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Optimising the resilience of shipping networks to climate vulnerability

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ABSTRACT
Climate extremes are threatening transportation infrastructures and hence require new methods to address their vulnerability and improve their resilience. However, existing studies have yet to examine the climate impacts on transportation networks systematically rather than independently assessing the infrastructures at a component level. Therefore, it is crucial to configure alternative shipping routes from a systematic perspective to reduce climate vulnerabilities and optimise the resilience of the whole shipping network. This paper aims to assess the global shipping network focusing on climate resilience by a methodology that combines climate risk indicators, centrality analysis and ship routing optimisation. The methodology is designed for overviewing the climate vulnerability of the current and future scenarios for comparison. First, a multi-centrality assessment defines the global shipping hubs and network vulnerabilities. Secondly, a shipping model is built for finding the optimal shipping route between ports, considering the port disruption days caused by climate change (e.g. extreme weather) based on the climate vulnerability analysis result from the first step. It contributes to a new framework combining the global and local seaport climate vulnerabilities. Furthermore, it recommends changing shipping routes by a foreseeable increase in port disruptions caused by extreme weather for climate adaptation.

KEYWORDS
Climate resilience; climate change adaptation; shipping network; centrality analysis; maritime transport

1. Introduction

The global awareness for climate change impact in urbanisation is growing as their consequences become increasingly apparent. Seaports, which are crucial for human activities and lives, are exposed to different climate impacts, and they are commonly susceptible to storms and sea-level rise (Becker et al. 2013). In addition, Emergency Events Database (EM-DAT) has revealed that climate disasters have become more severe and frequent. From the 1970s to the 2010s, the damages caused by extreme hot weather has been increased by more than eight times, and those by storm and flooding have been increased by more than five times and eleven times, respectively (Panwar and Sen 2020). For example, during the 2017 Atlantic hurricane season, more than nine hurricanes were threatening North American and Caribbean areas. Until October, hurricanes, including the most powerful Maria, brought more than GBP 150 billion lost and 103 death toll in the US (Poo et al. 2018).

Therefore, researchers and practitioners have been interested in mitigating the climate change effects by reducing the carbon footprint of maritime transport. The footprints are managed by designing decision-making tools for speed control, berth scheduling, routing control for managing

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CO_2 emission. Also, such pollutants as SOx and NOx from ships are policed to be reduced (Kim and Seo 2019). On the other hand, some scholars analyse climate change adaptation by investigating suitable adaptation measures for specific ports or regions. More than 100 relevant journal papers were featured in 65 internationally recognised journals between 2005 and 2018 (Wang et al. 2020), and it is necessary to implement decision-making tools for integrating the knowledge from different studies (Poo et al. 2018).

Port cities, including seaports and city zones, are risky to climate change as they lie along the coastline or other low-lying areas. Forty per cent of the global population are settling within 100 km along coastlines, and port cities, such as Shanghai, Rotterdam, and Singapore, concentrate the populations. Thirteen of the 20 most populated world cities are along the coasts. Extreme weather events, supercharged by climate change, affected approximately 62 million people worldwide in 2018. In addition, these port cities are crucial components for global economies as the total world seaborne trade has been tripled in the last 30 years (Becker et al. 2013).

Furthermore, extreme weather events can disrupt different ports, and hence a cascading breakdown of the involved shipping network(s) because the port cities mentioned above play essential roles for transhipments (Liu et al. 2018). For example, the high-risk level of marginalised ports will have less impact on the global network than the low-level risk of centralised nodes and vice versa.

It is undeniable that climate change can bring new opportunities for regional development (e.g. arctic shipping and coastal trade growth) and financial prosperity (e.g. the growth of red wine production towards Southern Australia regions). However, it has been witnessed with solid evidence that more extreme weather and climate risks have occurred with an increasing occurrence likelihood and more severe consequences in the past 50 years.

Therefore, climate impact or vulnerability assessments are not enough to independently focus on seaports, known as nodes of an integrated shipping network. To address this demand, network vulnerability studies from a global shipping system perspective are needed to test the network resilience from the failures in different seaports (Laxe, Seoane, and Montes 2012).

The upcoming part of the paper is organised as follows. In Section 2, the literature review takes place, and it includes vulnerability, resilience, centrality assessment in maritime transportation, and global in-port climate vulnerability and adaptation indices. Section 3 presents the centrality assessment for a global shipping network to calculate regional seaport vulnerability index, and an overall seaport vulnerability index is presented in Section 4 presents a resilience-based shipping routing optimisation modelling, and Section 5 includes a discussion on reducing climate vulnerabilities with in-port and inter-port perspectives by analysing the findings in Sections 3 and 4 holistically. Finally, Section 6 concludes the manuscript by highlighting its limitations and contributions.

2. Literature review

The literature review is split into three parts. First, vulnerability and resilience are defined for climate risks on maritime transportation. Second, a review on centrality assessment on maritime transportation is presented. Third, climate vulnerability assessments for port cities are presented.

2.1. Vulnerability and resilience

Transportation systems, including global shipping ones, usually have a network character. Therefore, other networks can refer to the resilience and vulnerability properties. Vulnerability is the adverse reaction of the system when they are facing hazardous events (Liu et al. 2018). So, it is an empirically proven concept for setting indices and measuring the risks faced by port cities in different aspects, including physical, social, and economic factors (Wang et al. 2020). By integrating all the factors, the levels of climate resilience can be obtained. Resilience can be split into two forms: the resistance strength of the whole system to threats and the recovery ability from disruptions (Proag 2014).

The increasing focus on vulnerability and resilience studies is ignited by the boost of adverse climate extreme events on transportation systems. Figure 1 shows the number of articles with the keyword string of '(transport or transportation) resilience' and '(transport or transportation) vulnerability', collected from keyword string search results of articles on the Web of Science year by year from 1996 to 2021 on 25 March 2022 by the authors using the analysis approach of Zhu and Liu (2020). Both trends are steadily increased in the last two decades (Poo et al. 2018). While vulnerability-related articles increased about 50% in 2016 compared to 2015, resilience papers grow faster than vulnerability research. However, there is still no complete concept on the detailed definitions of resilience and vulnerability at the conceptual level (Mattsson and Jenelius 2015; Liu et al. 2018). Therefore, the relevant concepts from climate disaster management, transportation system, and engineering are collected to formulate the definitions of climate resilience and vulnerability of global shipping networks in this paper.

The Intergovernmental Panel on Climate Change (IPCC) focuses on climate change issues and solutions. It presents the dimensions of climate vulnerability and climate resilience. In the climate change context, vulnerability is the state or general quality of being harmed by extreme weather events (IPCC 2014). Dispositions take place as an internal nature of the affected regions. Resilience is described as the ability of the state or a part of the system to expect, engage with, and recover from the impacts of extreme weather events efficiently and effectively, including the possibilities in improving and restoring the existing system (Reggiani, Nijkamp, and Lanzi 2015). Then, resilience is coping with one more component, a fundamental sense of adaptive capacity, than vulnerability. It includes the positive features of reducing climate change and the risk posed by a particular hazard (IPCC 2012). The relation between the fundamental concepts of climate vulnerability and resilience is demonstrated in Figure 2 by IPCC.

Scholars on transport systems have more and broader discussions on vulnerability and resilience compared to climate disaster management. Mattsson and Jenelius (2015) and Reggiani, Nijkamp, and Lanzi (2015) show comprehensive related articles and provide various definitions of vulnerability and resilience in transportation systems. It is necessary to reduce the vulnerability and strengthen the transport system's resilience to obtain a better reputation and mitigate risk transfer costs as a source of competitive advantage (Kwak, Seo, and Mason 2018). Topological-based and system-based studies of transport networks are different fundamental types of related studies. The main advantage of topological-based studies is that they require less data input. However, the straightforwardness of the method makes the result less realistic. Then, a system-based approach is

Figure 1. Trend of the transport vulnerability-related and resilience-related articles [Source: Web of science].

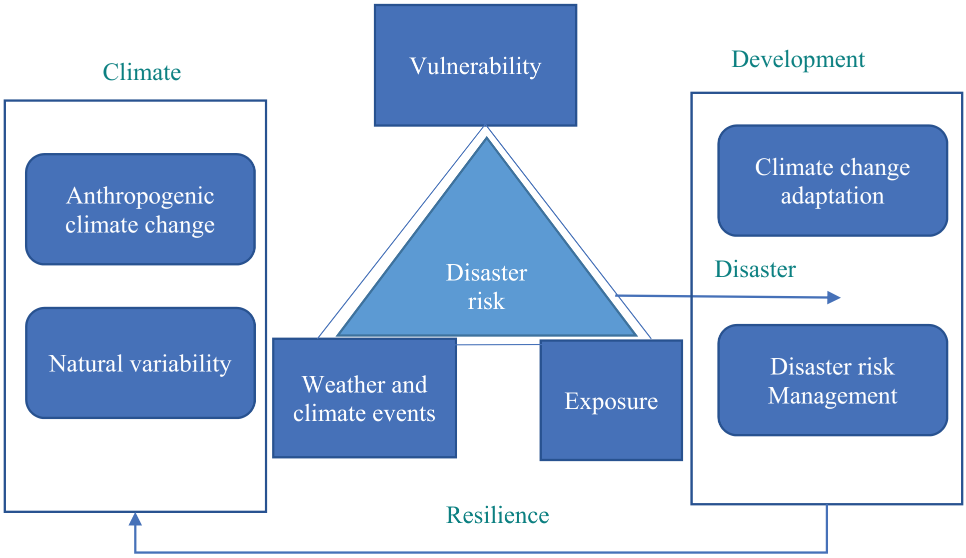

Figure 2. Key concepts of climate vulnerability and resilience by intergovernmental panel on climate change [Source: IPCC].

an alternative way for climate disaster management. Even though this approach provides comprehensive findings, this method is hungry for more data input such as travelling flows and related costs (Mattsson and Jenelius 2015). Furthermore, resilience requires including some socio-technical perspectives representing adaptation abilities (Becker et al. 2013). Furthermore, Reggiani, Nijkamp, and Lanzi (2015) prove that connectivity is another core concept as transportation systems are similar to other networking systems.

The network vulnerability is also assessed for a shipping network, in which the analysis is driven by network robustness (Liu et al. 2018). It can also be described as the network robustness as the first resilience approach, known as resistance. Therefore, two terms for seaports or port cities in a global shipping network are described, 'regional vulnerability' (Taylor 2012) and 'local vulnerability' (Knoop et al. 2012). 'Regional vulnerability' is inversely proportional to the high centrality of a network (Laxe, Seoane, and Montes 2012). 'Local vulnerability' refers to the climate vulnerability experienced by the port infrastructures and operation stability. It can be known as the stability of the node facing extreme weather events (Zhang et al. 2016).

2.2. *Centrality assessment in maritime transportation*

Centrality assessment is commonly used for assessing the connectivity of shipping networks to provide a comprehensive reference for promoting balanced and sustainable development (Liu et al. 2018; Wu et al. 2019). Mccalla, Slack, and Comtois (2005) provide a case study for container ports in Caribbean areas focusing on transhipment hubs. In 2009, Hu and Zhu (2009) investigated the global shipping system by different measurements with network perspectives: links mean container liners and nodes mean ports. Ducruet et al. analyse the changes of possible hub ports in the Atlantic and Northeast Asia regions (Ducruet, Lee, and NG 2010), and then the results provide the evolution of hub ports and global shipping lines. In the same year, Kaluza et al. (2010) analyse the shipping networks in three categories: container liner ships, dry bulk carriers, and others. Then, Ducruet and Zaidi (2012) use the centrality assessment to define the relative position for the global network by different centralities in 2012. In the same year, Laxe, Seoane, and Montes (2012) assess variations in the maritime transportation network upon the crisis, and Montes, Seoane, and Laxe (2012) compare how general and containerised traffic has been added from 2008 to 2011. In 2015, Li, Xu, and Shi (2015) define 25 geographical areas for analysing global shipping networks based on the new dividing areas. Then, Tovar, Hernández, and Rodríguez-déniz (2015) make a case study to evaluate main Canarian ports on accessibility and connectivity. In 2016 and 2019, two case studies analyse the centrality and connectivity of the Maritime Silk Road (Zong and Hu 2016; Wu et al. 2019). Liu et al. (2018) pioneer the analysis of vulnerabilities in shipping networks by centrality assessment. There are various tailored regional centrality assessments for specific regions, and therefore, it witnesses an increasing demand for a standardised framework for the systematic centrality assessment of global shipping networks. More importantly, the use of centrality indicators for the vulnerability analysis of maritime transport systems are still largely scanty in the current literature (Mansouri, Lee, and Aluko 2015).

2.3. Climate vulnerability assessment for port cities

Local vulnerability analysis is a more common topic compared to the regional one. Climate change vulnerability assessment and adaptation planning are trendy research topics. There are multiple focuses, including planning and operation, on transportation analyses (Sierra et al. 2017) and coastal areas analyses (Monioudi et al. 2018) They are different in terms of scales and dynamics to reflect different extreme weather events and social-economic factors. Most of them use a case study method for assessment and constrain the relevant studies to a single port or region assessment (Wan et al. 2018).

Hanson et al. (2011) and Briguglio (2010) provide an international insight for climate vulnerability studies, and they analyse the 136 port cities selected by the United Nations (UN). City selection is constrained to coastal cities with more than a million population. The global distribution of the selected port cities is centralised in Asia (38% or 52 ports). For the country level, China (10% or 14 ports) and the USA (13% or 17 ports) are the most concentrated countries.

The outcomes of the previous studies provide a comparative analysis on vulnerability and adaptation to assess climate risk by finalising the four categories of port cities. After mentioning the diversity in climate risks from different ports, it is necessary to provide a global shipping network analysis for assessing global climate resilience. The centrality assessment is used for the global vulnerability measurement, and the optimisation model is developed for estimating the new shipping routes based on the climate forecast.

The manuscript provides a method to foresee the future climate vulnerability on global shipping and forecasts future routing changes to fill the research gap. Therefore, a centrality assessment for regional seaport vulnerability analysis and a shipping routing optimisation model are provided in Section 3 and Section 4, respectively

3. Centrality assessment for regional seaport vulnerability analysis

Based on the graph theory, a network has two key components, which are nodes and links. The indices and categories set up by Briguglio (2010) define a regional vulnerability index for each of the investigated seaport cities (Liu et al. 2018). To identify the regional vulnerability index for each port city, an advanced multi-centrality indicator which is designed by Wu et al. (2019) to measure the importance, as known as hub nature, of ports by a more comprehensive analysis is applied in this paper to provide a global shipping network analysis for each of the 136 selected ports by UN for the first time as the following steps designed by Poo and Yang (2020):

(I) Data collection of global liner shipping
(II) Modelling the global shipping network
(III) Multiple centrality assessment
(IV) Validation of the results
(V) Comparative analysis for regional vulnerability and local vulnerability

(VI) Providing seaport climate vulnerability index

3.1. Data collection of global liner shipping

Structuring a suitable global maritime transportation network is crucial for evaluating the shipping network's climate vulnerability (Pape 2017). Therefore, it is necessary to set up a criterion to match seaports and their port cities before further investigation. The criterion is that a seaport within a 2-hour circle (i.e. about 200 km travelling distance) from a city can represent a city's shipping demand. Then, the related information for the seaport is checked on Google Maps. For example, Tema Harbour is close to Accra in Figure 3, and Thilawa Port is close to Yangon in Figure 4 (Google 2019).

After linking some rural ports to the associated cities, there are two mismatched port pairs. Using the above criterion, Hangzhou and Rabat can be represented by Ningbo and Casablanca ports, respectively, by the 2-hour circle rule. The 136 designated port cities are therefore reduced to 134 agglomerations.

The existing shipping route is used to construct the global shipping network, as shipping accounts for 80% of total exports and imports by volume globally (Mansouri, Lee, and Aluko 2015). Maersk shipping line data, in July 2019 from the official website, is chosen for sketching the unique shipping network. Maersk is chosen because it is the largest liner shipping company in the world, and it is sufficient to provide a worldwide shipping network for constructing the network. July data is chosen as Baltic Dry Index (BDI), which reveals that it presents more average traffic values than other months. The chosen port cities are undertaken for throughput data collection, and twenty transit ports are also selected by Poo and Yang (2020) for utilising the network. It is because they are essential transhipment ports for the whole global shipping network. Six agglomerations do not link with routes, including Sapporo, Nampo, Natal, Maceio, Dhaka, and Belem. 2397 linkages are in the networks between all the chosen 134 ports and the other 20 transit ports. Thus, the network involving 154 ports needs to be formed and modelled.

3.2. Modelling the global shipping network

For assessing different centralities, UCINET 6, which is commonly used in Window, is chosen for analysing social network data (Borgatti, Everett, and Freeman 2002), and it is used in the coming analysis. For creating a network by using the tool, an adjacency matrix $A_{n\times n}$ is created, a_{ij} is defined

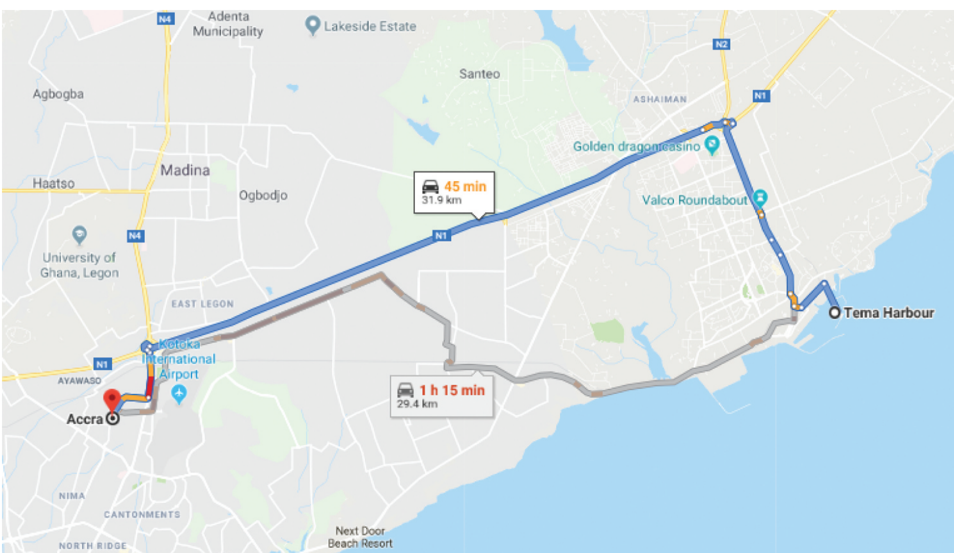

Figure 3. Google map recommended route from Accra city centre to Tema Harbour in Ghana.

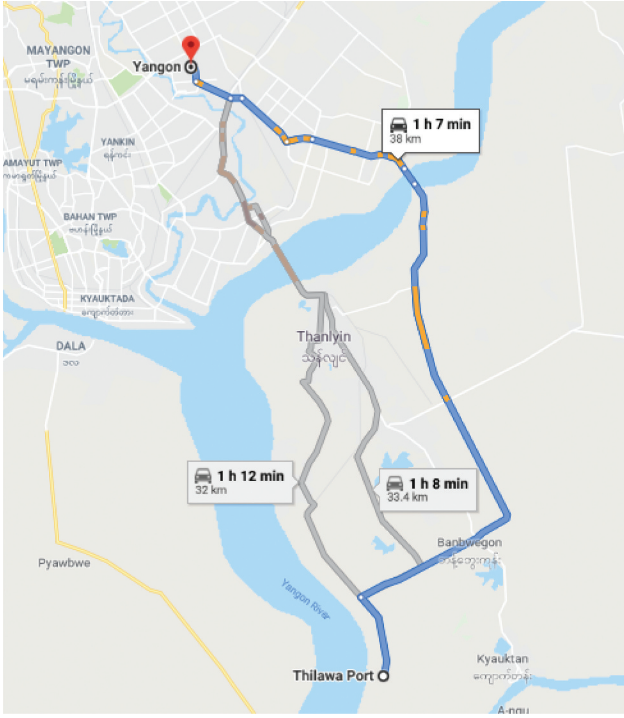

Figure 4. Google map recommended route from Yangon city centre to Thilawa Harbour in Myanmar.

by the route from port i to port j. $a_{ij} = 0$ means no linkage, and $a_{ij} = 1$ means otherwise. After inputting all a_{ij}, the network is constructed as shown in Figure 5. Due to the large number of nodes involved in the network, the centrality distribution of the nodes is visualised in Figure 5, while the corresponding centralities of all the nodes are provided in Table 1 and Table 2 in Section 3.3.

3.3. Multiple centrality assessment

The port centrality analyses in this section are firstly investigated different centralities, and they represent the modelled global shipping network. The results are used to analyse the relationship between the 154 port cities. Degree centrality is defined as the total amount of linkages directly connecting to a port. The lesser the degree value of a port, the further away it is from other ports, and vice versa. The degree centrality of port i can be computed by Equation (1):

$$D_i = \sum_{j}^{n} \delta_{ij} \quad (1)$$

where n represents the total ports within the network and δ_{ij} presents the corresponding links between port i and j.

Closeness centrality means the shortest distances from all different ports to a target port, which indicates the centralised level of the target port in the network. The lesser the closeness centrality value, the more challenging it is to reach other port destinations within the network, and vice versa. The closeness centrality of port i is between zero and one and can be calculated by Equation (2):

$$D_{C_i} = \frac{n-1}{\sum_{j}^{n} \delta_{ij}} \quad (2)$$

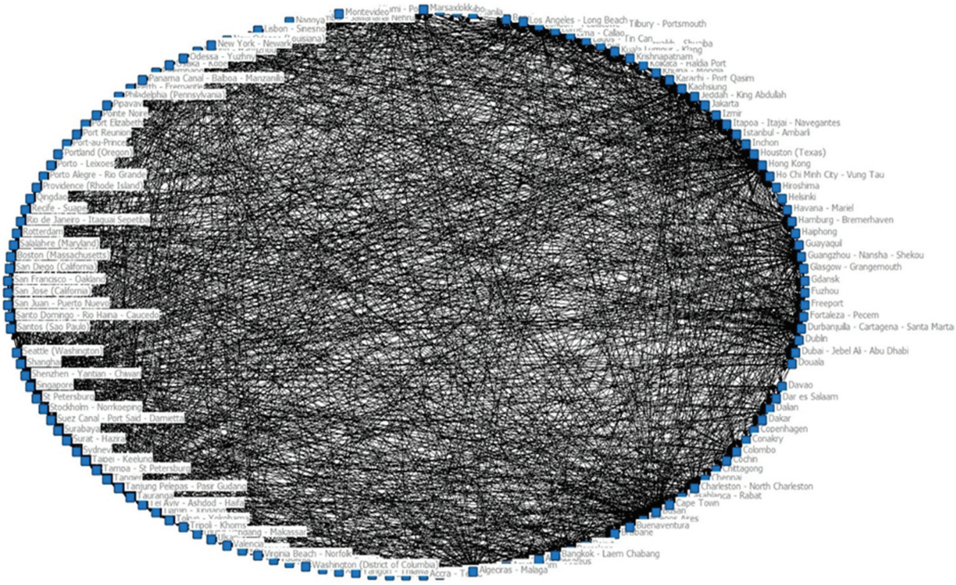

Figure 5. Global shipping network for centrality assessment.

where n−1 represents the total numbers of ports in the system except the target port and δ_{ij} presents the number of links between port i and j. In other words, it is the shortest distance between port i and j. Betweenness centrality describes whether the target port is in the middle of port s and t, which can reflect the ability of the node to be a hub in the network which can be calculated by using Equation 3:

$$B_{C_i} = \sum_{s,t \in v \; s,t \neq i} \frac{\delta(s,t|i)}{\delta(s,t)} \tag{3}$$

where $\delta(s,t|i)$ is the number of times the port s and t passes the port i with the shortest distance and $\delta(s,t)$ is the total count of the shortest paths for port s and t.

To measure the overall impact of the 154 ports, a scoring system is designed by combining all three different indicators for further investigation and the Borda Count method I being used for such integration (Liu et al. 2018). The Borda Count method can accumulate different centrality properties into one rank while embedding easiness and visibility into the calculation process. The three different scores are firstly given by the three different centralities as shown in Equations (4) to (6):

$$S_D(i) = n + 1 - \text{Rank}_D(i) \tag{4}$$

$$S_C(i) = n + 1 - \text{Rank}_D(i) \tag{5}$$

$$S_B(i) = n + 1 - \text{Rank}_B(i) \tag{6}$$

The ranks of degree and closeness consider two directions together, and then two sets of results are collected based on two directions, inbound and outbound. The three independent scores have equal weights. By obtaining the overall rank, the importance of a port to the global shipping network can be presented, and the overall rank score can be obtained by Equation (7):

$$S_o(i) = S_D(i) + S_C(i) + S_B(i) \quad (7)$$

Network efficiency and network average clustering coefficient are the chosen indicators for evaluating the finding of the multi-centrality indicator (Ducruet and Zaidi 2012; Liu et al. 2018; Wu et al. 2019). The clustering coefficient of an indicator is the density of its open neighbourhood. A graph $G = (P, E)$ consists of a set of vertices P and a set of edges E between them. An edge e_{ij} connects two vertices, v_i and v_j. The neighbourhood N_j for a vertex p_j is assumed as its directly connected neighbours, as shown in Equation (8). k_i is the number of nodes, N_i as a vertex and $|N_i|$ as a neighbour. Therefore, the local clustering coefficient for corresponding graphs is stated as Equation (9), and the network average clustering coefficient is presented as Equation (10).

$$N_i = \{v_i : e_{ij} \in E \vee e_{ji} \in E\} \quad (8)$$

$$M_i = \frac{|\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\}|}{k_i(k_i - 1)} \quad (9)$$

$$\bar{M} = \frac{\sum_{i=1}^{n} M_i}{n} \quad (10)$$

Network efficiency is defined average distance or degree between two nodes. L_{ij} is the distance from node i to j, and the network efficiency is shown as Equation (11).

$$\bar{L} = \frac{\sum_{i \neq j} L_{ij}}{n(n-1)} \quad (11)$$

The ranks based on Equations (4) to (6) are shown in Table 1.

Table 1 Degree Rank, Closeness Rank, Betweenness Rank for the global shipping network

Shanghai scores the highest in both degree rank and closeness rank, and Ningbo and Singapore are second and third, respectively. Singapore is at the top of the betweenness rank, and Shanghai and Ningbo score the second and third. Also, there are some important ports, including Rotterdam, Hong Kong, Guangzhou, and Busan, and they are both top 10 in three different ranks. By integrating all three ranks in Table 1, the multi-centrality ranking is shown in Table 2.

Table 2 Multi-centrality

All the top 20 ports are ranked and categorised regarding their locations in Table 2, and there are half of them in East Asia. As a result, the obtained centrality scores can be used to present the regional vulnerabilities of all chosen agglomerations as described in Section 2. These regional vulnerability scores will be analysed with local vulnerability data set jointly in Section 4 for rationalising ship routing to configure the optimal climate resilience of the whole shipping network.

3.4. Validation of the centrality analysis results

For verifying the port ranking in Table 2, the port nodes are removed one by one for a time from the network. By eliminating a node within the network and observing its effect on the network efficiency, the global influence of the port can be obtained. Network efficiency and network clustering coefficient are chosen to validate the result of the multi-centrality ranking in Section 3.3. The top 20 agglomerations are taken away from the network accordingly and independently to observe the changes, as shown in Figure 6. The agglomerations are listed from left to right according to their rank. The declines of both indicators are significant for Shanghai, Singapore, and Ningbo. The drops in network cluster coefficients are from 2.090%

Table 1. Degree rank, closeness rank, betweenness rank for the global shipping network.

Degree Rank	Agglomeration	Closeness Rank	Agglomeration	Betweenness Rank	Agglomeration
1	Shanghai	1	Shanghai	1	Singapore
2	Ningbo	2	Ningbo	2	Shanghai
3	Singapore	3	Singapore	3	Ningbo
4	Busan	4	Busan	4	Panama City
5	Guangzhou	5	Guangzhou	5	Busan
6	Shenzhen	6	Shenzhen	6	Rotterdam
7	Hong Kong	7	Hong Kong	7	Hamburg
8	Qingdao	8	Rotterdam	8	Hong Kong
9	Panama City	9	Qingdao	9	Guangzhou
10	Rotterdam	10	London	10	New York
11	New York	11	Panama City	11	Shenzhen
12	London	12	New York	12	Dubai
13	Hamburg	13	Hamburg	13	Qingdao
13	Dubai	14	Mumbai	14	London
15	Barranquilla	15	Santos	15	Barranquilla
16	Mumbai	16	Dubai	16	Baltimore
17	Santos	17	Barranquilla	17	Tianjin
18	Tokyo	18	Virginia Beach	18	Surabaya
19	Xiamen	19	Miami	19	Houston
20	Tianjin	20	Houston	20	Jeddah
20	Houston				
20	Miami				
20	Virginia Beach				

Table 2. Multi-centrality ranking for the global shipping network.

Rank	Final score	Region	Agglomeration
1	461	East Asia	Shanghai
2	458	East Asia	Ningbo
2	458	East Asia	Singapore
4	452	East Asia	Busan
5	444	East Asia	Guangzhou
6	440	East Asia	Hong Kong
7	439	East Asia	Shenzhen
8	437	South America	Panama City
8	436	Europe	Rotterdam
10	426	East Asia	Qingdao
11	425	Europe	Hamburg
11	425	North America	New York
13	418	Europe	London
14	414	West Asia	Dubai
15	403	South America	Barranquilla
16	397	West Asia	Mumbai
17	394	South America	Santos
18	390	East Asia	Tianjin
19	389	North America	Houston
20	382	East Asia	Xiamen

to 3.284%, and those of network efficiencies are from 0.832% to 1.313%. After that, the network cluster coefficient is reduced gradually from the fourth to the twentieth, and network efficiency changes are less significant as any individual impact is not more than 0.788%.

Even the sequences of network efficiency and network cluster coefficient have shown slight variation, and they still witness the same result that the higher the multi-centrality rank, the higher the importance/impact the port has to the global shipping network. Therefore, the multi-centrality ranking is validated, and the result is used as the regional vulnerabilities to combine with local seaport vulnerability data for optimal shipping network resilience in the next section.

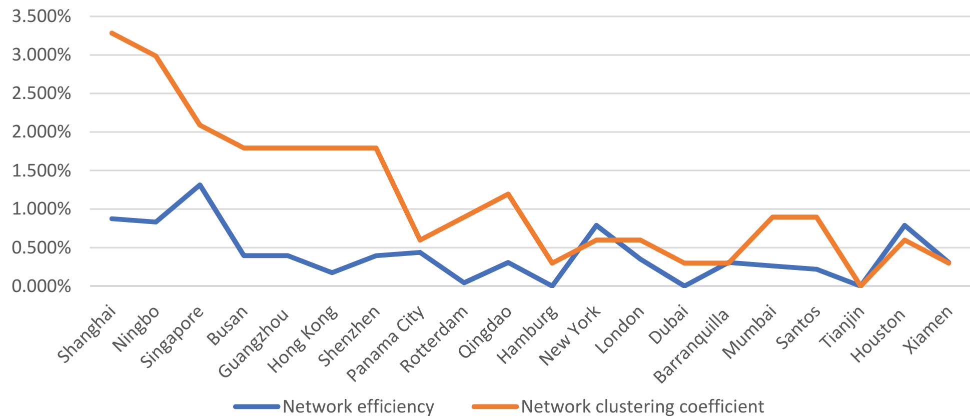

Figure 6. Drop of network efficiency and network clustering coefficient by removing an agglomeration.

3.5. Comparative analysis for regional vulnerability and local vulnerability

To systematically understand the climate change influences on the global shipping network, regional vulnerability and local vulnerability are introduced to observe the difference between the influences inside and outside a port city. By assessing the centrality of seaports, the regional vulnerability of each seaport is assessed. Therefore, the local vulnerabilities of all 154 port cities are assessed in this section. The indices and categories set up by Briguglio are used for defining the local vulnerability index for each agglomeration (Briguglio 2010). He refers to the exposed population and assets from Nicholls et al. (2008) on climate vulnerability and the UN Conference on Trade and Development data on the GDP per capita index, assumed to proxy adaptation abilities. By juxtaposing them, the extent to which climate change impacts each seaport can be assessed comprehensively.

Based on Briguglio (2010) finding, port cities can be defined into four categories, 'lowest-risk' countries, 'managed-risk' countries, 'mismanaged-risk' countries and 'highest-risk' countries. Multi-centrality ranking is implied to all agglomerations. For the six-port cities without any connection, Dhaka, Belem, Maceio, Natal, Nampo, and Sapporo, rank the lowest in every single-centrality ranking, and thus the final one. The complete comparative analysis is shown in Table 3. The total score is the sum of all seaports scores with the same category, and the total rank is the sum of ranks of all seaports with the same category. Average scores and ranks of four categories are defined as dividing total scores and ranks by the number of seaports, and they are used to describe the different distribution patterns between local and regional vulnerability.

Table 3 Multi-centrality scoring and ranking of four local vulnerability categories

There is just one port city of Category 1 in the top 20. The average rank of Category 1 port cities is the lowest in terms of climate vulnerability throughout all four categories. The only top 20 agglomeration of Category 1 is Singapore. On the other hand, there are eight Category 4 in the top 20, and the average rank value of Category 4 port cities is the second highest. The top 20

Table 3. Multi-centrality scoring and ranking of four local vulnerability categories.

Category	Vulnerability	Adaptation	Number of seaports	Number of top 20	Average score	Average rank
Lowest-risk (1)	Lower than mean	Higher than mean	32	1	171.125	79.594
Managed-risk (2)	Higher than mean	Higher than mean	27	8	256.259	49.788
Mismanaged-risk (3)	Lower than mean	Lower than mean	38	3	177.079	69.615
Highest-risk (4)	Higher than mean	Lower than mean	39	8	216.436	63.410

agglomerations of Category 4 are from China and India. Therefore, regional vulnerabilities are not related to local vulnerabilities. However, some critical highest-risk port cities should put more effort into climate change adaptation. On the other hand, some lowest-risk port cities can take more essential positions of the global shipping network. Therefore, a vulnerability assessment, accompanying both local and regional vulnerabilities, is needed to observe the potential climate vulnerabilities of seaports.

3.6. Seaport climate vulnerability index

A new index, seaport climate vulnerability index-V, is designed for measuring the climate vulnerability by integrating local vulnerability index-X and regional vulnerability index-Y. In addition, V is developed by jointly connecting X and Y in Equation (12). In terms of the two datasets, one is from multi-centrality assessment in Section 3 and the other from Briguglio (2010). X is referred from the adaptation score X_a and vulnerability score X_v defined by Briguglio (2010). The original local adaptability index X_o is defined by X_a subtracting by X_v in Equation (13). The lowest local adaptability index $X_{o,min}$ among 134 seaports, excluding 20 transhipment ports from total 154 ports, is used to adjust all X_o to positive values and transform the data to X in Equation (14). The overall rank score $S_o(i)$, defined in Equation (7), is used in Equation (15). The maximum overall rank score among 134 seaports is used to normalise the scores into Y.

$$V = X \times Y \tag{12}$$

$$X_o = X_a - X_v \tag{13}$$

$$X = 1 - \frac{X_o - X_{min}}{2} \tag{14}$$

$$Y = \frac{S_o(i)}{S_o(i)_{max}} \tag{15}$$

After defining the seaport climate vulnerability index, all 134 seaports can be assessed by Equations (12) to (15). The result is shown in Table 4. The order of agglomeration in Table 4 is different from that in Table 3. The cities in Category 4 have occupied the top 10 from China, India, Vietnam, and Thailand. On the other hand, the cities with high centrality in Category 1 and Category 2, such as Rotterdam, Hong Kong, and New York, rank out of the top 10.

Table 4 Seaport climate vulnerability index scoring and ranking

4. Shipping routing optimisation model

A shipping network model with all 154 seaports has been designed to find the optimum shipping route between ports based on their climate vulnerability indices and categories. Changes in route selections are obtained upon more port disruption days caused by extreme weather by referencing the data from Briguglio (2010). The top 20 ports, known as hubs, are found in the centrality assessment are exclusively tested on changes to look at the sensitivity on shipping networks between continents.

4.1. Problem formulation

The formulas are listed by the adoption of notations in Section 4.1.1. The equations are listed in Section 4.1.2, and the assumptions are presented in Section 4.1.3.

Table 4. Seaport climate vulnerability index scoring and ranking

Rank	Agglomeration	Score	Rank	Agglomeration	Score	Rank	Agglomeration	Score
1	Shanghai	0.800	46	Montevideo	0.301	91	Marseille	0.148
2	Guangzhou	0.773	47	Lome	0.301	92	Seattle	0.147
3	Mumbai	0.770	48	Singapore	0.288	93	San Juan	0.142
4	Shenzhen	0.698	49	Dakar	0.285	94	Perth	0.139
5	Ningbo	0.681	50	Baltimore	0.285	95	Auckland	0.138
6	Xiamen	0.580	51	Jeddah	0.281	96	Cochin	0.136
7	Qingdao	0.580	52	Houston	0.280	97	Athens	0.134
8	Tianjin	0.568	53	Haiphong	0.275	98	Brisbane	0.130
9	Ho Chi Minh City	0.557	54	Dar es Salaam	0.270	99	Khulna	0.126
10	Bangkok	0.526	55	Cape Town	0.262	100	Algiers	0.123
11	Rotterdam	0.483	56	Surat	0.256	101	Zhanjiang	0.122
12	Karachi	0.479	57	Santo Domingo	0.253	102	Palembang	0.115
13	Dubai	0.470	58	Lima - Callao	0.252	103	Montreal	0.111
14	Abidjan	0.465	59	Yantai	0.244	104	Adelaide	0.098
15	New York	0.464	60	Los Angeles	0.241	105	Boston	0.093
16	Lagos	0.455	61	Fuzhou	0.239	106	Naples	0.093
17	Dalian	0.438	62	Izmir	0.238	107	Havana	0.090
18	Miami	0.426	63	Luanda	0.235	108	Ulsan	0.090
19	Accra	0.425	64	Sydney	0.230	109	Mogadishu	0.085
20	Buenos Aires	0.425	65	Casablanca	0.230	110	Porto	0.085
21	Hong Kong	0.417	66	Maputo	0.229	111	Amsterdam	0.078
22	Rio de Janeiro	0.412	67	Philadelphia	0.226	112	Tel Aviv	0.077
23	Tokyo	0.411	68	Lisbon	0.226	113	Hiroshima	0.075
24	Busan	0.407	69	Nagoya	0.225	114	Maracaibo	0.074
25	London		70	Salvador	0.222	115	Port-au-Prince	0.073
26	Panama Canal		71	Alexandria	0.212	116	San Jose	0.072
27	Yangon		72	Kuala Lumpur	0.211	117	Providence	0.066
28	Jakarta		73	St Petersburg	0.207	118	Ujung Pandang	0.064
29	Chittagong		74	Recife	0.206	119	Tripoli	0.060
30	Hamburg		75	Barcelona	0.204	120	Glasgow	0.053
31	Chennai		76	San Francisco	0.202	121	Copenhagen	0.043
32	Guayaquil		77	Vancouver	0.201	122	Portland	0.042
33	Santos		78	Melbourne	0.200	123	Kuwait	0.041
34	Istanbul		79	Conakry	0.197	124	Dublin	0.041
35	Taipei		80	Fukuoka	0.192	125	Washington	0.039
36	Virginia Beach		81	Vitoria	0.189	126	Dhaka	0.038
37	Porto Alegre		82	Beirut	0.188	127	San Diego	0.029
38	Barranquilla		83	Tampa	0.186	128	Helsinki	0.028
39	Odessa		84	Douala	0.180	129	Nampo	0.028
40	Visakhapatnam		85	Benghazi	0.178	130	Stockholm	0.027
41	Osaka		86	Fortaleza	0.166	131	Natal	0.020
42	Kolkata		87	Manila	0.162	132	Maceio	0.020
43	Durban		88	Wenzhou	0.158	133	Belem	0.019
44	Surabaya		89	Inchon	0.152	134	Sapporo	0.009
45	New Orleans		90	Davao	0.150			

4.1.1. Notations

The following notations are adopted in the following mathematical model.

Sets:

N Set of ports;

K Set of transhipments, including no transhipment;

Indices:

i, j Set of transhipments, including no transhipment;

k Indices of transhipment stages;

a Indices of starting port;

b_k Indices of transhipment port;

c Indices of ending port;

Parameters:

Z	Total time;
Z_{ij}	Total time from port i;
T_{ij}	Travel time from port i to port j;
TT	Total travel time;
S_i	Service time at port i;
ST	Total service time;
S_i	Service time at port i;
S_i^b	Basic service time at port i;
I_i	Climate risk (CR) of a territory;
M	Very large positive constant;

Decision variables

x_{ij}	1 if directly travels from port i to port j; 0 otherwise;
$\emptyset_i$	Auxiliary variable associated with port i used for the sub-tour elimination constraint;

4.1.2. Equations

$$z = \sum_{i \in N} \sum_{j \in N \backslash \{i\}} z_{ij} \tag{16}$$

$$z_{ij} = \min_{k \in K} \left(TT_{ij,k} + ST_{ij,k} \right) \forall i \in N, j \in N \backslash \{i\} \tag{17}$$

subject to

$$TT_{ac,k} = T_{ab_1,k} + T_{b_1 b_2,k} + T_{b_2 b_3,k} + \cdots + T_{b_k c,k} \ \forall a, b_1, b_2, \cdots, b_k, c \in N \tag{18}$$

$$ST_{ac,k} = S_{a,k} + S_{b_1,k} + S_{b_2,k} + \cdots + S_{b_k,k} + S_{c,k} \forall a, b_1, b_2, \cdots, b_k, c \in N \tag{19}$$

$$S_i^b = S_i \ \times I_i \forall a, b_1, b_2, \cdots, b_k, c \in N \tag{20}$$

$$\sum_{j \in N \backslash \{i,a,c\}} x_{ij} \le 1 \forall i \in N \backslash \{a, c\} \tag{21}$$

$$\sum_{i \in N \backslash \{j,a,c\}} x_{ij} \le 1 \forall j \in N \backslash \{a, c\} \tag{22}$$

$$x_{ij} \in \{0, 1\} \forall i \in N \backslash \{a, c\}, j \in N \backslash \{i, a, c\} \tag{23}$$

$$x_{ii} = 0 \forall i \in N \backslash \{a, c\} \tag{24}$$

$$\emptyset_j = \emptyset_i + 1 - M\left(1 - x_{ij}\right) \forall i \in N \backslash \{a, c\}, j \in N \backslash \{i, a, c\} \tag{25}$$

$$\emptyset_i \ge 0 \forall i \in N \backslash \{a, c\} \tag{26}$$

Equation (16) is the objective function, which describes the total time of all delivery routes between the set of ports. Equation (17) represents the objective function of every single route, and the two components are travel time and service time. Constraint (18) defines the total travel time between the starting node, the k transhipment nodes, and the ending node, and Constraint (19) represents the whole service time between the starting node and the k transhipment nodes, and ending node. Constraints (20) define the service time of a node based on the climate performance index.

Constraints (21) and (22) limit all nodes being visited only once or none in each period. Constraint (23) states the decision variables in the binary system for routing, and Constraint (24) ensures no internal movement within the same port. Constraint (25) is the sub-tour elimination constraint. Constraint (26) controls all the auxiliary variables larger than zero.

4.1.3. Assumptions

Some possible solutions can minimise Z, known as the accumulated shortest paths between all nodes. Thus, several assumptions take place for setting up the model:

- The service time in the transhipment node is fixed, independent of cargo loading and unloading times;
- The travel time between the starting node, transhipment nodes, and ending node is fixed;
- The minimum service time is one day;
- Port disruption implies a static delay and is represented in basic service time.

4.2. Results

Two types of assessments are used to present the results. Hub assessment is used to investigate the busy port cities of the whole global shipping system, and global overall network assessment is used to overview the changes of the global shipping networks.

4.2.1. Hub assessment

The busiest port cities, mentioned in Table 2, are further investigated as they contribute as key routes for the whole global shipping system. Then, the changes among all origin-destination (OD) pairs of 20 ports listed in Table 2 are recorded. First, S_i^b is given one day and runs the programme as the baseline. Then, S_i^b is given the values of three days in the short future and five days in the long future climate projection scenarios, and the positive and negative changes are recorded. It is set to be three and five days because, for example, Shanghai gives more than 2.5 disruption days per year in August (Zhang and Lam 2015). Thus, for assessing the global shipping hub changes, it is possible to investigate the changes of main shipping routes rather than just counting up the changes of transhipment hubs. 190 OD pairs, with two directions, drive the hub assessment, and the result is listed in Table 5. First, it is noticed that some nodes remain unchanged, including Shanghai, Shenzhen, Santos, and Houston. Then, some nodes have provided higher port calls in the near and long future, including Panama City, Rotterdam, Mumbai, and Tianjin. Except for Singapore Hong Kong, the port calls of remaining agglomerations have slightly dropped less than 12%. Hong Kong has a significant drop of 15.6% for the near future, and the counts of Singapore have a significant drop in 31.5% and 16.4%, respectively. The assessment provided an insight that the hub calls may not be affected by climate changes as there is no correlation between climate risk and changes. Therefore, it is concluded that some key routes are essential even if there are more disruptions in the future. Furthermore, it is necessary to investigate the whole shipping network changes by another assessment.

Table 5 Hub assessment summary

4.2.2. Global overall network assessment

11,935 OD pairs in between 154 port cities are assessed, and the program evaluates the whole network. Basic service time is altered to observe the possible route changes for the whole network by the same method used in the previous section, as shown in Table 6 and Table 7. The total number of transhipments in the network is dropped by 14.22% in the near future and 19.12% in the long future. Then, some agglomerations with higher climate risks, such as

Table 5. Hub assessment summary.

Agglomerations	Current count	Count in the near future	Change	Count in the long future	Change
Shanghai	38	38	0.0%	38	0.0%
Ningbo	41	38	−7.3%	39	−4.9%
Singapore	73	50	−31.5%	61	−16.4%
Busan	42	38	−9.5%	42	0.0%
Guangzhou	48	45	−6.3%	45	−6.3%
Hong Kong	45	38	−15.6%	43	−4.4%
Shenzhen	38	38	0.0%	38	0.0%
Panama City	38	39	2.6%	38	0.0%
Rotterdam	41	47	14.6%	41	0.0%
Qingdao	39	38	−2.6%	38	−2.6%
Hamburg	53	51	−3.8%	53	0.0%
New York	39	38	−2.6%	39	0.0%
London	41	40	−2.4%	41	0.0%
Dubai	44	41	−6.8%	44	0.0%
Barranquilla	63	56	−11.1%	60	−4.8%
Mumbai	56	72	28.6%	64	14.3%
Santos	38	38	0.0%	38	0.0%
Tianjin	41	45	9.8%	41	0.0%
Houston	38	38	0.0%	38	0.0%
Xiamen	41	39	−4.9%	41	0.0%

Table 6. Rank of agglomerations with less port calls.

	Changes in the near future		Changes in the long future	
Rank	Agglomerations	Changes in transhipments	Agglomerations	Changes in transhipments
1	Kuala Lumpur	−530	Kuala Lumpur	−686
2	Shenzhen	−354	Busan	−420
3	Busan	−292	Santos	−379
4	Santos	−230	Shenzhen	−318
5	Dubai	−209	Hamburg	−310
6	Shanghai	−204	Dubai	−277
7	Barranquilla	−200	Shanghai	−258
8	Hamburg	−190	Panama City	−232
9	Ningbo	−184	Miami	−229
10	Miami	−184	Barranquilla	−214

Table 7. Rank of agglomerations with higher port calls.

	Changes in the near future		Changes in the long future	
Rank	Agglomerations	Changes in transhipments	Agglomerations	Changes in transhipments
1	Singapore	378	Singapore	739
2	Tokyo	185	Barcelona	257
3	Barcelona	138	Tokyo	225
4	Lisbon	63	Jeddah	112
5	Hong Kong	56	Lisbon	93
6	Yangon	50	Naples	54
7	Jeddah	46	Yangon	28
8	Naples	15	Athens	25
9	Montreal	5	Tel Aviv	19
10	Vancouver	4	Hong Kong	11

Kuala Lumpur and Shanghai. Alternatively, some agglomerations with lower climate risks, such as Tokyo and Singapore, obtain more transhipment passing through them. It presents that the climate change risks affect the influences of the ports in the future.

5. Discussion

The discussion can be split into two directions by defining global and local climate resilience. Local vulnerability has attracted more research interests in the past decade. More tailor-made adaptation plans for port cities should be designed for high-income and low-income port cities. Also, climate change will profoundly impact urban infrastructure systems, ecosystem services, and built environment. Hence, it could exacerbate existing social, economic, and environmental drivers. If the vulnerability assessment is considered in the scale mentioned by IPCC, agglomerations need to experience different extreme weathers, including extreme temperatures and extreme precipitation. Therefore, a more comprehensive international vulnerability assessment can be designed to assess the local vulnerability through the global shipping network.

From the analysis, it is evident that regional vulnerability is as crucial as local vulnerability. It is possible to reduce local vulnerability by new adaptation technologies. However, it is essential to enhance the resilience of the network by tackling regional vulnerability involving alternative routes. Weather-based routing optimisation, based on the methodology in this study, can provide recommendations for sailing under changing global weather forecasts. In other words, while each port can use their own resources to tackle their climate vulnerability at a local level, the transport authorities in the countries can use the global network resilience results to guide their investment being more rational. By evaluating network efficiency and network clustering coefficient properties in Section 3.4, decentralisation can increase system reliability, scale, and privacy. Therefore, the lowest-risk agglomerations mentioned in Section 4.1 should provide more routes to the global shipping network. However, geography is destiny as some port cities are necessary because of high populations and trades, such as Shanghai and New York. Also, straits and canals are crucial for cargo transhipments, and Singapore and Panama City are important port cities for global shipping and world trading. Therefore, the changes in 'geography' may be possible to diminish the vulnerability of the shipping network.

Also, new strategic shipping routes can be planned to reduce regional vulnerability, based on constructing new branch in the global shipping network model provided in the study. Furthermore, it has made more strategic contributions by being able to take into account future weather forecasting into the model to realise optimal shipping routes for today and future. Shipping companies can effectively use the model to proactively arrange their shipping routes and schedule to gain the best climate resilience for ensure their operation safety against climate change. For example, Arctic shipping routes, which are still mostly covered by sea ice, may be available for sailing during a part of the year, and lowest-risk port cities include some high latitude port cities, Montreal, Helsinki, Sapporo, Ulsan, Stockholm and Glasgow. Therefore, new shipping routes can be more critical and decentralise the world shipping network. Also, building up a new canal is a way to reduce the reliance on the existing straits and canals. For example, the Nicaragua canal can bear the workload and importance of the Panama Canal, and the Kra Canal can connect the Gulf of Thailand and Bay of Bengal. In addition, some new crucial port cities will take shape if the canals are constructed. Increasing the connections within the global shipping network can also be considered decentralisation to reduce the pressure of existing transhipment ports. Furthermore, the seaport climate vulnerability index can simulate the comprehensive decisions on shipping routing problems by combining the impact of both local and regional vulnerability.

6. Conclusion

This paper presents new ideas (i.e. simultaneous consideration of local level vulnerability and global network level resilience in Sections 3 and 4) and methods (i.e. climate risk based ship optimisation model in Section 4) for measuring the maritime transportation system's recent and future climate risks by integrating climate risk indicators, centrality assessment, and a shipping routing model.

Also, it shows the possible changes in shipping routing. Finally, except for reducing local vulnerability, some further regional assessments can be done as a new concept, climate-adapted decentralisation.

However, it is not enough to assess the climate resilience for seaports as climate sensitivity and adaptability are not assessed due to the lack of data. This manuscript uses secondary datasets holistically to form a new database for analysis, including shipping data from a shipping company and climate vulnerability data from other studies. For comprehensive assessment in future, if secondary data becomes unavailable, new climate vulnerability data can be collected through the interviews involving seaports and liner companies worldwide. Also, local vulnerability includes just climate threats from storming and sea-level rise in this article. Therefore, climate exposure is not fully assessed, and a more comprehensive global climate resilience framework is needed. The local climate vulnerability can be calculated by taking into account exposure, sensitivity, and vulnerability holistically. Hence, the vulnerability of each port can be more precisely expressed. Furthermore, regional vulnerability assessment with shipping routing modelling can focus on different regions and shipping companies, including fleet capacity and economic profit. Therefore, this paper pioneers a solution to integrating climate adaptation and routing modelling to enhance climate resilience in global shipping networks.

The proposed shipping network models can be tailored to tackle emerging risks of high impact on global shipping networks (e.g. COVID-19), in which both local node level risk and global network level resilience are required to be tackled simultaneously. More specifically, in terms of the methodology innovation, apart from assessing the climate risks for the shipping network, it can also be used to evaluate other issues or influences, such as COVID-19, if we can find related datasets or indicators for the nodes of a network being assessed. Therefore, their applications within the climate risk and resilience areas should not constrain their generality in other contexts.

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