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How to assess the resilience of the European container shipping network from a national perspective: A data-driven cascading failure model

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The European Container Shipping Network (ECSN) is highly interconnected due to the advanced water transport systems across European countries. Such highly connected feature makes the network complicated and vulnerable to disruptions, particularly to cascading failures triggered by extreme events like the COVID-19 pandemic and regional conflicts. A fundamental step in mitigating these failures involves simulating load redistribution, yet a robust modelling approach tailored to Europe's specific needs remains undeveloped. To fill these gaps, this study aims to develop an innovative framework for resilience analysis against cascading failures, designed to rigorously assess the impact of port disruptions on the resilience of individual countries within the ECSN. The proposed framework integrates a port importance assessment model, a multi-target cascading modelling approach, and three resilience metrics, all analysed from a national perspective. The detailed analysis and case studies across 172 European ports reveal that disruptions at the Port of Rotterdam could significantly compromise the network's resilience. To enhance the ECSN's resilience, this study recommends two primary strategies: expanding interregional strategic cooperation and maintaining adequate reserve capacity at critical ports. This study provides valuable insights for port and logistics stakeholders in managing unforeseen risks and in the planning and development of port infrastructure.

Keywords: Resilience analysis, European container shipping network, Cascading failure

1. Introduction

As a crucial subsystem within the global maritime transport system, the European Container Shipping Network (ECSN), established by European ports and their connected shipping routes, is characterised by dense connectivity, high throughput, and strategic geographical positioning (Lu et al., 2024). For instance, beginning in 2019, the COVID-19 pandemic resulted in labour shortages and severe congestion

at major European ports, such as Rotterdam, Antwerp, and Hamburg, leading to a substantial decline in the efficiency of cargo transshipment. In March 2021, the Suez Canal blockage halted the passage of hundreds of ships, compelling some to reroute around the Cape of Good Hope in Africa. Consequently, European exporters faced an acute shortage of empty containers due to extended transportation cycles and reduced efficiency in global container turnover. In addition, the ongoing geopolitical tensions stemming from the

Russia-Ukraine conflict have further destabilised the shipping market. Containerised freight rates from Europe to Asia and North America have undertaken significant turbulence, and container shipping networks are now grappling with greater risks of delays and regional uncertainties. To date, these events have caused not only short-term shocks to transportation and costs within European logistics systems but have also triggered long-term strategic adjustments by businesses and governments (Cao et al., 2024). These include strengthening supply chain resilience, enhancing risk management practices, and diversifying transportation strategies.

Theoretically, in shipping networks, resilience is defined as the ability of ports to absorb, adapt to, and recover from disruptions while maintaining essential functions and minimising economic and operational impacts. Broadly, resilience is characterised by two stages: response (the ability to adjust operations in reaction to changing conditions such as congestion and delays) and recovery (the process of restoring network performance) (Gu et al., 2023). Key factors influencing resilience include network topology, connectivity, redundancy, and the effectiveness of risk management strategies.

Existing research in this domain primarily focuses on resilience assessment from both static and dynamic perspectives, with a particular focus on the response phase. For instance, Xu et al. (2020) analysed the static topological characteristics and modularity of global liner shipping networks, highlighting their small-world economic properties and modular community structures. From a dynamic perspective, methods such as node deletion and cascading failure simulations have been applied to assess resilience. Liu et al. (2023), for example, developed three attack strategies based on centrality topology metrics (degree centrality, closeness centrality, and connection capacity) to simulate port failures in European port networks under different scenarios. Their study highlighted the high dependency of the European shipping market on key ports such as Rotterdam, Antwerp, Hamburg, and Piraeus.

Cascading failures, as a dynamic process triggered by disruptions, have also been studied to explore changes in resilience. In practical shipping operations, the closure or reduced capacity of a port can lead to cargo delays and the

rescheduling of shipments. To mitigate these delays, shippers or carriers may reroute cargo to alternative ports to maintain schedules or facilitate subsequent multimodal transport. However, if the redistributed loads exceed the reserve capacity of these alternative ports, new congestion arises, causing further redistribution of excess loads. Consequently, the core challenge in modelling cascading failures lies in developing appropriate load redistribution mechanisms to simulate and minimise potential damages to shipping network resilience (Cao et al., 2025).

As the earliest attempt, Motter and Lai pioneered a load redistribution model with node capacity constraints to model the propagation behaviour of cascading failures (Motter and Lai, 2002). Based on this foundation, various studies have emerged but a common gap in these studies is the oversimplified redistribution basis. For instance, Xu et al. (2022) proposed an average redistribution rule based on link addition policies. Bai et al. (2023) designed a redistribution method solely based on port size. Xu et al. (2024) developed an iterative redistribution strategy by considering distance. It can be found that the existing cascading failure models typically rely on a single criterion for target selection and load determination. This simplification indeed can reduce calculation complexity but limits its implications.

In general, the current resilience research and cascade failure modelling techniques in shipping reveal several gaps to address. This study by providing pioneering solutions to them, makes new contributions as follows:

- 1) Resilience assessment: To enable a more context-specific analysis, this study systematically quantifies the potential damage to the ECSN from disruptions at different ports by measuring overloaded ratios and reductions in efficiency. This approach provides metrics for both structural and functional resilience. Furthermore, these metrics are aggregated at the level of individual European countries, offering a practical reference for risk management and strategic planning in shipping networks from a national perspective.

- 2) Cascading failure modelling: This study proposes a load redistribution model based on a comprehensive port importance assessment. The importance of 172 European ports is evaluated by considering their size, connectivity, and strategic

location. Based on these evaluations, the proposed load redistribution model aligns more closely with the practical needs of the shipping industry.

The remainder of this study is structured as follows: Section 2 introduces the methodology, including resilience assessment metrics and the load redistribution model. Section 3 presents the data, analysis results, and scenario analysis. Section 4 concludes the paper.

2. Methodology

2.1. Cascading Failures Modelling

This study employs the load redistribution modelling approach to investigate the cascading failure within the ECSN. Triggered by unexpected events (e.g., strikes, accidents and extreme weather), disruptions act as catalysts that cause the affected port or shipping company to redistribute loads to neighbouring ports, thereby propagating failures throughout the network.

Firstly, the ECSN is defined as a directed weighted network G , where the load between any two ports i and j is e_{ij} . For port j , its weight is defined as $W_j = \sum_{i,j \in G} e_{ij}$. In practice, the weight value of a port is characterised by its throughput. Additionally, to maintain a safety backup, ports generally reserve a certain amount of security redundancy (also called reserve capacity). Therefore, for any port, its capacity can be expressed as:

$$C_j = \alpha \times W_j \quad (1)$$

where α indicates the redundancy ratio and typically $\alpha \geq 1$.

Furthermore, modelling cascading failures involves addressing two critical aspects: 1) the selection of targets in the load redistribution process, and 2) the determination of load redistribution ratios. To provide a robust and practical foundation, this study utilises a Borda counting method to assess the importance of ports within the ECSN. Specifically, after defining the network structure, this study ranks each port according to its degree value, weight, and betweenness centrality. Scores are then assigned based on each port's ranking for these attributes, and the scores for all three attributes are summed. For example, among the 172 ports included in this study, if port i has the highest degree value, weight and betweenness centrality, its importance

score would be $172+172+172=516$, denoted by I_i . This comprehensive assessment integrates port connectivity, size, and strategic location, aligning with the holistic considerations of stakeholders in practice (Cao et al., 2025).

Subsequently, in this study, it is assumed that port i has multiple neighbouring ports, i.e., ports with links connecting them. The closest K neighbouring ports are selected as redistribution targets. During the propagation of cascading failures, redistribution targets may have one of three states: 1) Failed. The port experiences a disruption, rendering its infrastructure non-functional; 2) Overloaded. The port's total load, including redistributed load, exceeds its capacity, leading to congestion despite intact infrastructure; 3) Normal. The port is neither failed nor overloaded. Therefore, the selected targets cannot be failed or overloaded ports. This strategy not only considers the practical requirement of minimising redistribution costs by focusing on nearby ports but also prevents exacerbating pressure by avoiding already overloaded ports.

Finally, this study adopts an adaptive load redistribution mechanism to meet operational needs. For failed ports, all their loads are redistributed; for overloaded ports, only the excess load beyond their capacity is redistributed. The load received by port j from port i at time step t is mathematically expressed as:

$$D_{ij}(t) = \begin{cases} W_i \times P_{ij}(t), & t = 0 \\ (L_i - C_i) \times P_{ij}(t), & t > 0 \end{cases} \quad (2)$$

Here, $P_{ij}(t)$ represents the proportional distribution of loads, calculated as $P_{ij}(t) = I_j(t) / \sum_{j \in K} I_j(t)$. The load of port j is then updated as: $L_j(t+1) = L_j(t) + D_{ij}(t)$. If the load of port j exceeds its capacity after the update, its state is marked as "overloaded".

The cascading failure process continues until one of two conditions is met: 1) all ports in the network are either overloaded or failed, signifying the collapse of the ECSN, or 2) no further loads remain to be redistributed, indicating that all loads have been absorbed. Once the process ends, all failed and overloaded ports are removed, and resilience metrics are calculated.

2.2. Resilience Assessment

In this study, two resilience indicators, namely the overloading rate and efficiency, are proposed. Specifically, within the ECSN, if specific nodes

(ports) or edges (routes) fail due to disruptions (e.g., strikes, accidents, or adverse weather conditions), these failures can trigger cascading effects, including congestion or overload at other ports. Consequently, one of the most direct quantitative indicators is the node Overload Rate (OR) within the network at a given time. The calculation is represented in Eq. (3), as follows:

$$OR = \frac{N_o}{N} \quad (3)$$

where N_o denotes the number of overloaded ports and N is the total number of ports. For a given network, a higher OR indicates greater damage to the network's structural resilience caused by cascading failures. Similarly, for a given country n , the cascading failures triggered by disruptions, whether occurring domestically or externally, can be assessed based on their impact on the country after propagation. In this case, the port overloading rate OR^n for country n is defined as the number of overloaded ports within the country divided by the total number of ports in the country.

In addition to the overloading rate, efficiency is a critical metric for characterising the functional performance of a network. As a weighted network, the ECSN exhibits varying levels of load across different links. Links with higher demand and cargo flow are of greater importance, and their disruption can have a more profound impact, as evidenced by events like the Suez Canal blockage. Accordingly, this study employs the weighted efficiency E to evaluate the functional resilience of the ECSN after cascade failure propagation. For any two ports i and j , the distance between them is denoted as d_{ij} , and the load between these two ports is assumed to be k times the number of standard units. If the load of one standard unit is expressed as one standard edge, there will be k standard edges between the two ports. After this normalisation for the whole network, the subgraphs G' can be extracted, where each subgraph only contains one standard unit of link. The standard efficiency calculation method is applied to each subgraph, and the efficiency sums of all subgraphs are aggregated to compute the weighted efficiency value for the entire network (Zhou et al., 2019), as shown in Eq. (4):

$$E = \sum_{G'} \frac{1}{N(N-1)} \sum_{i,j} \frac{1}{d_{ij}} \quad (4)$$

In the ECSN, ports that fail or become overloaded during cascading failures are treated as

functionally constrained nodes, leading to a decline in network efficiency. At this point, the network efficiency degradation rate (ER) is calculated as follows:

$$ER = \frac{E - E'}{E} \quad (5)$$

where E' indicates the remaining efficiency after the propagation of cascading failures. A larger ER indicates that the event has caused greater damage to the functional resilience of the network. Similarly, the intra-country efficiency degradation rate ER^n will be used to evaluate the extent to which a cascading failure, triggered by a port disruption event, damages the efficiency of the shipping network within the country n , as shown in Eq. (6):

$$ER^n = \frac{E^n - E'^n}{E^n} \quad (6)$$

where E^n denotes the original efficiency of country n and E' is the remaining efficiency after cascading failures. In this study, introducing this state-level assessment provides a more targeted and strategic analysis by shifting the focus from individual port disruptions on overall network to their cumulative impact on national resilience. Particularly, this evaluation measures the degradation degree of resilience, allowing for the identification of ports whose failures have the greatest impact on national resilience, thereby enabling national policymakers to prioritise investments and interventions that enhance the robustness of the overall system.

3. Results

3.1. Data

To construct the ECSN, this study utilises European container service route data spanning from 2020 to the second quarter of 2023. This data is sourced from the BlueWater Reporting Application Server (www.bluewaterreporting.com). The database covers 172 ports and 913 port-to-port service routes across Europe. For each service route, the database provides detailed information on the origin and destination ports, along with quarterly carrying capacities and average sailing times (Cao et al., 2024). Based on this information, this study constructs the ECSN as a directed weighted network structure, as illustrated in Fig. 1.

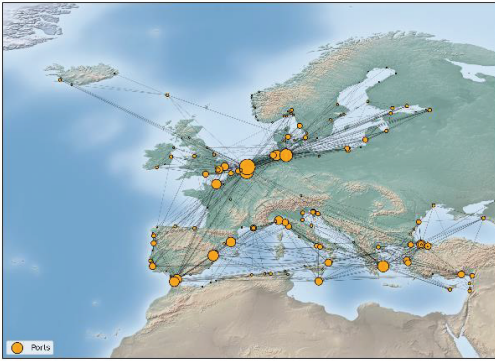


Fig. 1. The European Container Shipping Network

Subsequently, based on the port importance assessment method presented in Section 2.2, this study ranks the 172 ports in the ECSN. The top five ports and their importance scores are shown in Table 1. Notably, the ranking results align closely with real-world observations. As the largest port in Europe and one of the busiest globally, the Port of Rotterdam ranks first among the 172 ports in terms of size, degree value, and betweenness centrality. This highlights its critical importance in terms of throughput capacity, connectivity, and geographical location.

Table 1. Top 5 ports ranked by the importance assessment.

Port	Importance score
Rotterdam	516
Antwerp	512
Hamburg	508
Piraeus	506
Bremerhaven	503

3.2. Resilience Assessment

In this study, each of the 172 ports is sequentially set as an initial failure node. The failure of each port triggers a series of cascading failures based on the load redistribution method. Upon completion of the process, the OR and ER of the ECSN are recorded to quantify the impact of cascading failures caused by different ports. In this context, the top 5% of ports with the greatest impact on structural resilience (causing the most port overloads) and functional resilience (causing the greatest network efficiency degradation) are highlighted in Fig. 2 and Fig. 3, respectively. The

port names are denoted by their port codes ($\alpha=1.2$).

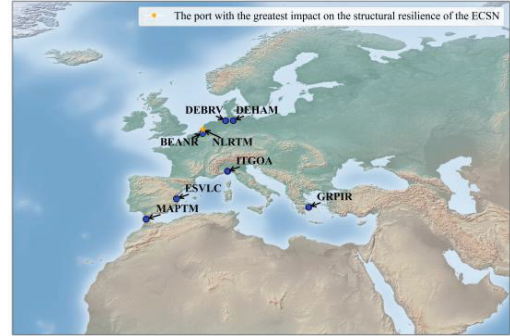


Fig. 2. The distribution of ports based on the OR

Overall, the resilience of the ECSN is susceptible to disruptions at critical ports. Failures at certain key ports can rapidly compromise the network's resilience in both structural and functional terms. One striking example is the Port of Rotterdam, where cascading failures triggered by its disruption result in the highest port overloads and the most severe network efficiency degradation. Ranked first in the port importance assessment conducted in this study, the Port of Rotterdam plays a pivotal role in the European shipping system. Situated in Rotterdam in the southern Netherlands, it is a major logistics and transport hub. With its deep-water berths, advanced logistics facilities, and well-integrated rail, road, and inland waterway transport networks, the port functions as a critical cargo distribution centre and facilitates multimodal transport across Europe. Consequently, a failure at the Port of Rotterdam triggers cascading failures that propagate rapidly through the ECSN. This is evident in the need to tranship loads to alternative ports. However, variations in port capacity mean these redistributed ports are often overwhelmed, leading to unsustainable cargo pressure and overloading.

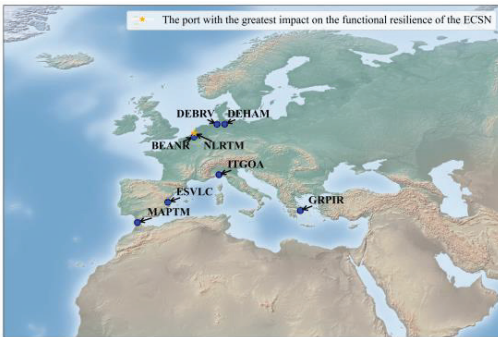


Fig. 3. The distribution of ports based on the ER

In addition to this, the stability of a number of other ports is also crucial for maintaining ECSN resilience. Ports with significant impacts on ECSN resilience include the Port of Antwerp, the Port of Hamburg, the Port of Bremerhaven, the Port of Valencia, the Port of Genoa, and the Port of Piraeus. A common characteristic of these ports is their strategic advantage in terms of throughput capacity or geographical location. For instance, the Port of Piraeus, situated south of Athens, Greece, acts as a vital gateway between Europe and Asia, linking the Balkans and Mediterranean Sea routes. The unique geographical position of this port establishes it as a key node within the ECSN. Many other ports and regions rely on this hub for transshipment or logistical connections. Disruptions at this port force shipping lines to divert to alternative ports to maintain their schedules, creating traffic imbalances and subjecting the alternatives to heightened pressure. These alternative ports often lack the capacity to handle sudden surges in cargo flow, resulting in congestion and reduced operational efficiency. Our findings, on one hand, comprehensively address the above implications, and on the other hand, show their advantages in quantifying the resilience and importance of key ports, which makes new contributions to the development of rational countermeasures ensuring the resilience of ECSN in a cost-effective way.

3.3. Sensitivity Analysis

In this study, the ports of Rotterdam and Antwerp are identified as the top two ports in the ECSN based on the port importance assessment. Furthermore, cascading failures triggered by disruptions at these two ports cause the most significant damage to the resilience of the ECSN. To better analyse the effect of the redundancy

ratio α in the cascade failure model in this study, as well as to offer more practical implications, the Port of Rotterdam and the Port of Antwerp are selected as case studies. In this section, in addition to exploring the sensitivity relationship between redundancy ratio α and cascading failure propagation, the impact is further explored separately at the country level. The findings can help validate the proposed model and results in part when benchmarking them with the reality/common practice.

Specifically, the Port of Rotterdam and the Port of Antwerp are input as failed ports in the cascade failure model described in Section 2.2. The node states of the ECSN are updated upon completion of the cascade failure process, and the OR and ER are calculated using Eq. (3) and Eq. (5), respectively. The results are displayed in Fig. 4 and Fig. 5. In the visualisation, each country is shaded from darker to lighter colours to indicate the degree of internal port damage, ranging from high to low. Overall, as the ECSN redundancy ratio α increases, the resilience of the shipping system improves, reflected by simultaneous reductions in OR and ER across most countries. This is also in line with the reality.

For the ports of Rotterdam and Antwerp, the cascading failures they trigger place increased pressure on numerous ports within the ECSN. Following a disruption, cargo flows are redistributed to neighbouring ports, such as the Port of Hamburg and Bremerhaven, which may face handling capacity shortages. As shown in Fig. 4 and Fig. 5, at low redundancy ratios (e.g., at $\alpha=1.1$), most European countries experience higher OR and ER values. Notably, the Netherlands, where the Port of Rotterdam is located, suffers severe impacts on its logistics, transport, and related industries. Neighbouring countries such as Germany, France, and Belgium, which depend heavily on the Port of Rotterdam for the import and export of goods, are also significantly affected in terms of economic activity. However, as α increases, the impact on countries further from the ports of Rotterdam and Antwerp diminishes substantially. With the exception of the UK, France, Spain, Portugal, Belgium and the Netherlands, OR and ER drop to almost 0 for other countries when $\alpha=1.3$, suggesting a significant mitigation of the damage caused by failures in the ports of Rotterdam and Antwerp. For those surrounding countries, the

results underscore the importance of optimising supply chain strategies to reduce reliance on single ports.

Cascading failures triggered by the disruption in Port of Rotterdam

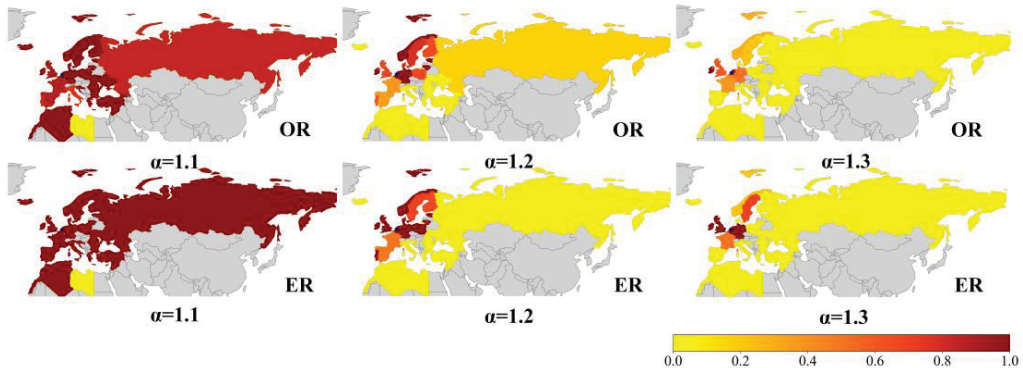


Fig. 4. The impact of cascading failures triggered by the Port of Rotterdam on different countries with changes in redundancy ratio.

Cascading failures triggered by the disruption in Port of Antwerp

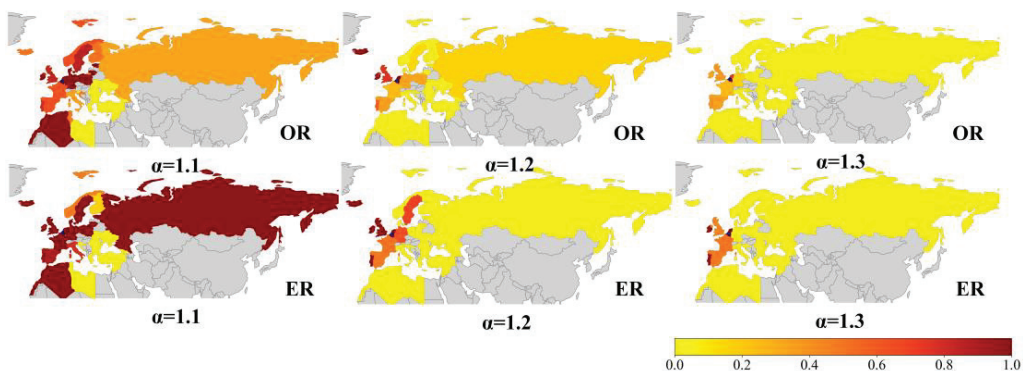


Fig. 5. The impact of cascading failures triggered by the Port of Antwerp on different countries with changes in redundancy ratio.

4. Conclusion

Various port disruptions in recent years have impacted the resilience of European shipping networks and logistics systems. Cascading failures triggered by these events have caused a sudden increase in pressure on key ports and routes, resulting in multiple ports and routes being functionally impaired, creating multi-point failures. Given this context, to further explore the potential damage that cascading failures triggered by port disruptions could potentially cause to the resilience of the ECSN, this study proposes the load

redistribution model based on port importance assessment. Subsequently, two resilience evaluation metrics are introduced to measure the impact of cascade failures on the structure and function at both the network and national levels, respectively. The findings of this study highlight that the stability of key ports is critical for maintaining ECSN resilience. Ports with large capacities (e.g., the Port of Rotterdam and the Port of Antwerp) or those in strategically significant geographic locations (e.g., the Port of Piraeus) require particular attention. Disruptions at these

ports can quickly propagate cascading failures, affecting neighbouring and subsidiary ports.

Therefore, building on this study as a benchmark, future research in this domain can be further refined in several ways. For example, an additional hyperparameter could be introduced to simulate varying degrees of port failure. An adaptive parameter assignment module could also be developed to better reflect the diverse operational redundancies across different ports, improving the model's applicability to real-world scenarios. Furthermore, to enhance resilience analysis, future studies should focus on developing port recovery models that comprehensively capture both the response and recovery phases of port disruptions, providing deeper insights into adaptive strategies and restoration processes.

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References

- Bai, X., Z. Ma, and Y. Zhou. 2023. "Data-Driven Static and Dynamic Resilience Assessment of the Global Liner Shipping Network." *Transportation Research Part E: Logistics and Transportation Review* 170 (February): 103016.
- Cao, Y., X. Xin, P. Jarumaneeroj, H. Li, Y. Feng, J. Wang, X. Wang, R. Pyne, and Z. Yang. 2025. "Data-Driven Resilience Analysis of the Global Container Shipping Network against Two Cascading Failures." *Transportation Research Part E: Logistics and Transportation Review* 193 (January): 103857.
- Cao, Y., X. Xin, X. Wang, and Z. Yang. 2024. "Resilience Analysis of Intra European Container Shipping Network against Cascading Failures." *The 34-th European Safety and Reliability Conference*.
- Gu, B., and J. Liu. 2023. "A Systematic Review of Resilience in the Maritime Transport." *International Journal of Logistics Research and Applications*, January, 1–22.
- Liu, Q., Y. Yang, A. Ng, and C. Jiang. 2023. "An Analysis on the Resilience of the European Port Network." *Transportation Research Part A: Policy and Practice* 175 (September): 103778–78.
- Lu, B., Y. Sun, H. Wang, J. Wang, S. Liu, and T. Cheng. 2024. "Dynamic Resilience Analysis of the Liner Shipping Network: From Structure to Cooperative Mechanism." *Transportation Research Part E Logistics and Transportation Review* 191 (September): 103755–55.
- Motter, E., and Y. Lai. 2002. "Cascade-Based Attacks on Complex Networks." *Physical Review E* 66 (6).
- Xu, M., Q. Pan, A. Muscoloni, H. Xia, and C. Cannistraci. 2020. "Modular Gateway-Ness Connectivity and Structural Core Organization in Maritime Network Science." *Nature Communications* 11 (1).
- Xu, X., Y. Zhu, M. Xu, W. Deng, and Y. Zuo. 2022. "Vulnerability Analysis of the Global Liner Shipping Network: From Static Structure to Cascading Failure Dynamics." *Ocean & Coastal Management* 229 (October): 106325.
- Xu, Y., P. Peng, C. Claramunt, F. Lu, and R. Yan. 2024. "Cascading Failure Modelling in Global Container Shipping Network Using Mass Vessel Trajectory Data." *Reliability Engineering & Systems Safety* 249 (May): 110231–31.
- Zhou, Y., J. Wang, and Q. Huang. 2019. "Efficiency and Robustness of Weighted Air Transport Networks." *Transportation Research Part E: Logistics and Transportation Review* 122 (February): 14–26.