5.2 Centrality-based investment prioritization to reduce network vulnerability

The strong concentration of degree, betweenness, and strength centrality at Ho Chi Minh and Hai Phong confirms that Vietnam's maritime network is highly centralized. While these ports are efficient gateways, their excessive centrality introduces a single point of failure risk. Investment strategies should therefore be differentiated. Resilience-oriented investments (redundant capacity, digital traffic management, climate adaptation) should be prioritized at Ho Chi Minh and Hai Phong to protect the core of the network. Capacity-expansion and connectivity investments should be targeted at secondary ports such as Vung Tau and Da Nang, which already exhibit moderate centrality and can realistically absorb spillover traffic during disruptions. This approach follows directly from the network's betweenness distribution, in which over 90 % of ports have zero betweenness and depend entirely on a few hubs.

5.3 Reinterpreting low clustering: the role of multimodal connectivity

The extremely low clustering coefficient does not imply weak functional integration of Vietnam's port system. It reflects the absence of Inland Waterway Transport (IWT) and barge-based feeder routes in the network model. In Southern Vietnam, especially within the Cai Mep-Thi Vai-Ho Chi Minh cluster, cargo movement relies heavily on barge transshipment. This finding implies that maritime policy should not be evaluated solely through deep-sea network metrics. Policymakers should adopt an integrated sea-river network planning framework in which investments in IWT terminals, barge capacity, and port-river interfaces are treated as core components of maritime resilience rather than peripheral infrastructure.

5.4 Strategic implications for Vietnam's role in regional maritime networks

The asymmetric connectivity observed in the network, with dense links to Asian hubs and limited direct connections to Europe and North America, suggests that Vietnam currently functions as a regionally embedded but globally dependent maritime node. Strengthening direct long-haul services from selected ports (e.g., Cai Mep-Thi Vai) while reinforcing regional feeder networks can help Vietnam transition from a hub-dependent exporter to a more autonomous regional gateway. This strategy aligns with Vietnam's long-term logistics development plans and its ambition to compete with established hubs such as Singapore and Port Klang.

5.5 Implications for future network-based policy design

The study demonstrates that network metrics can inform actionable policy decisions when interpreted correctly. High path length indicates where direct links are most needed; centrality metrics indicate where disruption risk is concentrated. Clustering results highlight the importance of multimodal integration. For Vietnam, incorporating network analysis into national port planning can

support evidence-based prioritization, ensuring that limited public investment yields maximum gains in efficiency, resilience, and competitiveness.

6. Conclusions

This study applied complex network analysis to investigate the structural characteristics, connectivity patterns, and port-level roles within Vietnam's maritime network. Based on a network of 75 ports and 146 shipping links, the findings reveal a highly sparse and centralized hub-and-spoke system. Ho Chi Minh and Hai Phong clearly dominate the network in terms of degree, betweenness, and strength centrality, functioning as indispensable gateways for both domestic and international maritime flows. While this configuration supports economies of scale and efficient long-distance trade, the extremely low network density, minimal clustering, and long average path length indicate a structural dependence on a limited number of hubs, exposing the system to elevated vulnerability in the event of disruptions.

By benchmarking Vietnam's network metrics against regional and international maritime studies, this research demonstrates that Vietnam's port system is more centralized and less redundant than those of established Southeast Asian hubs such as Singapore or Malaysia. The results, therefore, empirically contribute to the maritime network literature by providing one of the few Vietnam-specific, port-level analyses grounded in formal network topology rather than in throughput or policy indicators alone. Methodologically, the study illustrates how network measures can be used to identify hidden systemic risks that are not apparent from conventional port performance statistics.

From a policy and planning perspective, the findings highlight the need for a differentiated and resilience-oriented development strategy. While Ho Chi Minh and Hai Phong require continued investment in redundancy, climate adaptation, and operational reliability, secondary ports such as Da Nang and Vung Tau emerge as realistic candidates for selective capacity expansion and enhanced direct international connectivity. Reducing excessive reliance on a single gateway through targeted new services and regional subnetworks could shorten routing distances, improve system flexibility, and strengthen Vietnam's position within Asian supply chains. Importantly, the low clustering observed in the deep-sea network underscores the necessity of integrating inland waterway and barge-based feeder systems into maritime policy frameworks, particularly in Southern Vietnam.

Despite its contributions, this study has several limitations. The analysis adopts a static, single-layer network perspective based on scheduled services for a specific period, and therefore does not capture seasonal variation, dynamic route adjustments, or shock-induced network reconfiguration. Moreover, excluding hinterland transport and inland waterway connectivity may lead to an underestimation of functional integration and resilience at the national level. Future research should adopt a multilayer network approach that integrates maritime, river, rail, and road systems, as well as dynamic data across multiple years, to better assess Vietnam's port system performance under evolving economic, environmental, and geopolitical conditions. Such extensions would further enhance the value of network analysis as a decision-support tool for sustainable maritime and port development in Vietnam.

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Declaration of generative AI in scientific writing

The authors used ChatGPT (OpenAI) and Grammarly for assistance in conceptualization and grammar refinement of the manuscript. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and

conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRediT author statement

Maneerat Kanrak: Methodology; Formal analysis; Investigation; Writing – Original Draft; Writing – Review & Editing; Visualisation; Supervision. **Surakan Keawphinuek:** Conceptualisation; Data curation; Writing – Original Draft; Resources. **Nutchajarin Lohapan:** Formal analysis; Investigation; Writing – Original Draft. **Jing'en Zhou:** Data curation; Writing – Original Draft; Resources.

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