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Shipping network analysis: state-of-the-art and application to the global financial crisis

César Ducruet¹

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Introduction

The empirical analysis of shipping networks, for long a negligible subpart of several disciplines, is increasingly seen as a new emerging field on its own (Kanrak et al., 2019; Ducruet, 2020; Avarez et al., 2021; Shankar et al., 2021). Increased shipping data availability and computational power permitted novel analyses in the domain of big data (Munim et al., 2020). Research is particularly active in specific domains for which recent reviews have already been provided, such as on port and maritime disruptions (Wendler-Bosco and Nicholson, 2020; Nguyen et al., 2022), bilateral connectivity in liner shipping networks (Ansorena, 2018), evaluation methods of port dominance (Wang et al., 2021), and the visualization of vessel trajectory data (Liu et al., 2021), among others. The increasing interest in shipping network analysis resulted in a multiplication of publications. This trend has not been reviewed yet, however, through a systematic bibliometrical analysis. Existing reviews only look at one facet only of the emerging set of studies. Therefore, this chapter confronts such a lacuna head on.

The chosen study period starts in 2007, with the first article in physics dealing with shipping networks (Xu et al., 2007), the first analysis of inter-Korean maritime linkages using Lloyd's List data (Ducruet and Roussin, 2007), and the analysis of Maersk's global port network based on carrier schedule data (Frémont, 2007). As underlined by Ducruet (2020) in his long-term review of maritime network analysis, there were very rare works of the kind since the initial application of graph theory to shipping data in the unpublished PhD dissertation of Robinson (1968), which had no followers. Before 2007, the complex networks framework, which emerged in the late 1990s, had only been applied to other types of (transport) networks, such as airlines, roads, railways, commuting flows, the Internet, and the World-Wide-Web (Ducruet and Lugo, 2013). Lloyd's data was only used in another unpublished PhD dissertation (Joly, 1999) although it proved later on to be a very fertile material to study shipping networks. The case study of Maersk was soon highly cited as a reference for the analysis of shipping line networks and carriers' coverage.

Beyond the review of existing works, this chapter underlines that the global financial crisis (2008-2009) has not been analyzed yet from a shipping network perspective. A new case study is thus proposed based on untapped shipping data, to verify the existence of regularities in the spread of this shock across port hierarchies and geographic scales. Notteboom et al. (2021) recalled that world container shipping demand in TEU-mile fell by 12.4% in 2009 as a result of the crisis, due to order

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postponements or cancellations, vessel layup, suspension of liner services, and slow steaming. Crisis impacts were also on the medium-term, as major mergers and acquisitions only started in 2014, while the bankruptcy of Hanjin Shipping took place in 2016. Their analysis, however, did not include network-analytical tools, and the mapping of port-level traffic changes based on TEU mainly showed an overall growth despite the shock (see also Pallis and de Langen, 2010). It is believed that more complex impacts occurred in terms of connectivity. In addition, the change in 2008-2009 would need to be compared with the previous and next evolutions, 2007-2008 and 2009-2010, to test its specificity and the pattern of recovery.

In the next section, we present an in-depth literature review of shipping network analysis, to better situate our case study. It is followed by a presentation of the shipping data source used to conduct the analysis of the global financial crisis impacts. Main results are provided from diverse angles, documenting centrality shifts across the port hierarchy and geographical scales. We conclude about the contribution of this study to shipping network research.

Literature review: the corpus of shipping network studies

Corpus construction and publication trend

In this chapter, we constructed a corpus of no less than 212 publications on the theme of shipping networks using several criteria (see Appendix 15.1). First, all papers are empirical studies of real-world shipping networks, contrary to most of the literature in operations research and engineering. The latter deploys mathematical programming and modeling to simulate shipping networks for various purposes, such as optimization of ship routing and scheduling. Such a selection criterion allows a discussion on the various types of shipping data used to construct networks. Second, the search in Google Scholar dated 20th October 2022 included all papers mentioning « maritime network » or « shipping network » in their title or abstract, excluding conference papers, books, and book chapters. The retained papers are those published in peer-reviewed academic journals. Third, we excluded the works in history, archaeology, anthropology, and linguistics dealing with shipping networks, to keep a corpus focusing on the contemporary period, and because such disciplines usually work without data. Other works on tactical networks in maritime warfare were also excluded as they focus more on telecommunications between ships.

We selected the time period based on the earlier review by Ducruet (2020) who underlined the sporadic and low number of publications on shipping networks before the late 2000s. Starting in 2007, we collected articles up to present-day, namely over 16 years. As seen in Figure 15.1, the number of articles remained relatively modest until the late 2010s. The year 2018 marks an important turning point, as well as 2022, which recorded the highest number of publications. While the covid-19 crisis has been an important driver of such a trend, this surge of interest had started earlier, driven by other dynamics, as demonstrated in the next sections.

[Insert Figure 15.1 about here]

Content classification and analysis

As illustrated by Tables 15.1 and 15.2, the corpus is marked by an extremely wide diversity of approaches. Certain large categories are even diversified internally, like « maritime transport » including articles in geography, economics, management, and policy. Thus, shipping network

research is not bound to a specific disciplinary focus. The distribution amongst two sub-periods demonstrates the more early involvement of geography for instance, as well as physics/natural sciences, although these two disciplines are not, a priori, the closest to the operational logics of the shipping industry. As underlined by Ducruet (2020) in his previous review, shipping networks, due to their global coverage, high economic importance, and particular topology, have become a study object far beyond industry-specific matters. In natural sciences, engineering and computer science, the focus might be more about the « network » dimension, while transport journals may be more interested by « shipping » issues. The importance of geography comes from the fact that shipping networks can reveal interesting spatial patterns and regional shifts, simply by mapping raw data or by applying particular techniques.

[Insert Table 15.1 about here]

[Insert Table 15.2 about here]

The global nature of shipping networks is well reflected in the predominance of analyses at the world scale, which constitute no less than half of the corpus (Table 15.3). The increasing availability of global-level data motivated scholars to map and analyze the complete maritime system. Increased computational power also allowed to manipulate large datasets. Another particularity, compared with airline network studies for instance, is the overwhelming importance of China (internal and external networks), Asia, Europe-Asia, and the Maritime Silk Road – the latter being understood as an extension of China's influence. Other world regions lag far behind, with the only exception of Europe. Such an emphasis on the « factory of the world » is in accordance with the spatial distribution of the trunk lines connecting major markets, especially because most of the literature is devoted to container shipping. A closer look at authorships reveals that most scholars working on shipping networks actually originate from China (55%), followed by Europe (13%) and the rest of Asia (10%).

[Insert Table 15.3 about here]

The research themes developed in shipping network analyses are very diverse, but dominantly focus on topological aspects (network structure, multilayered network, cluster identification) and port hierarchies, as network analysis allows to complement classic port performance indicators by those of centrality (see Table 15.4). The main goal of such studies is to test the existence of structural properties in the statistical distribution of network-specific indicators. A widely shared experiment in this part of the corpus is the look at degree distribution, to check if the shipping network is « scale-free », i.e. organized around a few large hubs polarizing many small nodes, as in the seminal work of Barabasi and Albert (1999). It is usually found, however, that shipping networks are not as centralized as in the model, due to physical constraints and to polycentricity.

Another important theme is regional inequality, or the uneven distribution of shipping flows through the network, as well as relationships between cities and ports. Very strikingly, only one article was devoted to environmental issues in the whole corpus (Tran and Lam, 2022), despite the surge of interest for this domain in the wider port and maritime literature. Similarly, very little has been done so far about the relationship between shipping networks and the economy in general. Only six articles deal with maritime connectivity as a determinant of trade, using the UNCTAD's Liner Shipping Connectivity Index (Hoffmann et al., 2020; Fugazza and Hoffmann, 2017) or running gravity models on country-level bilateral datasets (Xu et al., 2020; Saeed et al., 2021; del Rosal and Moura, 2022). The impact of oil price fluctuations on shipping network structure was also tested (Yu, 2019). The closest works to industry aspects are those looking at the port networks of ocean carriers, especially in the case of changes induced by strategic alliances or mergers (Yap, 2018; Wang et al., 2020). A

specific case is the study by Ducruet and Itoh (2022) about the influence of technological innovations (i.e., steam, container) on the evolution of shipping network structure.

All in all, we counted no less than 70 different methodologies used in shipping network analysis (see Table 15.4 for the most recurrent). Complex networks is the dominant framework. It is important to note, however, that scholars often use complex networks, graph theory, and social network analysis interchangeably when calculating port centrality/connectivity. Degree centrality, betweenness centrality, and closeness centrality have become very popular measures to characterize and compare ports. At the level of the whole network, degree distribution is frequently accompanied by measures of efficiency (average shortest path length, diameter) and meshedness (density, average clustering coefficient). Table 15.4 provides an additional level of detail whenever possible, as methods such as single and multiple linkage analysis, assortative mixing, bipartite networks, modularity, and hypergraph can be considered as being part of the wider categories of graph theory and complex networks. Many studies, however, only mention the main data source (AIS, carrier schedules) and not the precise method. Studies using big data and simulations models, such as SCGE and machine learning, remain relatively scarce, compared with the ones providing descriptive statistics on network structure and port centrality.

[Insert Table 15.4 about here]

Shocks, crises, and disruptions in shipping networks

Works on vulnerability constitute the second largest category of the corpus by the number of articles. It includes seven articles on the covid-19 crisis, but also on other major events, of which interoceanic canal disruption (Ducruet, 2016; Wu, 2019; Saito et al., 2022) and natural disasters (Shen, 2019; Rousset and Ducruet, 2020; Poo and Zhang, 2022). A wide array of methodologies has been employed to test the robustness or resilience of shipping networks to random or targeted attacks on nodes or on links, based on the idea of the « optimal terrorist » (Earnest et al., 2012). Since shipping networks are not made of tangible infrastructure but of « imaginary routes » (Robinson, 1968), such simulations remain rather abstract compared with the ones performed on land-based networks. Although certain of these experiments attempt to provide potential solutions for rerouting, they do not account for real-world decision-making tools. They mainly serve to advance knowledge in network science about connectivity, from an academic point of view.

Some scholars have tried to identify the effects of economic crises on shipping network structure, such as before and after the global financial crisis (Freire Seoane et al., 2013; Montes et al., 2012; Gonzalez-Laxe et al., 2012). Fang et al. (2018) documented the effects of military conflict, lifted economic sanctions, and government elections on South Asian shipping networks. An early and extreme example of a constrained economy is scrutinized in the work of Ducruet (2008) on North Korea. The multiplication of linkages across the Korean peninsula, as well as among Maghreb ports (Mohamed-Chérif and Ducruet, 2016), was due to the formation of a hub-and-spoke system rather than economic integration.

We find little evidence for the search of regularities in the advent of a shock. Still, when studying the impact of the covid-19 crisis, Guerrero et al. (2022) found that « large ports seem to have resisted better than smaller ports », while small ports with a high clustering coefficient were also more resilient than average, in terms of weighted degree (i.e., total traffic). Despite inherent differences in the nature of the shocks felt at Kobe (Hanshin earthquake), New Orleans (hurricane Katrina), and New York (Twin Towers attack), Rousset and Ducruet (2020) highlighted similar outcomes in all three

cases, namely a subsequent port traffic growth inversely proportional to the distance from the epicenter. When it comes to connectivity gains or losses, most other studies looked at network-level rather than port-level impacts. One exception is Ducruet (2016) when estimating centrality changes in the advent of interoceanic canal disruption, underlining the specific weakness of European ports (see also Lhomme, 2015).

Case study: the shipping network effects of the global financial crisis

Data and methodology

Historical, daily data on containership movements was obtained from Lloyd's List Intelligence, world leader in maritime information and insurance. It allows us to trace the impacts with precision, in order to study port traffic dynamics, network topology, and geographical variations. The datasets cover one entire month of navigation during January 2007, 2008, 2009, and 2010, in order to compare the state of the global container shipping network before, during, and following the crisis. The data is highly accurate and representative as it covers the world's entire container fleet. Comparing network structures based on the same month allows to avoid the likely influence of seasonality on the results.

Methods are borrowed from the field of graph theory and complex networks. For each month, we build a network where ports are nodes and inter-port vessel voyages are links, based on the space-L topology (direct voyages). The retained method is relatively straightforward. Two centralities are calculated for every port each year, namely degree centrality, a local measure (number of links, or adjacently connected ports) and betweenness centrality, a global measure (number of occurrences on all possible shortest paths). Both measures, calculated with TULIP software, are among the most classic ones in network analysis and are very complementary. From different angles, our study will verify the absolute and relative evolution of these two measures across ports of the world.

Preliminary results are provided in Table 15.5. As already depicted in numerous reports and scientific works, world container traffic has declined in 2009 due to the financial crisis, due to recession and dramatic drop in consumer spending. However, the 10.4% drop in traffic remains much stronger than the drop of the number of port nodes (-2.8%) and inter-port links (-5.4%). Thus, trade variations do not necessarily overlap network changes, as the topology has been more resilient than traffic volume. Looking at other global-level measures gives us some hint about the topological effects of the crisis. The decline of both the diameter and the average shortest path length (ASPL) mean that circulations even became more "optimal" (shorter navigation through the network). This would suggest that in 2009, the fall in demand resulted in fewer ports and routes, making the network easier to navigate, but the scores in 2010 had already gone back to previous levels. It is, therefore, tempting to disaggregate the network into different layers to better observe for which nodes and which regions the crisis had been the most critical.

[Insert Table 15.5 about here]

Hierarchical effects

The first hypothesis to test is the existence of hierarchical effects of the crisis among world ports. For each initial year, degree and betweenness have been classified among ten classes (percentiles). Table 15.6 presents the results of the average difference or growth of centrality compared with the

subsequent year per percentile. Prior to the crisis (2008-2007), the average difference of centralities did not show any specific behavior, as low or high values were distributed rather randomly among classes. During the crisis however (2009-2008), there is clear evidence that the largest ports in terms of centrality (average difference) have been the most impacted. This logic continues between 2009 and 2010 albeit with a lower magnitude.

[Insert Table 15.6 about here]

In terms of centrality growth rates, those are higher as the ports are smaller, which recalls the work of Lemarchand and Joly (2009) on the container traffic dynamics of maritime ranges. The authors particularly demonstrated that in a well-integrated port region, there is an inverse relationship between average port throughput and the standard deviation of growth rates along a given period. We confirm such a relationship with Figure 15.2 (a). Figure 15.2 (b) provides a similar result, namely a deviation from Gibrat's Law, whereby (absolute) growth rates of betweenness centrality (2008-2009) are inversely proportional to betweenness centrality in 2008. The major change during and after the crisis is the shift from positive to negative growth rates for the three classes of the largest ports. Growth rates of smaller ports have lowered considerably for betweenness, and became negative for many classes of smaller ports in terms of degree. While smaller ports have recovered rapidly in 2010, the biggest ports still experienced negative growth rates between 2009 and 2010.

[Insert Figure 15.2 about here]

Such evolutions raise a number of questions about the underlying logics at stake across the world port hierarchy and the global container shipping network. Since the mid-1990s, liner shipping networks went through consolidation and optimization (Ducruet and Notteboom, 2012). Growing ship sizes via economies of scale irremediably affected ports, as seen with the concentration of trunk lines at a fewer set of hub ports and gateway ports. After a new escalation of ship size in 2006 (E Class), the largest vessels became demanding for port infrastructures, and fewer ports were capable of handling them (Rodrigue, 2022). This led to the formation of an increasingly centralized system regionally and globally, to such an extent that the shock of 2009 was felt at major hubs mainly.

Geographical effects

Our second hypothesis is that the crisis had geographically differentiated impacts. As a matter of fact, North America, the cradle of the shock, appears in Table 15.7 as the most affected region for all indicators, except for the average growth rate of degree centrality (0.7), which stands before Latin America (-3.7). In terms of recovery (2009-2010), North America has the best score for the average difference of betweenness (and also degree), but the lowest for its growth rate. In comparison, East Asia is the only region having gained absolute betweenness during the crisis, followed by West Asia, the lowest loss. Asia as a whole had already exhibited the highest average difference of betweenness before the crisis (2007-2008). However, such regional dynamics are not a structural trend opposing East and West; they do correspond to the financial crisis itself, given the recovery of North America already in 2010.

In Table 15.8, the geography of crisis impacts is more apparent, at the thinner level of port ranges. For betweenness centrality, The East Coast of North America and Canada have the most negative growth rates between 2009 and 2008, and the first is the strongest absolute loss. For degree centrality, if we exclude West Africa, the strongest absolute losses are found in the Americas:

Caribbean (-3.2), Central America (-2.7), South Pacific (-2.7), North Pacific (-2.6), Caribbean basin (-2.4), North Atlantic (-1.9), and Canada East Coast (-1.3).

We zoom in Table 15.9 on individual ports, focusing solely on the average difference of betweenness, which appeared to be specific to the region in the previous results. The results are striking. While the decreasing order of betweenness centrality loss in 2008-2009 broadly corresponds to the hierarchy of port throughput in TEUs around 2008, there are important discrepancies. New York, which ranked third among U.S. container ports in 2008 for TEUs after Long Beach and Los Angeles, had been the most severely impacted port during the crisis, no less than 5 times more than Long Beach, and 15 times more than Los Angeles. In addition, although North America as a whole recovered from the crisis in 2009-2010 (Table 15.7), this is not the case of New York, which continued to lose centrality in 2010, witnessing the highest loss after Manzanillo in Mexico. As a matter of fact, New York has encountered the world's strongest absolute loss of betweenness centrality of all ports.

[Insert Table 15.7 about here]

[Insert Table 15.8 about here]

Such evidences are only partly in line with observers at the time, who commented the 30% decline of New York port, 25% at Los Angeles-Long Beach, 37% at Seattle, and 31% at both Houston and Charleston (Trotta and O'Connor, 2009). Thus, networks effects do not match TEU figures. One likely explanation is the fact that New York was the epicenter of the phenomenon, while Pacific ports benefited from dynamic trade with Asia, and could recover relatively rapidly, compared with Atlantic and Gulf ports.

[Insert Table 15.9 about here]

Functional effects

One last dimension to consider is the evolution of centrality according to the status or function of ports in the network. The clustering coefficient (percentage of existing triangles in the maximum possible number of triangles) is a relevant measure to express whether a port is a hub or not. The lower the clustering coefficient, the more likely is the port in a dominant position among its neighbors, which can only connect by passing through it (star-shaped system), as in the hub-feeder configuration in liner shipping.

In Table 15.10, we observe a similar distribution than in Table 15.6, namely a stronger impact on the strongest ports. Ports with the lowest clustering coefficient (hubs) have lost centrality in various ways, especially the class situated between 0 and 0.2, which includes ports such as Singapore for instance. Zero values are peculiar as they may correspond to a sink (1-degree nodes or isolated nodes) or to a "pure hub" with no neighbors connected. Thus, except for the growth rate of degree, the class of 0-2 witnessed the most dramatic losses of centrality. This confirms that all facets of connectivity have been impacted by the crisis.

Figure 15.3 wishes to determine whether all hubs have been impacted the same throughout the world. It applies a single linkage algorithm to the 2008 dataset in order to bisect the graph into nodal regions and to reveal the latent hub structure of the network. The main finding is that there is not such a "rule" about the spread of the crisis in relation with hub functions. Some hubs have gained in absolute betweenness in 2009 (e.g., Singapore, Jebel Ali, Busan, Algeciras, Rotterdam, Hamburg)

while others have lost (e.g., Gioia Tauro, Hong Kong, Valencia, Kingston), without necessarily belonging to the same region.

[Insert Table 15.10 about here]

[Insert Figure 15.3 about here]

Discussion and conclusion

Shipping network research is undoubtedly a buoyant field today, given the number of publications and the diversity of approaches. Since the recent review by Ducruet (2020) on maritime networks, the number of articles has nearly tripled, which justifies a new, updated review although the trend may continue in the coming years. What can we learn so far? What are the drivers of such a surge of interest for shipping networks? Are existing studies in line with societal expectations in the light of the current covid-19 crisis, and in relation with shipping industry changes? How does shipping network research contribute to network science in general?

Overall, our review helps to conclude that the majority of shipping network analyses is either abstract or limited to the delivery of very descriptive statistics on network structure or port connectivity. Abstract means that the analysis is conducted in topological space, regardless of real-world circulations or distance metrics. One crucial element to consider is that the abstraction of the shipping network into a graph made of juxtaposed inter-port segments has never been a subject for discussion in this literature. The relevance of such a study object is taken for granted, although in reality shipping networks, especially in container shipping, function more through call sequences. This is partly addressed when considering space-P topology instead of space-L, namely when including indirect linkages between ports (see Hu and Zhu, 2009). But this may be fallacious, as there is no proof that a ship calling at ports A, B, and C creates a link between A and C in addition to A-B and B-C. As mentioned earlier, studies on shipping network vulnerability based on inter-port vessel flows is not self-critical, as such flows are ephemeral and do not constitute proper infrastructure. It is, perhaps, time for deeper collaborations between operations research and complex networks, as the two approaches have significantly ignored each other so far. This would bring network-analytical exercises closer to industry needs and make the results more realistic.

The same applies to port connectivity studies. The meaning of port connectivity is rarely addressed. What does an accessibility indicator mean in a network made of ephemeral linkages? How does it vary over time, especially at a thinner scale than the year? Research on daily, weekly, and monthly shipping network connectivity was proposed, but not sufficiently pursued (Guinand and Pigné, 2015), mainly due to lack of precise data. AIS data is very precise over time and space, but it needs careful adjustments before becoming usable for studying ports (Alessandrini et al., 2017). An overestimation of betweenness centrality, for instance, was found in earlier works (Kaluza et al., 2010), due to the assignment of AIS signals to the wrong port locations. It seems important to shift back the discussion on connectivity within a conceptual framework which has been fiercely left behind, such as the one on centrality and intermediacy proposed by Fleming and Hayuth (1994). Without theory, ranking ports with connectivity may not be much more effective than with any other performance indicator. Efforts to confront connectivity with throughput are, however, a promising direction, as it allows to distinguish size and function of transport nodes, but most analyses neglect such a possibility.

Links between shipping network research and the shipping industry are, to date, very weak. Only five articles dealt with the relationship between network structure and industry changes, such as merger,

alliance formation, and shifts in route deployment. This is largely influenced by the fact that most studies rely on the most recent carrier schedule data at the time of their research, avoiding any possibility to look back in time and analyse possible evolutions. Historical shipping data is relatively expensive, and AIS data cannot go back before the late 2000s. The discovery of the Lloyd's List Intelligence corpus, published daily since the late 19th century and providing information on companies, tonnage, date of build, ports and dates of arrival and departure, and so on, allowed more dynamic analyses (Ducruet et al., 2015), but disaggregated studies at the firm level remain to be done. When it comes to the relationship with the economy, links are also relatively tenuous, as there is no study at the firm level on network structure. There are some works on cities and regions and a few others on trade, but more research is needed on whether and how connectivity fosters urban or economic growth, and the other side of the coin – how shipping networks are influenced by territorial structures. We believe that all these aspects constitute a promising research agenda for future shipping network research.

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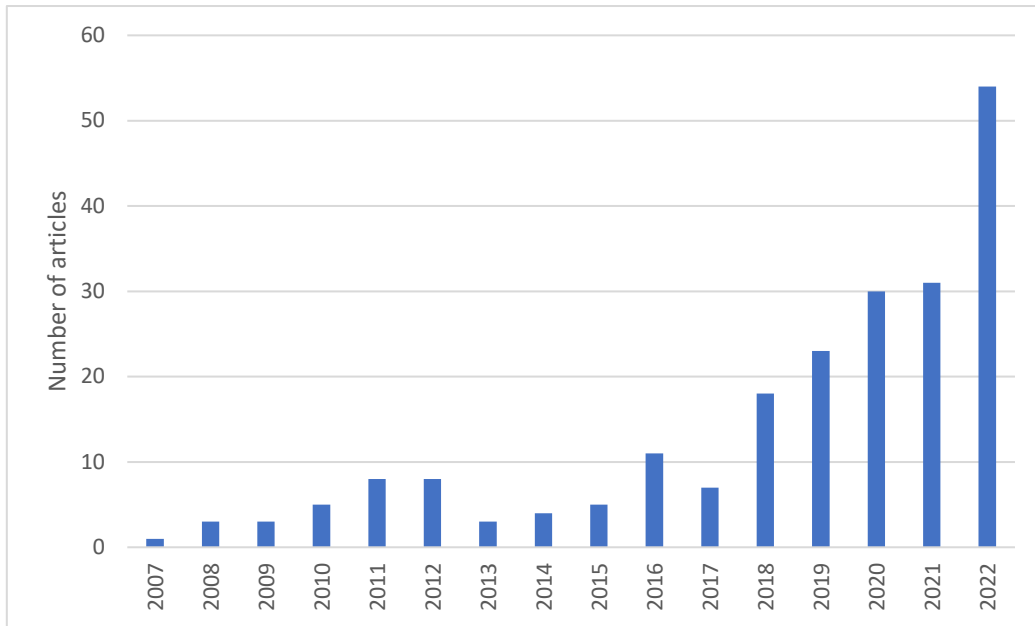


Figure 15.1: Publication trend about shipping networks, 2007-2022

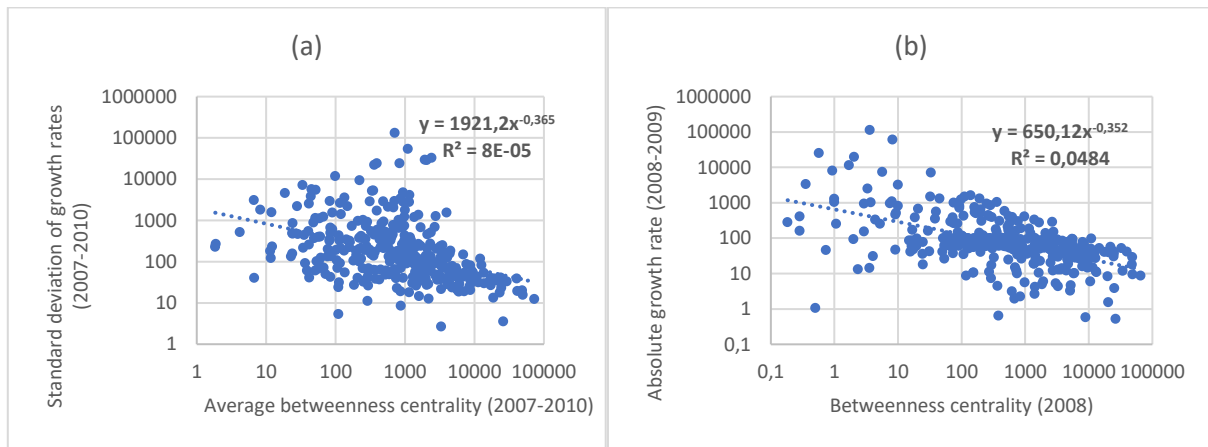


Figure 15.2: Relationship between size and growth at world ports

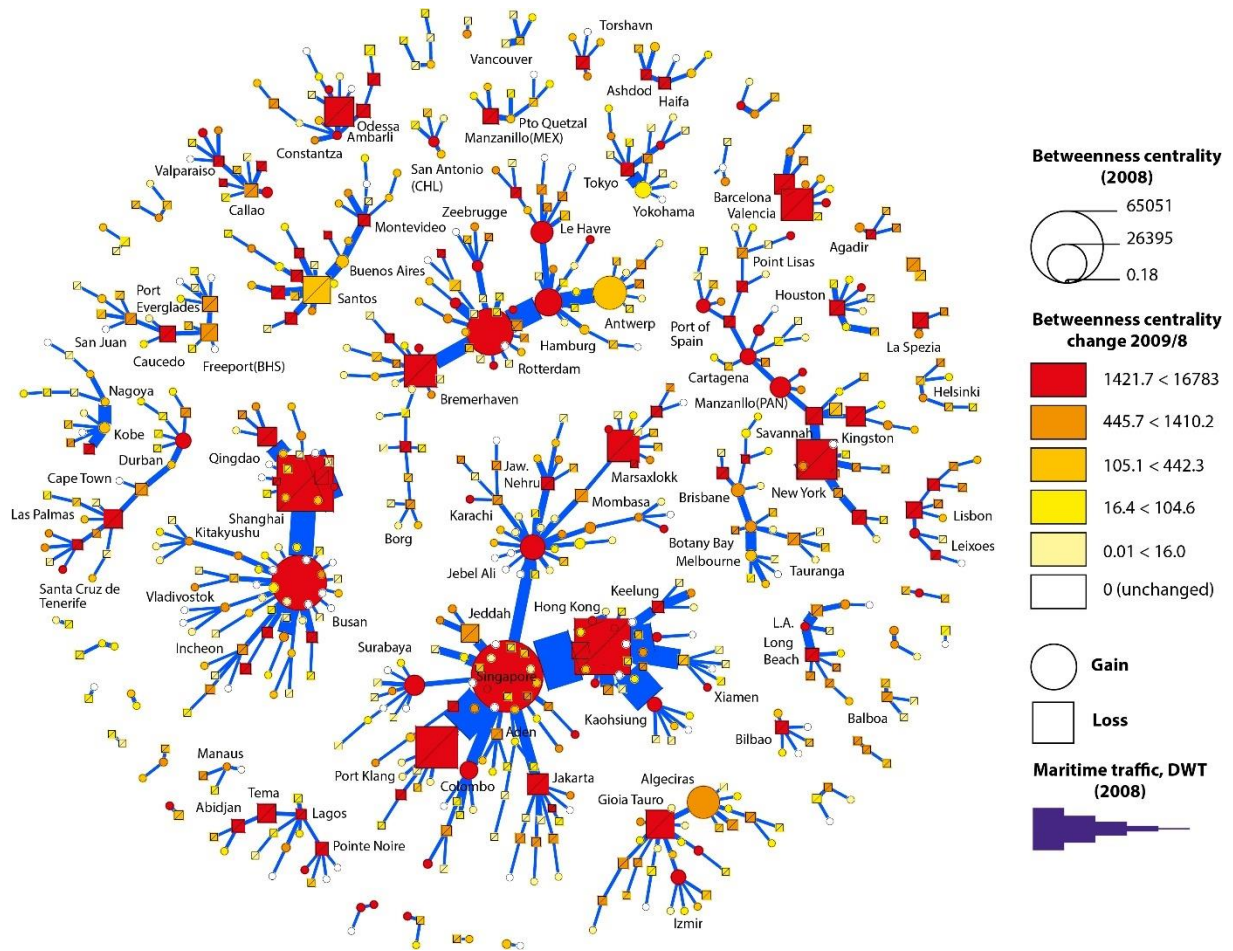


Figure 15.3: Hub structure and centrality changes in the global shipping network

Study area	2007-2017	2018-2022	Total
Maritime transport	13	31	44
Geography	20	24	44
General transport	10	24	34
Multidisciplinary	6	28	34
Engineering & computer science	3	16	19
Physics & natural sciences	7	10	17
Marine sciences	-	9	9
Geosciences	-	8	8
Operational research	-	2	2
Management	-	1	1
Total	59	153	212

Table 15.1: Distribution of articles by journal background

Journal	No. articles
Journal of Transport Geography	26
Maritime Policy & Management	21
Maritime Economics & Logistics	11
Transport Policy	9
Physica A	8
Sustainability	6
GeoJournal	5
Networks and Spatial Economics	5
Transportation Research Part E	5
IEEE Access	4
Ocean & Coastal Management	4
Energy	3
ISPRS International Journal of Geo-Information	3
Journal of Geographical Sciences	3
Reliability Engineering & System Safety	3
Nature Scientific Reports	3
Sensors	3
The Asian Journal of Shipping and Logistics	3
Transportation Research Record	3

Table 15.2: Journals with at least three publications about shipping networks

Area	2007-2017	2018-2022	Total
World	30	58	88
Asia	7	20	27
Maritime Silk Road	-	24	24
China	6	17	23
Europe	3	12	15
Other	6	2	8
Africa	2	3	5
Europe-Asia	1	4	5
Oceania	-	5	5
Americas	2	2	4
Arctic	-	3	3
Caribbean	1	1	2
Antartic	-	1	1
Atlantic	1	-	1
Mediterranean	-	1	1
Total	59	153	212

Table 15.3: Geographic scope of the studied shipping networks

Research themes	No. Articles	Research methods	No. Articles
Network structure	52	Complex networks	56
Crisis/vulnerability	39	AIS	16
Port centrality/connectivity	32	Carrier schedules	15
Multilayered network	14	Composite centrality	9
Regional inequalities	14	Graph theory	8
Cluster identification	10	Geospatial analysis	7
Port-city relationships	6	LSCI	7
Trade determinants	6	Single linkage analysis	7
Carriers' coverage	6	Gravity model	6
Evolutionary dynamics	4	Attack simulation	5
Network optimization	4	Foreland linkages	5
Ship trajectory	4	Social Network Analysis	3
Hub / nodal regions	3	Bipartite networks	2
Throughput determinants	3	Flow-based model	2
Flowmapping	2	Hypergraph	2
Innovation diffusion	2	Machine learning	2
Marine bioinvasions	2	Modularity	2
Environmental impact	1	Multiple linkage analysis	2
Historical	1	SCGE modeling	2
Port choice	1	TOPSIS	2
Price fluctuations	1	Weighted ego network analysis	2
Route volatility	1	Assortative mixing	1
Safety & security	1	Attacker-defender model	1
Second-tier hubs	1	Big data system	1
Shipping demand	1	Bisecting k-means	1

Table 15.4: Research themes and methods developed by shipping network research

	2007	2008	2009	2010
Total traffic (M DWT)	747.3	813.2	729.0	789.9
Number of nodes	662	715	695	700
Number of links	3493	3716	3515	3549
Diameter	10	10	7	8
Density	0.016	0.015	0.015	0.015
Clustering coefficient	0.536	0.549	0.545	0.524
Avg. shortest path length	3.372	3.378	3.348	3.373

Table 15.5: Selected features of the global container shipping network, 2007-2010

Centrality percentiles (initial year)	Betweenness centrality						Degree centrality					
	Avg. Difference			Avg. growth rate (%)			Avg. Difference			Avg. growth rate (%)		
	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9
0 (zero values)	166.9	89.4	128.8	-	-	-	-	-	-	-	-	-
1 (lowest)	151.3	58.7	102.2	8018.9	3903.0	11748.9	1.3	1.5	1.3	126.5	17.9	128.0
2	58.6	457.5	363.0	1096.9	7743.3	4008.0	1.0	1.2	1.2	48.4	-10.2	60.0
3	113.2	81.3	213.2	474.0	242.7	688.3	1.3	0.7	1.1	44.7	-4.9	36.6
4	204.5	109.7	291.4	358.3	139.9	458.1	0.6	-0.2	1.0	14.5	-14.9	23.9
5	429.9	247.9	216.9	322.7	162.6	113.3	0.0	0.2	0.1	0.0	0.7	1.0
6	401.4	310.8	38.7	131.1	88.8	7.6	0.0	-0.2	0.2	-0.2	-7.3	2.7
7	-87.5	307.3	292.3	-13.8	42.1	34.7	-0.2	-0.5	0.6	-1.3	-6.7	5.2
8	320.7	-269.2	-240.4	8.8	-17.6	-17.3	0.5	-1.4	-0.4	3.4	-13.4	-3.1
9	73.0	-1030.9	-134.5	4.4	-29.7	-4.4	0.2	-1.9	-1.5	0.7	-11.3	-6.7
10 (highest)	1399.1	-1823.3	-387.1	8.2	-16.4	-7.2	0.9	-3.2	-1.2	1.3	-7.0	-2.5

Table 15.6: Centrality changes across the world port hierarchy, 2007-2010

World region	Betweenness centrality						Degree centrality					
	Avg. Difference			Avg. growth rate (%)			Avg. Difference			Avg. growth rate (%)		
	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9
Africa	112.9	-147.4	-40.4	2547.5	1233.6	1669.9	0.7	-0.7	0.9	31.5	14.5	45.7
East Asia	304.1	2.8	182.3	737.9	1207.1	752.7	0.8	-1.4	0.1	9.0	2.5	13.9
Europe	257.9	-111.9	113.6	1384.2	2350.8	3214.2	1.0	1.1	0.3	20.0	34.8	16.3
Latin America	246.0	-102.1	-78.8	364.7	264.3	485.1	1.6	-1.9	-0.9	34.9	-3.7	4.6
North America	156.2	-785.9	272.9	1.1	-13.4	467.1	0.1	-2.1	1.6	12.7	0.7	27.9
Oceania	166.2	-125.0	230.2	1791.2	519.1	2225.6	0.9	-1.2	-0.1	22.5	4.2	19.5
West Asia	408.6	-9.4	-149.7	291.2	712.5	1137.3	0.6	0.1	-0.6	6.4	13.7	7.0
World	253.7	-124.7	80.4	1021.3	1218.2	1597.2	0.9	-0.6	0.1	18.8	13.0	17.1

Table 15.7: Centrality changes across world regions, 2007-2010

Port range	Betweenness centrality						Degree centrality					
	Avg. Difference			Avg. growth rate (%)			Avg. Difference			Avg. growth rate (%)		
	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9
North Am. Atlantic	-40.3	-1727.0	185.9	-23.8	-50.0	21.6	-0.3	-1.9	1.2	24.4	-2.0	17.0
Black Sea	839.9	-1009.9	-68.6	169.4	207.2	2137.4	1.3	4.4	-0.4	54.6	110.1	22.4
West Africa	594.4	-878.9	268.5	651.5	177.1	377.5	1.0	-3.2	2.2	53.2	-10.0	93.7
Southwest Europe	148.5	-632.4	285.4	2545.8	1667.3	193.7	0.6	0.5	0.3	21.2	40.8	13.2
Mediterranean*	206.6	-570.5	136.5	2929.1	822.7	1512.0	0.8	2.1	-0.2	27.9	59.3	15.1
U.S. Gulf	410.7	-562.6	64.6	-1.9	50.4	91.1	1.1	-0.3	1.2	36.5	7.8	35.8
Caribbean	647.7	-390.0	-138.8	659.1	491.1	-20.1	4.1	-3.2	-0.2	81.0	-22.4	13.0
Canada East Coast	-457.2	-344.4	228.1	-46.0	-85.3	1530.1	-0.3	-1.3	2.5	-11.1	-11.1	53.6
South Am. Atlantic	260.4	-242.8	203.5	242.1	301.0	643.1	0.7	-0.9	-1.5	15.8	13.8	-9.7
Indian subcont.	414.3	-212.8	90.9	173.8	49.4	1008.2	0.0	-1.8	0.1	4.3	-7.1	13.4
East Med.	356.7	-204.7	-821.0	679.8	196.8	961.1	1.3	2.5	-2.0	5.5	22.9	-8.2
Caribbean**	194.2	-180.6	-275.4	397.7	418.2	634.4	2.1	-2.4	-0.5	49.3	-6.8	14.3
North Am. Pacific	70.6	-142.9	695.9	-24.1	25.0	811.7	-0.2	-2.6	2.1	-4.5	-7.5	25.2
Oceania	166.2	-125.0	230.2	1791.2	519.1	2225.6	0.9	-1.2	-0.1	22.5	4.2	19.5
Northeast Asia	310.8	-69.9	-163.5	1004.1	1430.7	805.4	0.5	-1.8	0.2	4.5	-4.6	21.9
Red Sea	-81.8	18.8	4.7	-99.3	1013.0	11.3	1.0	1.5	-1.0	-12.5	23.3	-11.1
North Africa	-42.1	37.9	297.0	4448.6	22.4	4165.1	0.7	2.2	0.6	23.5	45.0	16.4
Central Am.	220.2	93.6	-897.0	120.1	11.0	1086.3	0.9	-2.7	-0.3	19.9	3.4	28.7
Southeast Asia	288.8	164.0	952.5	176.0	696.0	635.7	1.3	-0.4	-0.2	19.1	18.3	-4.1
Scandinavia	18.7	236.5	208.4	349.7	3335.8	11823.7	0.6	0.5	0.6	12.9	14.1	21.2
South Am. Pacific	-7.0	259.7	-70.2	450.6	55.6	106.7	1.3	-2.7	0.0	21.1	-21.2	23.4
Persian Gulf	529.8	307.6	-393.3	548.7	1426.4	1022.9	1.4	1.3	-1.2	12.8	26.2	2.0
Southern Africa	-308.6	556.1	-805.5	3347.2	4110.3	419.8	0.1	-0.4	-0.7	17.4	17.1	12.4
Northwest Europe	354.0	666.5	64.5	1211.8	3382.0	107.6	1.5	0.7	0.8	12.3	15.4	19.3

* combination of Southwest Europe, North Africa, and East Mediterranean

** combination of U.S. Gulf and Caribbean

Table 15.8: Centrality changes across world port ranges, 2007-2010

Port	Range	2008/7	2009/8	2010/9	Port	Range	2008/7	2009/8	2010/9
New York	USA	8110	-16783	-2149	Boston(USA)	USA	-1455	-26	176
Long Beach	USP	2968	-3422	1585	Seattle	USP	462	-13	1568
Houston	USG	3881	-3360	35	Portland(OR USA)	USP	-274	-13	30
Charleston	USA	-2528	-2783	123	Tampa	USG	-20	-7	21
Manzanillo(MEX)	MEX	5784	-2112	-3608	Saint John(CAN)	CAN	0	-3	0
Savannah	USA	2193	-1500	1890	San Francisco	USP	-12	-2	10
Port Everglades	USA	1752	-1248	1267	Wilmington(NC USA)	USA	-23	0	43
Los Angeles	USP	49	-975	1670	Freeport(Texas)	USG	0	0	0
Portsmouth(VA USA)	USA	-2205	-793	481	Port Arthur	USG	0	0	-
Montreal	CAN	-180	-557	-	Kodiak	USP	0	0	0
Halifax	CAN	-1192	-474	456	San Diego	USP	-118	0	21
Palm Beach	USA	595	-442	-421	Prince Rupert	USP	0	16	-9
Lazaro Cardenas	MEX	355	-440	941	Honolulu	USP	-116	29	335
Jacksonville	USA	-480	-379	-501	Altamira	MEX	-43	30	-34
Veracruz	MEX	-680	-271	10	Mazatlan	MEX	-18	37	-
Philadelphia	USA	-3829	-246	19	Mobile	USG	-4	41	14
Miami	USA	-1988	-242	2058	Fraser River Port	USP	-41	48	-39
Vancouver(CAN)	USP	-49	-141	7	Ensenada(MEX)	MEX	48	194	904
Baltimore	USA	-52	-123	3	Norfolk(USA)	USA	-58	490	-372
Wilmington(DE USA)	USA	129	-104	-14	Tacoma	USP	-1842	989	306
New Orleans	USG	-166	-51	253	Oakland	USP	-109	1628	3564

Table 15.9: Betweenness centrality absolute evolution at North American ports, 2007-2010

Clustering coefficient	Betweenness centrality						Degree centrality					
	Avg. Difference			Avg. growth rate (%)			Avg. Difference			Avg. growth rate (%)		
	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9	2008/7	2009/8	2010/9
0	125.0	-60.9	44.2	-73.1	1098.7	1621.0	0.1	1.4	0.5	-23.3	120.5	30.0
0 – 0.2	3319.9	-1444.1	763.9	3074.4	-16.7	57.1	4.6	-2.6	-0.2	32.8	-5.5	0.1
0.2 – 0.4	624.5	-487.5	-39.0	1257.9	923.4	3144.9	2.0	-1.7	-0.4	29.0	-5.6	10.5
0.4 – 0.6	-76.6	88.4	189.2	733.9	78.2	362.8	0.6	-1.1	0.6	24.8	-8.6	23.5
0.6 – 0.8	-94.1	192.5	-5.7	1785.0	2258.9	1775.5	0.4	-0.2	0.1	33.8	0.2	14.2
0.8 – 1	-80.1	102.6	-11.1	-75.4	4788.8	1014.6	0.2	0.6	0.2	-0.8	27.3	21.2

Table 15.10: Centrality evolution and hub functionality across world ports, 2007-2010

Appendix 15.1: Corpus of selected shipping network studies

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